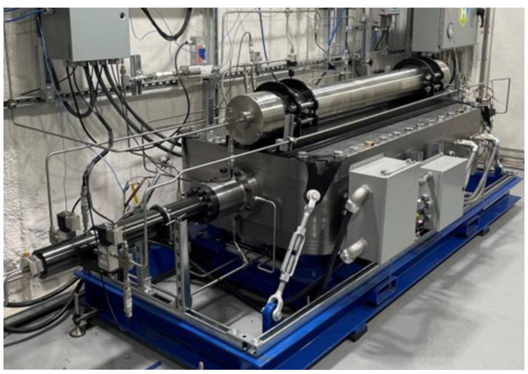
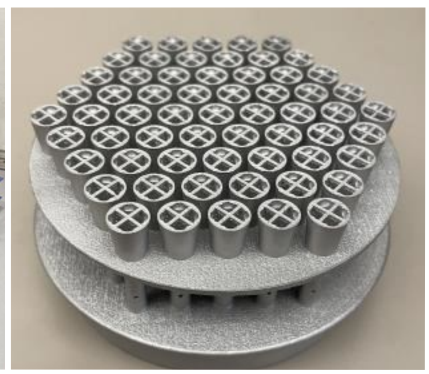
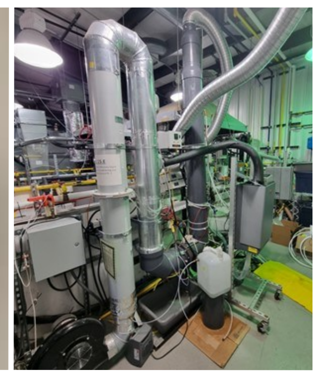
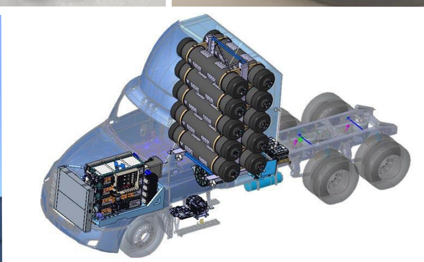
UTD

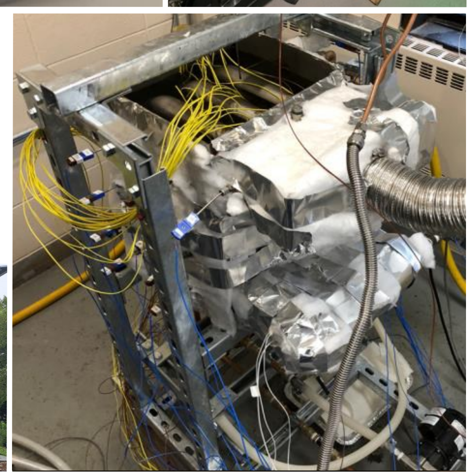
Utilization Technology Development

RESEARCH PROJECT SUMMARIES

2022-2023







Utilization Technology Development, NFP
RESEARCH PROJECT SUMMARIES
2022 - 2023

Legal Notice

UTD RESEARCH PROJECT SUMMARIES
2022 - 2023

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Letter to Our Stakeholders

Twenty-one leading North American utilities that supply gaseous fuel are addressing energy use opportunities and challenges for their 37+ million customers through Utilization Technology Development, NFP (UTD), a not-for-profit applied research organization. UTD-sponsored researchers create, develop and demonstrate new products and technologies in partnership with the U.S. Department of Energy (DOE), California Energy Commission (CEC), Propane Education & Research Council (PERC), national laboratories, university researchers, entrepreneurs, leading manufacturers, utility customers, and others.

Accelerating the availability and use of higher-efficiency, gas-fired technologies and products will hasten market transformation and help ratepayers continue to enjoy affordable energy costs while leveraging the superior reliability and resiliency of the underground gas distribution system. One example is gas-fired heat pumps (GHPs) which provide efficiencies far greater than 100%. This past year saw significant developments for GHPs, including the start-up of the ANESI GHP factory production line after long-time technical development support from UTD.

This report summarizes 70+ UTD-sponsored research projects to advance innovations spanning residential, commercial, industrial, and clean transportation markets. These projects enable more integration of renewable energy (e.g. via solar thermal and PV, renewable natural gas, or hydrogen), reduce emissions, and enhance the efficiency, safety, and resiliency of end-user operations. These innovations also help UTD members strengthen their utility energy efficiency, emerging technology, and market transformation programs.

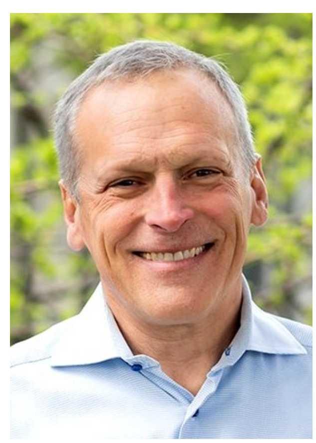
We thank the researchers, innovators, governmental funding agencies, and partners from academia, industry and elsewhere who work with us to advance applied research. UTD's efforts reduce GHG and other emissions, increase the use of renewable energy while handling supply variability, and retain affordable energy choices for consumers while addressing society's environmental challenges and need for economical, resilient, reliable energy.

UTD Members

> APGA Research Foundation
> Atmos Energy Corporation
> Dominion Energy
> DTE Energy
> Duke Energy
> Enbridge Gas
> Intermountain Gas Company
> Louisiana R&D Committee
  - Atmos Energy Corporation
  - CenterPoint Energy, Inc.
  - Entergy Corporation
> National Fuel Gas Distribution Corp.
> National Grid
> New York State Electric & Gas Corp./ Rochester Gas and Electric Corp.
> NW Natural
> Nicor Gas
> Oklahoma Natural Gas Company
> Pacific Gas and Electric Company
> Peoples Gas, a WEC Energy Group Co.
> Southern California Gas Co., a Sempra Energy Utility
> Southwest Gas Corporation
> Spire Energy
> TECO Peoples Gas

Joann Wehle
Chair

Ron Snedic
President



UTD IMPACT

Utilization Technology Development

December 2023

Leading researchers, entrepreneurs, universities, governmental agencies, governmental laboratories, customers, manufacturers, and others partner with UTD as a 501(c)(6) not-for-profit organization of utilities to develop and demonstrate affordable new gas solutions for end users, and accelerate the transition to a lower-carbon future.

Development and demonstration of economical new products, systems, and technologies helps customers save money, save energy, reduce GHG emissions, integrate renewable energy (including renewable natural gas and RE-derived hydrogen), and maintain safe, reliable, resilient operation of their homes and facilities with superior environmental performance.

Please contact us if you have any questions about UTD.

Ron Snedic (1.847.768.0572) **Rich Kooy** (1.847.768.0512)

UTD's 20 members serve more than 37 million natural gas customers in North America.

UTD helps utilities create exciting new products for their customers and maximize the impact of their energy-efficiency programs.

Together we're shaping the energy future with clean, efficient end-use technologies.

Visit www.utd-co.org for more information.

COMMERCIALIZED PRODUCTS

SMTI ANESI Gas-fired Absorption Heat Pump for Space Heating and/or Water Heating

Provides AFUE-rated efficiency of 140% (~45% gas savings) with ultra-low NOx emissions of ≤14 ng/J while using zero GWP fluids, and performs reliably in extreme cold weather. Commercially introduced in 2023 after long-term technology RD&D support from UTD, including laboratory work and prototype field applications in CA, WI, IL, TN and Canada, with support from U.S. DOE, CEC and others.

SMTI ANESI
Scott Reed
818-421-4229
sreed@stonemtntechnologies.com
www.AnesiComfort.com

Lochinvar XRGI MicroCHP

Lochinvar's XRGI efficiently produces heat and 24kW of power from the same fuel source. UTD collaborated with the CEC, SoCalGas and the others to advance this engine-based micro-CHP system towards compliance with California Air Resource Board requirements. UTD is also prototyping its use for multi-family buildings or multi-unit applications.

Lochinvar
Eric Morrow
615-318-4919
enmorrow@lochinvar.com
www.lochinvar.com

COMMERCIALIZED PRODUCTS (continued)

CleanO2 CarbinX™ Carbon Capture

CleanO2’s revolutionary CarbinX unit captures CO2 from the flue gas of boilers and furnaces to reduce GHG emissions, and turns it into a beneficial consumer product. UTD’s members provided technology development expertise and support to CleanO2 since 2018 to refine early prototypes and partner with CleanO2 to identify and make product improvements.

CleanO2, Inc.
Jaeson Cardiff
carbinX@cleano2.ca
www.carbinx.com

Yanmar 3-Pipe Engine-driven Gas Pump

Yanmar’s 3-pipe, 14-ton Gas Heat Pump (GHP) with variable refrigerant flow (VRF) offers an important energy-efficiency option for the North American market by combining heat recovery with simultaneous heating and cooling. In a 2018-23 field tests, UTD validated equipment performance and produced public summaries of the results.

YANMAR America Corp.
Eddie Caton
770-877-7733
eddie_caton@yanmar-es.com
www.yanmar-es.com

GRIDIRON PowerPlant™ H24 and HA65

The PowerPlant HA65 from GRIDIRON (formerly M-Trigen) provides high-efficiency microCHP with integrated cooling to homeowners, small businesses, and other users. UTD provided technical support for a notable demonstration by partnering with NYSERDA, National Grid, NJNG, and PERC to independently validate performance. UTD also supported GRIDIRON in its optimization of PowerPlant HA65 to minimize emissions, and its development of PowerPlant H24.

GRIDIRON
713-574-4506
info@gridironenergy.com
www.gridironenergy.com

Sierra™ Engine-driven Gas Heat Pump

Sierra’s (formerly NextAire™) 11-ton packaged GHP can efficiently heat and cool commercial buildings (up to 1.4 COP) while reducing electric demand. Also available are 8- and 15-ton GHPs with VRF multizone capabilities. UTD’s field studies are supporting best practices for siting. UTD partnered with NYSERDA and National Fuel in a field test in NY state.

Blue Mountain Energy
Tom Young
702-339-7395
tyoung@bluemountainenergy.com
www.bluemountainenergy.com

Cannon Boiler Works Ultramizer®

The Ultramizer is an advanced heat-and-water recovery system for larger commercial and industrial boilers, of which there are more than 140,000 in the U.S. It increases boiler efficiency from 80% to 93% - saving customers 15% in energy while also reducing water demand.

Cannon Boiler Works, Inc.
Chris Giron
724-335-8541 x414
sales@cannonboilerworks.com
www.cannonboilerworks.com

U.S. Boiler K2 High Efficiency Gas Boiler

The K2 high efficiency condensing gas boiler offers 95% AFUE with 10:1 turndown, and uses a novel sheet metal burner from Europe. UTD validated its performance via laboratory tests to support potential gas utility MT incentives, and identified pathways to achieve <5 ppm NOx emissions.

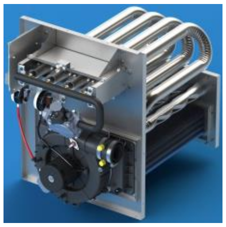
U.S Boiler Inc.
Craig Eshenaur
717-239-4490
ceshenaur@usboiler.net
www.usboiler.net

COMMERCIALIZED PRODUCTS (continued)

Condensing Dedicated Outside Air System/Rooftop Unit

Condensing heating versions of Munters Dedicated Outside Air System (DOAS) and other rooftop unit (RTU) products increase heating efficiency from 80%-81% to 90%-93%. Multiple RTU manufacturers are now offering DOAS with 90+% efficiencies, facilitated by the availability of condensing duct furnace modules first developed with UTD support.

Munters Corporation
Larry Klekar
210-249-3883
larry.klekar@munters.com
www.munters.com



Condensing Duct Furnace Modules

High-efficiency condensing heating modules developed with UTD support are now available from Beckett Gas and other OEMs, including Heatco, and are being applied to DOAS and other products including Make-Up Air Units available from multiple manufacturers including Aaon, Daikin, and RuppAir.

Beckett Gas, Inc.
Joel Mohar
440-783-7610
jmohar@beckettcorp.com
www.beckettgas.com

Gas Quality Sensor

The Gas Quality Sensor (GQS) uses solid-state infrared light absorption spectroscopy to measure Btu content and composition of natural gas and bio-methane fuels. It provides faster response at much lower cost than a gas chromatograph. It was developed with UTD support and was commercially introduced by CMR Group in 2019.

CMR Group
Jon Stendbebach
724-452-2200
918-407-4005
jon.stendebach@cmr-group.com
www.cmr-group.com

Dettson Chinook Low-Capacity Furnace

This novel low-capacity furnace permits right-sizing for low-load buildings and aids integration with renewable energy and improved building envelopes. UTD researchers identified best application practices and provided supporting technical info.

Dettson
Philippe Verhas
1-800-567-2733
pverhas@dettson.ca
www.dettson.com

iFLOW and Advanced Combination Systems

UTD researchers demonstrated how a forced-air condensing tankless water heater combi system using the iFLOW can achieve 30-50% energy savings relative to best-in-class condensing furnaces and water heaters, and used a rigorous Virtual Test Home analysis to assess annualized performance.

iFLOW
Steve Bagshaw
1-800-985-9227 ext 102
steve.bagshaw@iflowhvac.com
www.iflowhvac.com

S.U.N. Equinox Solar-Assisted Heating System

The Equinox system is a combination solar/natural gas water heating system that uses an efficient evacuated tube design. It can be used in residential, commercial, or industrial locations and can meet 100% of domestic hot-water and space heating needs. UTD validated its energy performance in a field demonstration.

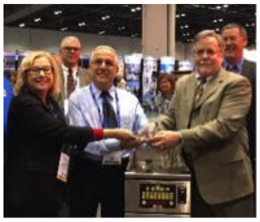
Solar Usage Now, LLC
Thom Blake
260-657-5605
tblake@solarusagenow.com
www.solarusagenow.com

iGEN Self-Powered Furnace

The innovative iGEN furnace generates its own electric power and contains an integrated battery, providing homeowners with continuous heating even during electricity outages. UTD supported the technical refinement of this product with laboratory testing, validation, and recommendations.

iGen Technologies
Michael Chatzigrigoriou
letstalk@igentechnologies.ca
www.igentechnologies.ca

COMMERCIALIZED PRODUCTS (continued)



ENERGY STAR® Fryers

Royal Range introduced the high-efficiency RHEF-75 fryer in 2019 - building on the success of the smaller-capacity, high-efficiency RHEF-45 fryer that received the National Restaurant Association's Kitchen Innovation Award and GFEN's Blue Flame Product of the Year Award. Independent testing showed 63% heavy-load cooking energy efficiency.

Royal Range of California
Robert Lutz
951-360-1600
robert@royalranges.com
www.royalranges.com

Low-Oil-Volume Fryers

Marketed by Frymaster as Protector® fryers, this equipment increases energy efficiency while also extending cooking-oil quality and life to provide significant customer savings. Field demonstrations completed by UTD have shown an average savings of $4,800 per year per fryer.

Frymaster
800-221-4583
www.frymaster.com

ENERGY STAR Conveyor Oven

ENERGY STAR rated conveyor ovens from Lincoln include an advanced energy-management system to reduce energy consumption up to 38%.

Lincoln, a division of Manitowoc Foodservice
260-459-8200
www.lincolnfp.com

ENERGY STAR Convection Oven

This unit showed improved efficiency and 40% energy savings compared to a standard oven during field testing and achieved an ENERGY STAR rating.

Garland
905-624-0260
www.garland-group.com

High-Efficiency Broiler

This broiler features infrared burners and an energy-saving hood that showed an average of 23% energy savings during field testing. It offers more efficient cooking as well as reducing heat gain to the kitchen.

Royal Range of California
800-769-2414
www.royalranges.com

ENERGY STAR Countertop Steamer

A compact, gas-fired countertop steamer for commercial foodservice offers enhanced cooking rates while providing energy savings and reduced water consumption. It was the first gas-fired boilerless steamer on the market and received an ENERGY STAR rating.

Market Forge Industries Inc.
617-387-4100
866-698-3188
custserv@mfii.com
www.mfii.com

High-Efficiency Broiler

The Montague Company commercialized a version of the advanced broiler technology using thermostatic broiler-temperature control and an energy-saving hood. It was recognized with a Kitchen Innovations Award in 2013.

Montague
800-345-1830
www.montaguecompany.com

COMMERCIALIZED PRODUCTS (continued)

Cummins Westport 8.9L Near-Zero Emission NGV Engine

This 8.9L 320-HP NGV engine is widely used, with 50,000+ engines sold for transit, refuse-collection, and regional hauling applications since 2007. In 2016, it was advanced to become the first engine certified in North America to meet the 0.02 g/bhp-hr optional Near Zero (NZ) NO_x emissions standard (i.e. 90% lower than the current EPA NO_x limit of 0.2 g/bhp-hr).

Cummins Westport Inc.
Yemane Gessesse
812-377-5000
yemane.gessesse@cummins.com
www.cumminswestport.com

Cummins Westport 6.7L Medium-Duty NGV Engine

This 6.7L 240-HP natural gas vehicle (NGV) engine is used in school buses, shuttle buses, medium-duty trucks, and other vocational uses. It went into full commercially production in December 2016. It meets U.S. 2017 EPA GHG requirements as well as NZ NO_x emissions standard of 0.02 g/bhp-hr.

Cummins Westport Inc.
Yemane Gessesse
812-377-5000
yemane.gessesse@cummins.com
www.cumminswestport.com

Cummins Westport 11.9L Near-Zero Emission NGV Engine

This 11.9L 400-HP NGV engine is used in large trucks, buses, and refuse vehicles. Engine sales since 2013 are approaching 10,000 units and 25,000+ engines will likely be sold in N.A. by 2020, yielding emissions reductions and $600+ million in annual fuel sales. In Model Year 18, it became CWI's second engine certified to meet NZ NO_x emissions standard of 0.02 g/bhp-hr.

Cummins Westport Inc.
Yemane Gessesse
812-377-5000
yemane.gessesse@cummins.com
www.cumminswestport.com

EcoZone Ribbon Burner System

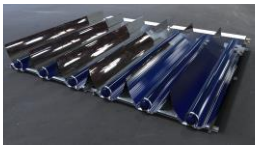
UTD and SoCalGas are supporting the demonstration of Flynn Burner's advanced new EcoZone combustion system which integrates traditional ribbon burners with metal-fiber infrared burners. An installation in California at a large commercial bakery operated by a leading U.S. grocer will evaluate NOx and CO_2 emission reductions.

Flynn Burner
Travis Eddy
518-791-7682
travise@flynnburner.com
www.flynnburner.com

Heat Sponge Economizer for Industrial/ Commercial Boilers

In either condensing or non-condensing configurations, this heat recovery system for commercial and industrial boilers (over 140,000-unit market in U.S.) increases boiler efficiency from 80% to a range of 85%-93% (validated by UTD lab testing). It also saves customers 5%-15% in annual energy costs. UTD completed a field test in Utah to validate energy savings.

Boilerroom Equipment, Inc.
866-666-8977
www.heatsponge.com

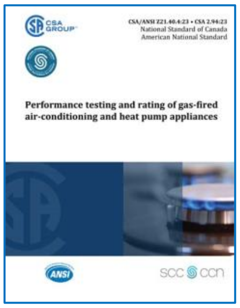


External Concentration Parabolic Collector

This patented, non-tracking, extremely-low-profile concentrator can achieve 200°C (392°F) solar thermal energy to economically serve commercial and industrial facilities and reduce GHG emissions. It can also be integrated with natural gas as a supplemental energy source. UTD provided technical and product development support and experimental validations over a seven-year period.

Artic Solar Inc.
Bill Guiney
904-513-4638
bill@articsolar.com
www.articsolar.com

KEY INFORMATION & ANALYTICAL TOOLS



CSA/ANSI Z21.40.4-23/CSA 2.94-2023 Performance Testing and Rating of Gas-Fired Air Conditioning and Heat Pump Appliances Technical Committee Support

ANSI/CSA Z21.40.4 issued in 2023 and was a major upgrade and update to the 1996 edition of this Method of Test for GHPs. Updates included: increasing what can be rated with residential seasonal efficiency metrics; enhanced calculations and test conditions to better reflect systems designed for heating operation; more optional operating points; and expanded scope to include VRF-type engine-driven systems. UTD supported participation on the Technical Task Force that updated the Standard.

Available at https://webstore.ansi.org

Reliability, Cost and Environmental Impacts of Standby Generation Systems

Generac's website provides technical information related to emissions, reliability and costs of natural gas generators that was developed with UTD's support. For example, UTD researchers published a white paper that provided new data on the reliability of natural gas service and assisted in the development of a Total Cost of Ownership calculator that compares emissions and costs of natural gas vs. diesel-fueled standby generators.

Available at https://www.gti.energy/wp-content/uploads/2019/02/Assessment-of-Natural-Gas-Electric-Distribution-Service-Reliability-SummaryReport-Jul2018.pdf and https://www.generac.com/Industrial/all-about/natural-gas-fuel

U.S. DOE Building America

Under five separate UTD projects from 2011 to 2021, UTD has developed key information and tools to support the U.S. DOE's Building America research, development, and demonstration program, which helps accelerate use of best practices by residential builders, remodelers, installers, code officials, designers, raters, teachers, and others.

Available at https://www.gti.energy/BuildingAmerica and https://basc.pnnl.gov/library

Commercial Foodservice (CFS) Equipment Calculator

This website provides the restaurant industry and others with information and tools to determine the economic and environmental benefits of using new, more advanced and efficient CFS equipment. The website was developed with UTD support and has been showcased at several restaurant trade shows. Further enhancements are underway in 2023.

Available at http://cfscalc.gastechnology.org. For more info, contact Frank Johnson; fjohnson@gti.energy

Commercial Foodservice Energy Monitoring Systems (FEMS)

A real-time energy monitoring system for use in cooking demonstrations, trade shows, test kitchens, and similar venues was developed to help CFS customers better understand the GHG reduction and economic benefits of using higher-efficiency equipment.

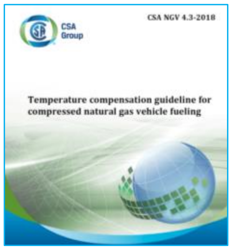
For more info, contact Shawn Scott; sscott@gti.energy

Virtual Test Home

A Virtual Test Home (VTH) in a laboratory was developed with UTD's support. The VTH holistically analyzes equipment and system performance by assessing part-load, annualized performance for various locations. The VTH helps accelerate the adoption of advanced gas technologies (such as GHPs, combis and modulating furnaces) in the marketplace and in performance assessment tools such as U.S. DOE's *EnergyPlus*™ or other energy software.

For more info, contact Tim Kingston; tkingston@gti.energy An overview is also available at https://neea.org/product-council-documents/virtual-test-home

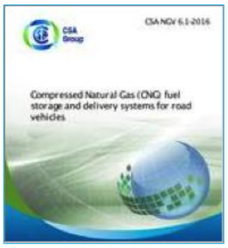
KEY INFORMATION & ANALYTICAL TOOLS (continued)



CSA NGV4.3 NGV Storage and Delivery Standard Technical Committee Support

CSA NGV4.3 was updated in 2022 and specifies requirements for temperature compensation control used to prevent compressed natural gas (CNG) dispensing systems from exceeding a safe fill level of vehicle fuel storage container(s). It contains safety performance guidelines and field evaluation methods for existing dispensing systems. UTD supported participation to lead the Technical Task Force that created the Standard in 2018 and updated it in 2022.

Available at www.csagroup.org



CSA NGV6.1 NGV Storage and Delivery Standard Technical Committee Support

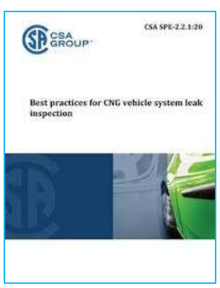
CSA NGV6.1 was introduced in 2016 and defines the requirements for the balance of systems and equipment onboard a NGV, which is not otherwise defined by NGV1 for the receptacle or NGV2 for the storage containers. UTD supported participation on the Technical Committee.

Available at www.csagroup.org

CSA NGV5.1 and NGV5.2 Fueling Appliance Standard Technical Committees Support

CSA NGV5.1 was introduced in 2015 and updated in 2016, and provides mechanical, physical, and electrical requirements for residential fueling appliances (RFAs) that dispense natural gas for NGVs, including indoor and outdoor fueling appliances that connect to residential gas piping. A complimentary standard, NGV5.2 for vehicle fueling appliances (VFAs) in non-residential locations, has been developed and was published in late 2017. UTD supported participation on both of the Technical Committees.

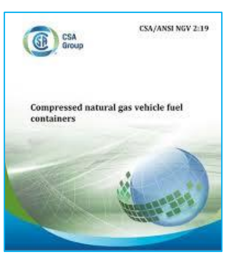
Available at www.csagroup.org



CSA SPE-2.21.1:20 Best Practices for CNG Vehicle System Leak Inspection Standard Technical Committee Support

In 2020, the first edition of CSA SPE-2.21.1 was published. It provided additional specific guidance and best practices to enhance user safety and mitigate potential leaks. Recommendations regarding in-service leak detection, inspection and repair are provided, including leak detection methods. UTD supported participation on the Technical Committee.

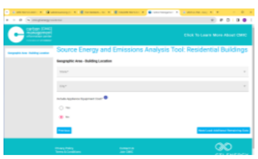
Available at www.csagroup.org



CSA NGV2 CNG Vehicle Fuel Containers Standard Technical Committee Support

The sixth edition of CSA NGV2 issued in 2019 and contains updated information and requirements for the material, design, manufacture and testing of serially-produced, refillable Type NGV 2 containers intended only for the storage of CNG for vehicle operation. The 2019 revision includes localized fire tests and conformable storage topics. UTD supported participation to lead the Technical Task Force that created the Standard.

Available at www.csagroup.org



Source Energy and Emissions Analysis Tool

The Source Energy and Emissions Analysis Tool (SEEAT) calculates source energy and greenhouse-gas emissions related to point-of-use (site) energy consumption by fuel type for each energy-consuming device in residential and commercial buildings. The methodology accounts for primary energy consumption and related emissions for the full fuel cycle.

Available at https://cmic.gti.energy/residential and https://cmic.gti.energy/commercial

TECHNOLOGY ADVANCEMENTS

Hydrogen-Blended Gas in Residential, Commercial and Industrial Applications

UTD is performing substantial testing on the blending of hydrogen into natural gas and the performance of blended fuels in multiple categories of equipment that are commonly used in residential, commercial and industrial applications. UTD is also developing new burner technologies that can operate on up to 100% hydrogen fuel.

Project Managers: Multiple

Robur K18 Gas Heat Pump for Residential Space Heating and/or Water Heating

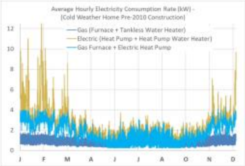
UTD is supporting the potential introduction into the North American market of Robur's K18 Gas Absorption Heat Pump. This 60,000 Btu/hr thermally-driven air-source heat pump will offer very high efficiency operation, with support from a long-established manufacturer. UTD is performing laboratory testing to establish detailed performance curves, which can be incorporated into energy modeling tools in order to accelerate product adoption in North America.

Project Manager: Alejandro Baez Guada

Ultra-Low NO_x Burner

This innovative firetube boiler technology has more than three years of proven successful operation at a Mission Linen Supply facility in California. It improves efficiency and achieves NO_x emissions below 9 vppm, while avoiding the significant efficiency, capital cost, and/or operating cost penalties if conventional Selective Catalytic Reduction or burner enhancements such as external Flue Gas Recirculation and/or High Excess Air firing were used.

Project Manager: David Cygan



Hybrid Fuel-fired and Electric-driven ResCom HVAC Systems

Researchers are evaluating emerging or commercially-available hybrid gas furnace/electric heat pump products in the North American market, in order to identify the more promising hybrid systems and develop installation and operation guides that can help end users accelerate their integration of electricity derived from renewable energy with fuel-fired equipment.

Project Manager: Navin Kumar

FlexCHP High-Efficiency Ultra-Clean Power and Steam Package

This innovative CHP package allows flexible steam production while meeting stringent California emission levels without a SCR system and across the full range of firing rates — achieving NO_x levels 50% below CARB limits. An installation in California operates with 84+% system efficiency and system emissions well below 9 ppm NO_x. UTD has provided long-term support, including efforts to apply the technology to broader application sizes (e.g. to 400 kW / 400 BHP).

Project Manager: David Cygan

Boostheat Thermal Compression Heat Pump

UTD researchers are collaborating with a European developer of a novel high-efficiency thermal compression-based heat pump technology, to help accelerate its potential introduction into North America. Leveraging global technology developments and partners can speed time to market for new technologies for end users, and help address key North American needs such as optimizing application with forced-air distribution systems, and potential integrated air conditioning capability.

Project Manager: Alex Fridlyand

TECHNOLOGY ADVANCEMENTS (continued)

Gas-Fired Warewasher

A gas-fired warewasher is being advanced in conjunction with a leading OEM. The estimated annual savings for restaurant, cafeteria, and other commercial food service operators is $1,100-$9,000 per warewasher (depending on size and type) while also saving energy and chemicals, when compared to electrically-heated warewashers that operate at lower temperature and thus require one-time use and environmental impact of chemicals.

Project Manager: Shawn Scott

Cost-Effective Compressor/Expander for Natural Gas and Hydrogen-fueled Vehicles

With UTD cost share and U.S. DOE funding, GTI Energy and the University of Texas, Austin developed a novel approach using a linear motor compressor with only one moving piston. The technology was recently scaled up to 50 SCFM capacity with UTD funding, and gas expansion applications are also being developed. The technology has the potential to significantly enhance CNG and H2 vehicle fueling operations.

Project Manager: Jason Stair

On-Demand Heat and Power System

This unique new technology has received a remarkable three rounds of funding from U.S. DOE ARPA-E, along with UTD and other co-funding support. This technology captures and stores renewable energy (or other resources, including waste heat), augments it with natural gas as needed, and delivers heat and power on-demand to commercial, industrial, and other users. The technology has been demonstrated at a pilot field installation in California.

Project Manager: David Cygan

SMTI Gas-fired Absorption Heat Pump Residential Water Heater

A field test of five prototype units of this efficient residential Gas-Fired Heat Pump Water Heater was successfully completed in Southern California during 2020, with support from CEC, UTD, SoCalGas and a prospective manufacturing partner. The unit has a projected Uniform Energy Factor (UEF) of 1.20-1.30 and ultra-low NOx emissions of ≤10 ng/J. Potential commercial production is being evaluated.

Project Manager: Paul Glanville

Energy Recovery Heat Exchanger

UTD researchers collaborated with CEC to demonstrate in California an advanced recuperator to increase energy efficiency at an aluminum die casting operation. Test results (independently audited) demonstrated 6-16% energy reduction. A technology transfer plan to introduce this technology from Europe to North America was developed to take next steps.

Project Manager: David Rue

Customized Affordable Retrofits of Building Envelopes and Mechanicals

Researchers are advancing a new technology that can rapidly integrate highly innovative building envelope improvements with next-generation HVAC equipment retrofits to reduce GHG emissions by >50%, while providing significant operating cost savings for and minimal disruption to homeowners, residents in income-eligible housing or multi-family buildings, and others.

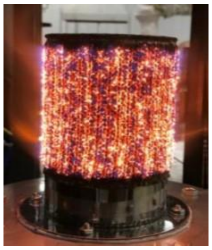
Project Manager: Jason LaFleur

TECHNOLOGY ADVANCEMENTS (continued)

HeatAmp Adsorption Thermal Heat Pump

The product development effort couples a proprietary triple-state sorption technology with a novel product design integration that is expected to yield a family of cost-effective, high-efficiency, robust appliances with few moving parts. Example applications are water heating or combination water/space heating. UTD is helping HeatAmp develop its new product with laboratory testing, validation, design recommendations, and a review of applicable N.A. engineering standards.

Project Manager: Paul Glanville



ThermoLift Ultra-High-Efficiency, Heating/Cooling Vuilleumier Cycle Heat Pump

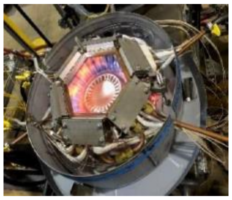
Vuilleumier cycle-based heat pumps could provide a step-change efficiency improvement over vapor absorption- or compression-based cycles, achieving cooling COP > 1 and heating COP > 2. UTD is working with a leading developer to advance key system components using both computational and experimental analysis, to help achieve performance goals in alpha prototype testing funded by DOE, UTD and others.

Project Manager: Alex Fridlyand

Next Generation Liquid Dessiccant-based, Heat-Driven HVAC System

Liquid desiccant-based systems can efficiently remove moisture from air and reduce the amount of mechanical energy and water required by conventional HVAC technologies that de-humidify, condition, and re-humidify space air. In cooperation with NYSERDA and others, UTD is testing a novel new non-corrosive, non-toxic desiccant in a gas-driven system that offers a potential 30% increase in COP on a seasonal basis over conventional HVAC technologies.

Project Manager: Rich Swierczyna



Self-Powered Water Heaters

Higher-efficiency water heaters typically require the added expense of an electrical connection and are susceptible to power outages unless a separate battery back-up system is installed. UTD researchers have assessed leading thermoelectric generator (TEG) technologies, and in 2023 are further analyzing opportunities in coordination with a major OEM to economically integrate TEGs and other technologies into a prototype water heater design.

Project Manager: Sandeep Alavandi

Emerging Fuel Cells

UTD researchers are experimentally testing and evaluating several fuel cells that are entering (or exploring entry into) the North American market in order to serve residential and light commercial end users. UTD research is also working to identify and optimize the applications that can maximize the benefit of the high efficiency and reliability of these units.

Project Manager: Tim Kingston

High-Efficiency Gas-Fired Thermal Vacuum Heat Pump for Food Processing

UTD partnered with CEC, SoCalGas, and others to demonstrate an innovative high-efficiency, thermal-vacuum, gas-fired heat pump technology for food drying applications at a commercial food processing company. It has the potential to be about twice as efficient as conventional processes. A prototype system at a field host site generated performance data during 2021. Other applications of this technology for agricultural applications are underway by UTD in 2023.

Project Manager: Dave Cygan

TECHNOLOGY ADVANCEMENTS (continued)

CNG/RNG Locomotive

With prime funding from U.S. DOE, UTD and other entities are funding the development of a prototype locomotive that can run on fossil or renewable natural gas to serve Class I, II or III railroads in multi-engine, line-haul service, but achieve Near Zero Emissions and target 20% less fuel consumption than a diesel locomotive. UTD's project partners include Cummins Inc.

Project Manager: Bart Sowa

Distributed RNG/Biogas Production

UTD is partnering with leading technology developers such as Chomp to increase renewable natural gas (RNG) or biogas production at end-use customer sites in order to reduce landfill requirements, reduce the transport of food waste, and meet de-carbonization goals. UTD is supporting technical advancements such as improved instrumentation and designs.

Project Manager: Travis Pyrzynski

High Efficiency Convection Oven

In partnership with a leading OEM, UTD researchers tested design changes and innovations to achieve a 10% efficiency improvement vs. best-in-class Energy Star convection ovens. By their inherent design, these ovens constantly flow hot air out of the oven. There are an estimated 650,000-700,000 convection ovens in the US, according at a 2015 DOE study.

Project Manager: Shawn Scott

Thermal Ejector Technology to Recover Energy and Water from Hot Flue Gases

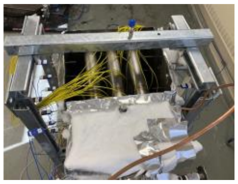
In a field demonstration at a large industrial plant in California, UTD researchers partnered with CEC and a major manufacturer to apply a novel new thermal ejector technology which recovers useful process water from the plant's humid exhaust gas, which in turn increases energy efficiency. Discussions to install the technology at larger scale at other facilities are in progress.

Project Manager: Lee Van Dixhorn

Energy Recovery System for Brewing and Distilling Operations

UTD researchers are testing a novel heat exchange system to recover previously-wasted energy at two micro-breweries in California, with funding from UTD and prime funding from CEC. Project goals include to recover 15-25% of heat from brew kettles, and reduce CO_2 emissions by up to 25%, while maintain superior process operations.

Project Manager: David Rue



Ionic Liquid Technology for Residential and Commercial Gas Heat Pumps

Researchers at the University of Florida and Micro Nano Technologies are partnering with UTD to design and demonstrate an early prototype of a low-cost, ultra-high-efficiency thermally-driven heat pump for residential and commercial water heating or combination water heating/space heating which employs the unique thermal properties of ionic liquids.

Project Manager: Paul Glanville

TECHNOLOGY ADVANCEMENTS (continued)

High Efficiency Commercial Clothes Dryer

An advanced natural-gas-fired commercial clothes dryer is being created and demonstrated at laboratory scale that has the potential to save at least 50% of the energy used in the commercial clothes drying sector. It is being developed in partnership with Oak Ridge National Laboratory and others, with financial support from U.S. DOE and UTD.

Project Manager: Dave Cygan

Next Generation Infrared Burner

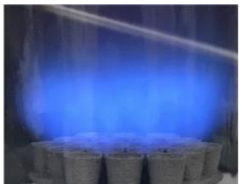
In partnership with a leading OEM, UTD-funded researchers are testing a variety of unique metal foam materials in a laboratory to evaluate their potential performance as next-generation, high-efficiency, rapid-response, low-emission infrared burners that are directly fired with fossil or renewable natural gas. Field tests are in development.

Project Manager: Sandeep Alavandi

Furnace Retrofit for High-Efficiency Heating and Humidification

Tests of a patented Transport Membrane Humidifier (TMH) technology in four homes in Minnesota demonstrated a 14% increase in furnace efficiency while providing humidification without water supply. Interested licensees should contact Rich Kooy at rich.kooy@utd-co.org.

Project Manager: Dexin Wang



Low NO_x Energy-Efficient Advanced 3D-Printed Nozzle Burner

A novel design for next-generation retention nozzles leverages new additive manufacturing capabilities and equipment. In 2023, UTD is evaluating applications for boilers, water heating and air heating. Laboratory tests have demonstrated a robust, high-efficiency (3-6% increase), ultra-low emissions burner, with >10:1 turndown. It achieved 50%-75% reduction in NO_X emissions compared to current burners, with the potential to reach <5 ppm NO_X.

Project Manager: Sandeep Alavandi

WORKING WITH PARTNERS TO CO-FUND UTD INITIATIVES

In 2022, each $1.00 in new UTD funding was leveraged by $4.8 of funding from government and industry partners for related end-use R&D. GTI Energy secured $15.1 million from federal and state government partners and $9.9 million from manufacturing partners and other gas industry resources (outside of UTD) for related end-use R&D. Manufacturing partners also provided significant additional in-kind co-funding.

Examples include:

- U.S. Department of Defense (DOD) funding of $8.1 million to apply advanced energy efficiency, renewable energy, microgrid, and hybrid technologies to reduce DOD GHG emissions and energy use while increasing resiliency.
- U.S. Department of Energy (DOE) funding of $2.3 million to develop and test novel technologies to achieve very high space heating efficiencies, and to advance hydrogen as a transportation fuel.
- California Energy Commission (CEC) funding of $3.7 million for new projects to advance hydrogen as a low carbon fuel for transportation, industrial, and large commercial customer applications.
- New York State Energy Research and Development Authority (NYSERDA) funding of $0.8 million to develop innovative insulation technologies to achieve deep energy building envelope retrofits.

Example Technical Publications/Presentations 2022-23
developed in part with UTD's Support

Ahsan, A., "Distributed Carbon Capture for Buildings", ACEEE Hot Air & Hot Water Forums, San Diego, CA, March 7-9, 2023 https://drive.google.com/file/d/1zsA4TkrBJptLeaVRmgy0Uzi2MQt2eHjg/view (results in part from UTD project 1.21.C).

Air-Conditioning, Heating, and Refrigeration Institute Report No. 8030, "Role of Combustion-based Building Equipment in Decarbonization", prepared by GTI Energy, April 2023 https://www.ahrinet.org/system/files/2023-06/AHRI%208030%20Final%20Report.pdf (results in part from UTD projects 1.16.I, 1.19.D. 1.19.I, 1.20.H and others).

Alavandi, S., Abbasi, H., Cygan, D. and Wagner, U.; "Design and Development of Advanced 3-D Printed Burner for Process Heating Applications", American Flame Research Committee conference, Denver, CO, Sept. 25-27, 2023 (results in part from UTD project 2.20.A).

Barnes, T., and Sowa, B. "Field Demonstration of a Near-Zero, Tier 5 Compliant, Natural Gas Hybrid Line-Haul Locomotive", U.S. Department of Energy Annual Merit Review, Washington D.C., June 14, 2023 (results in part from UTD project 2.21.F).

Bhagwat, R., Schmid, M., Ahsan, A., Kumar, N., Glanville, P., "Ionic Liquid Absorption System for Dehumidification and IAQ Enhancement in Built Environment", 14th International Energy Agency Heat Pump Conference, Chicago, IL, May 15-18, 2023 (results in part from UTD project 1.20.I and 1.21.I).

Bhagwat, R., Schmid, M., Glanville, P., "Hybrid Thermally Driven Ionic Liquid Heat Pump Water Heater and Dehumidifer For Commercial Applications", 14th International Energy Agency Heat Pump Conference, Chicago, IL, May 15-18, 2023 (results in part from UTD project 1.20.I and 1.21.I).

Ekblad, M., "Commercializing a Cost-Effective Residential Retrofit Gas Heat Pump Water Heater", ACEEE Hot Air & Hot Water Forums, San Diego, CA, March 7-9, 2023 https://drive.google.com/file/d/1J3Dv6dD8hx3JE5SSnT5E7UlDavrlXUii/view (results in part from UTD project 1.21.A).

Fridlyand, A., Zhao, Y., Asher, W., and Glanville, P., "Burner Design Considerations for Hydrogen-blended Gas Operation", ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023* Vol. 129 Issue Part 1, pp. 83-91 (results in part from UTD project 1.20.H and 1.21.H).

Fridlyand, A., "Hydrogen in Buildings - Ongoing Research and Outstanding Questions", 2023 ASHRAE Winter Conference presentation, Atlanta, GA, Feb. 8, 2023 (results in part from UTD project 1.22.A and 1.22.G).

Glanville, P., Fridlyand, A., Sutherland, B., Liszka, M., Zhao, Y., Bingham, L., and Jorgensen, K., "Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance", *Energies* 2022, *15*, 1706. https://doi.org/10.3390/en15051706 (results in part from UTD project 1.20.H).

Glanville, P., Fridlyand, A., Zhao, Y., (2023) "From Town Gas to Hydrogen: Historical and Modern Perspectives on Transitions Between Delivered Fuels in the Built Environment", ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023* Vol. 129 Issue Part 1, p. 92-102 (results in part from UTD project 1.20.H).

Glanville, P., Fridlyand, A., Zhao, Y., Sutherland, B., Jorgensen, K., and Bingham, L., “Looking Beyond the Meter - Customer-Side Impacts of Natural Gas/Hydrogen Blends in North America”, 28th World Gas Conference paper, May 23-27, 2022 (results in part from UTD project 1.20.H).

Glanville, P., Kumar, N., Ahsan, A., Fridlyand, A., Ekblad, M., Hallin, I., Blackman, C., Contreras, N., “Development of a Novel Sorption-Type Heat Pump Water Heater for North American Homes”, 14th International Energy Agency Heat Pump Conference, Chicago, IL, May 15-18, 2023 (results in part from UTD project 1.21.A).

Glanville, P., Zhao, Y., “Decarbonizing California’s Industry with Hydrogen: Preliminary Assessment”, ACEEE Summer Study on Energy Efficiency in Industry conference presentation, Detroit, MI, July 11-13, 2023 (results in part from UTD project 1.20.H and 2.23.A).

Guada, A.B., “Reducing Greenhouse Gas Emissions and Improving Energy Resilience with Integrated Energy Systems”, ACEEE Hot Air & Hot Water Forums, San Diego, CA, March 7-9, 2023 https://drive.google.com/file/d/1qVxKj7J3MwZOtB3loogPlnluWXbFrpd0/view (results in part from UTD projects 1.19.D, 1.19.I, 1.20.G and 1.20.J).

Guada, A.B. and Kingston, T., “Challenges of Integrating mCHP and SOFC Systems in Nano-Grid Environments for Thermal and Power Management Solutions in Integrated Energy Systems”, ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023* Vol. 129 Issue Part 1, pp. 311-319 (results in part from UTD project 1.20.F).

Halliday, D., “Free-Piston Expander for Hydrogen Pre-Cooling”, U.S. Department of Energy Annual Merit Review, Washington D.C., June 5-8, 2023 (results in part from UTD project 2.18.I).

Kingston, T., and Guada, A.B., “Simulated Use Performance of an Integrated Energy System for Thermal and Power Management with Micro-Combined Heat and Power in Nano-Grid Environments”, ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023* Vol. 129 Issue Part 1, p. 536-544 (results in part from UTD project 1.20.G).

Kumar, N., “Laboratory Evaluation of a Packaged Thermal Heat Pump and Electrical Air Conditioning Unit for Space Conditioning and Hot Water”, ACEEE Hot Air & Hot Water Forums, San Diego, CA, March 7-9, 2023 https://drive.google.com/file/d/1hx8T4m36sGZxlrMUfJefoHRTh_Pafb8x/view (results in part from UTD project 1.18.F).

Kumar, N., Guada, A.B., Asher, W., Fridlyand, A., Glanville, P., Blaylock, M., Strong, T., “Performance of a State-of-Art Packaged Heat Pump for Residential Space Conditioning and Hot Water”, 14th International Energy Agency Heat Pump Conference, Chicago, IL, May 15-18, 2023 (results in part from UTD project 1.18.H).

LaFleur, J., Goldstein, D., “Façade-Integrated Mechanical Systems”, ASHRAE Decarbonization Conference presentation, Arlington, VA, Oct. 26, 2023 (results in part from UTD projects 1.22.E)

Rowley, P., Mahderekal, I., Ravi, A., Walburger, A., Genzel, N., Henderson, H., Dentz, J., Zhu, S. “Cold Climate Performance Assessment of a Natural Gas Engine-Driven Heat Pump Rooftop Design”, ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023* Vol. 129 Issue Part 1, pp. 173-180 (results in part from UTD project 1.18.I).

Stein, J., Glanville, P., Fridlyand, A., LaFleur, J. and Mensinger Jr., M. “Translating Equipment Efficiency to Delivered Efficiency in Thermally-Driven Heat Pump Combi Systems”, ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023*, Vol. 129 Issue Part 1, pp. 293-301 (results in part from UTD project 1.13.F and 1.16.I).

Swierczyna, R., Johnson, F., LaFleur, J., and Stein, J., “Evaluating Residential Kitchen IAQ and Hood Performance”, ASHRAE 2022 Winter Conference paper, ASHRAE Transactions 2022 Vol. 128 Issue Part 1, pp. 429-436 (results in part from UTD project 1.20.K).

Zhao, Y., “Technical Considerations of Hydrogen Blending into End Use Infrastructures”, AEE World Energy Conference presentation, Orlando, FL, Oct. 26, 2023 (results in part from UTD projects 1.20.H and 1.21.H).

Zhao, Y., Glanville, P., Fridlyand, A., and Sutherland, B., “Inline Hydrogen Sensor Monitoring of a Tankless Water Heater Operating Up to 30% Hydrogen Blending”, ASHRAE 2023 Winter Conference paper, *ASHRAE Transactions 2023* Vol. 129 Issue Part 1, pp. 103-111 (results in part from UTD project 1.18.F and earlier UTD-funded research).

Zhao, Y., Pixler, J., Sutherland, B., Daniels, N., and Johnson, F., “Non-Powered Commercial Cooktop Burners Optimization for Efficiency Improvement/NOx Reduction and Hydrogen Blending Efforts”, Western States Section Combustion Institute Fall 2023 Technical Meeting, October 16-17, 2023 (results in part from UTD projects 1.17.F and 1.21.H).

* * *

Other final research reports are publicly available from the U.S. Department of Energy, California Energy Commission, Minnesota Conservation Applied Research and Development, and other governmental agencies which provided prime research funding and for which UTD provided cost share co-funding. Examples include:

Garrabrant, M. and Newland, J. of Stone Mountain Technologies Inc. “Improving Reliability, Weight and Cost of Gas-Fired Absorption Heat Pumps” U.S. Department of Energy Final Report DE-EE0008687, March 31, 2022 https://www.osti.gov/biblio/1886933 (results in part from UTD project 1.19.E).

Sweeney, M., Glanville, P., Mort, D., Hoeschele, M., and Grant, P.. 2020. “Demonstration and Assessment of Gas Heat Pump Water Heaters in the Los Angeles Basin”, California Energy Commission. Publication Number: CEC-500-2023-047 June 2023 https://www.energy.ca.gov/sites/default/files/2023-07/CEC-500-2023-047.pdf (results in part from UTD project 1.16.I).

RESIDENTIAL AND LIGHT COMMERCIAL, INCLUDING mCHP

UTD Utilization Technology Development

Next-Generation Residential Gas Heat-Pump Water Heater

A research team designed and demonstrated the first residential gas-fired heat-pump storage water heater. This project advanced this technology from laboratory prototype through multiple field demonstrations, including in California through 2020. It provides a uniform efficiency factor of ≥1.2, to offer homeowners ≥50% energy savings.

Project Description

The industry's first residential gas heat-pump water heater (GHPWH) is near commercialization, with multiple OEM partners and a series of successful field trials advancing the design of each generation of prototypes.

In partnership with other research funding agencies, UTD co-funded a team of researchers to develop the residential/small-commercial GHPWH, reduce its costs, and improve reliability by refining a number of system components.

The initial GHPWH development initiative was funded by the U.S. Department of Energy (DOE). This UTD project effort has been a steady development led by Stone Mountain Technologies, Inc. (SMTI) along with commercial OEM partners and GTI Energy.

The first-generation GHPWH units were designed and demonstrated through laboratory testing from 2011 to 2013. Subsequently, six GHPWH units were installed and monitored in the field. Through these initial field tests, critical information was used to improve the GHPWH control strategies and future design improvements (including system sizing).

The most recent phases of this UTD project focused on supporting an additional five field demonstrations in a program sponsored by the California Energy Commission (CEC) with financial support from Southern California Gas Company (SoCalGas) in addition to UTD, and also investigating enhanced options for system diagnostics and grid interactivity.

In phase 5, the teams goal will be to reduce installation cost/barrier of condensate drain, by developing a proprietary method of neutralizing, collecting, and disposing of combustion condensate, and improving Onboard Diagnostics through Enhanced Solution Level Control (ESLC) to improve system reliability and long-term performance.

In phase 6, the team will be developing strategies to deploy the residential GHPWH as distributed energy resource (DER) for residential grid-level shed and shift events and developing methods to improve DHW capacity with supplemental gas/electric "boost" capabilities.

Benefits / Market Implications

The motivation for developing a GHPWH is efficiency driven. When delivered to the market, the GHPWH will be the only technology and product of its kind with a primary energy efficiency of greater than 100%. These efficiency gains are significant, with project uniform efficiency factors (UEFs) of 1.20 or greater, and consistent field results of 50% or greater energy savings over conventional water heaters, respectively.

Results from this project have the potential to reduce the cost, increase the reliability, and more than double the efficiency of the next generation of gas heat-pump water heaters for homeowners and light commercial end users.

Technical Concept & Approach

The GHPWH units are driven by an air-source single-effect absorption heat pump, itself driven by a gas burner, capable of Coefficients of Performance (COP) of 1.4-1.9. This can yield a UEF of 1.20, more than twice the efficiency of standard gas storage water heaters, which are in, for example, 74% of California homes.

Water Heater Testing Area Test Installation Progress

"SoCalGas RD&D continues to be impressed with the capabilities of the UTD team. They helped identify test sites, coordinate with installation partners, and share the results with the public through a webinar. This type of partnership and research project is just one way SoCalGas is working to be the cleanest, safest, and most innovative energy company in America."

- Neil Navin
Vice President, Clean Energy Innovations
SoCalGas

Based upon a recent certification, the units are ultra-low-NO_x compliant. The packaged GHPWH heats the 60 to 80 gallons of stored water with a nominal 10,000 Btu/hr output ammonia-water absorption heat pump, driven by a small 6,300 Btu/hr low-NO_x gas burner. With such a small combustion system, the GHPWH offers retrofit installation advantages over other high-efficiency gas products.

Through the broader project funded by the CEC and cofunded by UTD and SoCalGas, the project team focused on the testing of GHPWH units and the development, use, and refinement of advanced fault detection and diagnosis. The goal was to demonstrate that the projected delivered efficiencies of 130% or greater are valid, robust, and are not achieved through a loss of user comfort. Researchers estimated the annual energy, operating cost, and emissions savings and solicited feedback from host end users and installation contractors through pre- and post-installation surveys.

Results

Following a laboratory development program, the first prototype gas heat-pump water heater was installed in a Tennessee residence and investigated over a 10-month period. The laboratory-validated performance and preliminary field test data suggested that the 1.20 UEF target was feasible and the technology could be competitive with other available high-efficiency gas water-heating options.

In 2015, project efforts focused on transitioning the purpose-built prototype from field testing to reliability testing. Reliability testing was completed in 2016.

A report on the initial phases of the project was issued in 2017. In these phases, six GHPWH prototypes were subjected to extended reliability testing. Researchers also performed an analysis of how the GHPWH is impacted by relevant codes and standards in the U.S., Canada, Mexico, and Europe.

In 2017, seven new GHPWH units were built during Phase 4: five units for residential field demonstration; one for evaluation at SoCalGas' *Engineering Analysis Center;* and one for proprietary testing by a manufacturing partner.

In 2018, the project team monitored the performance of the five gas GHPWHs installed at the test sites, which continued through June 2019. Data continued to confirm that ~50% energy savings was achieved on a site-by-site basis and improved as the ambient temperatures rise. Data was collected, aggregated, and analyzed.

Also in Phase 4, two fourth-generation GHPWH units were received from California, with one partially installed in a laboratory. Additional preparations were made to initiate standardized and non-standardized efficiency testing.

In 2020, Phase 5 involved additional laboratory testing of the GHPWH to improve onboard diagnostics and to explore innovations to ease how condensate is handled.

Phase 6 is now expanding grid-interactive capabilities and variable performance to further enhance customer's comfort and operating flexibilities. Efforts are under way to develop and demonstrate strategies to deploy the residential GHPWH as a distributed energy resource for residential grid-level shed and shift events, and develop and explore methods to improve domestic hot water capacity with supplemental gas/electric boost capabilities.

In 2021, the project team expanded its laboratory space to accommodate appliance/water-heating tests. This "Advanced Appliance Assessment" (A3) laboratory was prepared for installation and operation of GHPWH hardware. The infrastructure and instrumentation/emissions measurement capacity were completed and commissioned, with hot/chilled water circulation loops functional for water-heater testing.

For Phase 6, an agreement with SMTI to produce a next generation alpha prototype GHPWH was completed, with expectations that SMTI will deliver the updated unit in the fourth quarter of 2023. Researchers completed the Phase 6 test plans and fabricated prototypes of the additional features being developed in Phase 6.

Status

Technical tasks under Phases 5 and 6 are advancing, including the final design and fabrication of test setups to evaluate the proof of concept of the liquid level sensor (LLS) platform and the de-condensator concept.

The project team continue to make and refine upgrades in the laboratory space, impacting both phases (phase 5 and 6) in the "Advanced Appliance Assessment", or "A3" laboratory. The ESLC and de-condensator test plans were completed and the team has begun to make progress in the fabrication and assembly of the ESLC and de-condensator test rig. The project team anticipates completing testing in the next period under Phase 5 and preparing for receipt of the SMTI prototype to close out both coincident phases.

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UTD Utilization Technology Development

Investigating Multi-Family Infrastructure Challenges

Researchers investigated the current challenges and opportunities for the natural gas industry to better serve multi-family new construction owners, architects, and builders with advanced, efficient technologies.

Project Description

There is a significant opportunity for natural gas to better serve the growing multi-family new construction market; however, there are also significant barriers, many of which have been the focus of research in recent years.

Starting in 2014, in Phase 1 of this project researchers investigated national trends regarding gas and electric multi-family market shares, the economics of energy services, building codes, and installation practices.

In Phase 2, the project team provided regional multi-family market paths for advanced products that provide promising opportunities in this sector, a portfolio, and examples and discussion of successful utility initiatives.

Phase 3 recommended implementation of opportunities for specific regions or utilities, including holding utility-sponsored design-planning sessions in the form of charrettes with stakeholders within the development, design, and building communities.

The final Phase 4 effort focused on developing detailed market transformation implementation tools and action plans to optimally connect new development decision-makers with financial, marketing, and technical resources suitable for the multi-family new construction sector. Deliverables included a report with sample case studies (customizable by UTD member utilities with utility logo and program details), a review of emerging gas technologies to better serve multifamily buildings, and continuing education credit curriculum.

Benefits / Market Implications

Pilot studies on the multi-family market identified key economic issues, code barriers, and product gaps that require investigation and resolution. Addressing these issues, gaps, and barriers will enable more multi-family end ratepayers to benefit from the lowest-cost energy option and improve energy efficiency.

This project highlighted and created resources that improve existing avenues of support for developers, utilities, and end-users to leverage natural gas as a fuel choice.

Several demonstrations showcasing innovative gas technologies are summarized in consumer-friendly case studies of successful multi-family developments.

Technical Concept & Approach

Key earlier project tasks included:

- **Multi-Family Market Data Collection & Analysis**

Researchers used census data and other available resources to obtain a 2015 snapshot of builder and developer energy choices in the multi-family new construction market by U.S. region and by building type. The assessment included, to the extent possible, gas and electric utility rates and incentives, the availability of gas service, market trends, and code differences.

- **Multi-Family Market Preliminary Recommendations**

Researchers reviewed the analysis and developed preliminary recommendations for a path forward in each region.

- **Technology Solutions**

The project team reviewed the market data and up-to-date technical equipment and system information to recommend advanced resource-saving technology solutions.

- **Multi-Family Stakeholder Charrette**

The project team held three stakeholder charrettes in 2018 in targeted geographical regions across North America that showed the greatest need or desire for multi-family development support.

•**Development of Supporting Utility Programs**

Researchers recommended utility program features and best practices that were observed to be successful.

Current research pursues:

•**Guidance for Design and Construction Professionals**

Leveraging the insights from Phase 3, researchers created tangible market guidance tools tailored for design and construction professionals that could be branded by UTD member utilities.

•**Case Study Development**

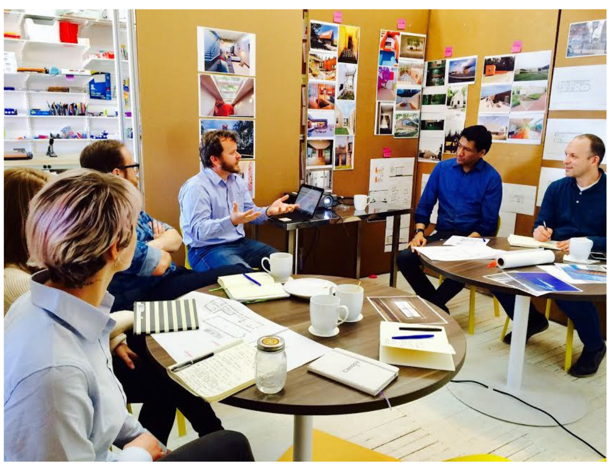
Three case studies were developed to showcase successful pathways to natural gas inclusion in multi-family developments.

•**Curriculum Development**

The project team will develop curriculum geared towards design professionals in a one-hour presentation format.

•**Multi-Family Emerging Technologies Strategy and Needs Assessment**

Investigators identified promising natural gas emerging technologies or innovation needs that can leverage the benefits of using natural gas in the multi-family market.



Early Design Charrette

"The Multifamily Infrastructure Challenges project has given us a comprehensive insight into customer concerns. We have used this insight to develop outlines and resources to help build a greater understanding of the benefits of natural gas in multifamily developments."

- April Arnold
Manager
ONE Gas, Inc.

Results

The project team held interviews with key national-level players active in the multi-family market, including representatives from industry associations and gas utilities. These discussions covered past activities each of these organizations have undertaken within the multi-family market segment, current challenges, and key concerns of stakeholders. Project representatives also held discussions with many U.S. utilities and performed significant outreach to the building and development community to obtain their perspectives.

Phase 1 research reported on key trends in the housing market, the use of heating fuels, and the use of electricity. The rebounding of electricity as the majority space-heating fuel can be seen in both low-rise (2-4 units) and high-rise (5+ units) buildings, while the volume of gas-heated units shows either modest or no growth. However, this trend is not reflected in water heating, where gas still plays a strong role.

In Phase 2, researchers identified the key economic and non-economic factors driving the selection of energy sources as service in new construction multi-family buildings.

In Phase 3, specific UTD members participated in stakeholder charrettes (i.e., focus group sessions) to garner feedback and dialogue with real estate developers, architects, engineers, and others involved with multi-family projects. Detailed recommendations were developed for UTD members to address economic challenges, provide technology-based solutions, and enhance their service to multi-family stakeholders, architects, builders, and others.

In Phase 4, practical tools were created to facilitate market transformation and connect utility partners with new development decision-makers, such as guidance for design and construction professionals, case studies, a "Train the Trainer" packaged curriculum, and multifamily emerging technology information snapshots. Tools and resources aimed to overcome the barriers identified in previous phases of the project and support multi-family gas end users were developed.

Status

The project is complete. Final Reports summarized the progress completed in each phase. The Phase 4 Final Report issued in March 2023, and an informational webinar was provided to UTD members in May 2023. The tools, templates and information developed in this project provide resources for UTD members to better support multi-family developers and customers in their service territories on an on-going basis.

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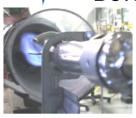
Next-Generation Advanced Residential Gas Clothes Dryer



Researchers are investigating next-generation technologies so that a residential gas clothes dryer can economically provide gas consumers with faster drying times, while achieving 5%-15% higher efficiency than standard-efficiency gas dryers.

Project Description

In this project, researchers are investigating next-generation technologies – including heat recovery, indirect firing, direct venting, and advanced burners – to determine potential efficiency boosts for residential dryers. All of these techniques and technologies were shown to increase efficiencies in other areas, but scaling them to a residential dryer size, determining the additional cost to the dryer, and quantifying the efficiency increases will help dryer manufacturers determine the best path to further advance gas-fired dryers while minimizing cost increases.

UTD's guiding Technical Project Committee indicated that there is also an interest in reducing drying times if possible. This is a benefit of gas dryers for end users – the potential to increase firing rates to reduce drying times. Modulation may allow a high firing rate in the early stages and a low firing rate later to both reduce drying time and save energy.

The goal is to find a technology to achieve a 5%-15% boost over standard-efficiency gas dryers. Project deliverables include an early-stage prototype incorporating the most promising technologies, optimizing their operation in a prototype dryer, and preparing reports detailing the performance improvement provided by all of the technology options investigated.

Benefits / Market Implications

Gas-fired dryers have not had many technological advances in recent years; however, there is potential to enhance the technology. Since about 81% of U.S. households have a clothes dryer, potential efficiency improvements in the design of gas dryers represent sizable savings to residential ratepayers.

Although electric clothes dryers represent the majority of U.S. residential dryers, a 2011 study by others indicates that it is not consumer preference for electricity that is the driving force. Although 60% of survey respondents were currently using electricity for clothes drying, only 34% stated that they actually preferred electricity. In contrast, 40% of respondents stated they currently used gas for clothes drying and 53% said they would prefer to use gas. These results indicate that the cause for gas dryer's minority market share is not due to the inherent characteristics of gas as a fuel, but is driven by other factors such as cost, availability, and other regional factors.

Technical Concept & Approach

The project team will investigate high-efficiency dryer technology options, such as heat recovery, modulating burners, indirect firing, direct venting, and advanced burners. Researchers are also investigating the potential for technologies to reduce drying times.

The effect of each technology modification is being tested using standard methods to determine the performance improvement (efficiency, drying time, etc.) in comparison to the baseline unmodified model. The most promising technologies will be incorporated into an early prototype for demonstration.

Researchers will take the best performing technologies from Phase 2 and combine them into a prototype dryer in Phase 3. The prototype will be modified and optimized to get the best performance of the technologies working together. The prototype will be tested to determine the performance improvement of the technologies (efficiency, drying time, cloth temperature, etc.).

New Environmental Tet Chamber during Construction

Results

Phase 1 of this project focused in part on assembling a test station in an environmental chamber to maintain temperature and humidity to ensure accurate testing. It had become apparent during previous UTD dryer research that room temperature and humidity have a very large effect on the dryer efficiency rating. Although the test standard allows for 40%-60% relative humidity (RH) during the test, a dryer will be much more efficient at 40% RH than at 60% RH. With that in mind, researchers decided that it was necessary to arrange the test in an environmental chamber.

Technicians completed the first modifications to the dryer. The unit was fully instrumented to allow for testing different design changes, including changes to primary aeration and air-to-fuel ratio, followed by potential heat-recovery options. Designs to recover heat from the flue were implemented and show promise for improved efficiency in testing. Overall, the heat recovery appears promising while providing a small cost added to the dryer.

Researchers attempted many different configurations for sealing the dryer to maintain stable combustion, and investigated simple heat-recovery options with many different alterations. In the end, it was determined that a novel heat-recovery setup, along with a newly configured and sealed dryer combustion chamber, showed the most promise, with a 4% boost to the dryer efficiency while adding very little cost to the dryer.

For the study, a total of 42 temperature sensors, five gas sample points, a gas meter, and electric power meter were fitted to the dryer.

In Phase 2, researchers investigated additional heat-recovery options, modulation techniques, indirect-fired methods, direct venting, and alternate burners.

Researchers set up a new dryer in the test stand in the environmental test chamber. The project team also set up a new washer test stand to provide clothes with the needed temperature and remaining moisture content for dryer testing.

The research team developed a slightly modified test procedure to provide repeatable results that will allow comparison to technology improvements on a common basis. After this modified procedure was adapted, baseline testing was completed. Researchers also investigated the effect of firing rate on the dry time and efficiency.

It was noticed from previous dryer research that results of dryer efficiency testing according to the U.S. Department of Energy test procedure can vary based on a few factors. The current standard requires allowing the automatic moisture sensor to automatically stop the load. An issue is that the moisture sensor can create significant variability in the test results based on when it determines the load is dry. In many instances, the load is fully dry, but the dryer keeps running before the moisture sensor eventually shuts it off. Researchers need good repeatability to compare the baseline testing of a standard dryer to each technology that is being tested to improve efficiency.

The project team was able to achieve good repeatability by creating a slightly modified test procedure that measured flue RH and determined when the clothes were dry based on the flue RH.

In Phase 3, the project team developed a slightly modified test procedure to reduce variability of the results and provide repeatable results that will allows researchers to compare technology improvements on even ground. After this modified procedure was adapted, baseline testing was completed of the DOE test clothes as well as a real-world towel load baseline test. Researchers completed single-stage modulating testing at four firing rates, with results showing around a 2% boost consistently with lower firing rates. Technicians then insulated and sealed the dryer to test potential boost from better sealing and allow for implementing heat recovery. After several variations, the team was able to achieve a 5%-6% increase in efficiency with insulation and sealing as well as a 6% reduction in drying time.

The insulation and sealing also allowed for the implementation of a new heat-recovery design. An external air-to-air heat exchanger was purchased and installed on the dryers to determine the potential boost from heat recovery. Testing of the dryer in the environmental chamber demonstrated a 10%-11% boost to the efficiency of the dryer.

Status

The team will begin to incorporate heat recovery, modulation, and insulation together to determine the maximum efficiency that can be gained through all the technologies working together.

A new environmental test chamber is being setup in the new Advanced Appliance Assessment Lab. The new chamber is close to being finished. The project team has begun to move the test setup into the chamber in order to prepare for the next round of product development and testing.

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UTD Utilization Technology Development

Gas-Fired High-Efficiency Liquid Desiccant Air Conditioning and Humidity Control

A research team is partnering with a chemical manufacturer, two HVAC manufacturers, and others to develop and demonstrate a very-high-efficiency gas-fired liquid-desiccant-based air-conditioning and humidity-control system that uses a novel, non-corrosive, non-toxic desiccant.

Project Description

The goal of this project is to develop a gas-fired liquid-desiccant dedicated outdoor air system (LDDOAS) that addresses many of the critical issues now facing owners and operators of commercial HVAC systems.

The LDDOAS is designed to significantly reduce primary energy consumption, on-peak electrical demand, and water use for air conditioning in commercial buildings. The system can deeply dry a building's ventilation air without inefficient overcooling or reheating, which will enable advanced HVAC solutions (e.g., chilled beams, displacement ventilation, and other approaches) to essentially eliminate fan power for recirculating air within buildings.

In this project, a research team is partnering with a manufacturer to compare the current state-of-the-art LDDOAS technology to other advanced systems, including a concept involving a sub-atmospherically-regenerated LDDOAS system with internal water recovery and reuse capabilities.

The current Phase 2 involves demonstrating this novel technology in a laboratory to determine its potential value to end users. In Phase 2, the project team will design and experimentally evaluate a breadboard LDDOAS test rig rated at approximately 100 CFM capacity using a novel non-corrosive, non-toxic desiccant.

Researchers are partnering with the New York State Energy Research and Development Authority (NYSERDA), a chemical manufacturer, and two HVAC industry partners in Phase 2.

Benefits / Market Implications

New cooling designs that integrate desiccant drying and indirect evaporative cooling in compact cost-effective configurations have the potential to provide residential and commercial market end users with new high-efficiency product choices.

For a summer design day, the LDDOAS' primary energy Coefficient of Performance (COP) is 18% higher than the conventional alternative. This advantage is projected to increase to 30% when averaged over a cooling season. The effective COP for the LDDOAS is estimated to be 2.77 (where the LDDOAS is credited with energy savings for the advanced HVAC systems that it enables). The LDDOAS can also eliminate water use for air conditioning in the more humid eastern U.S.

The burden that air conditioning now imposes on electric grids

The regenerator tower

The conditioner tower

can be eased as peak loads drop by approximately 75%, from about 1.01 kW/ton-hour to 0.26 kW/ton-hour of cooling.

Technical Concept & Approach

Desiccant-based dehumidification and air-conditioning systems can employ an open drying cycle wherein a humid gas (generally, air) comes into contact with a desiccant and is dried. The dried air continues to subsequent processes (e.g., sensible cooling), and the desiccant is regenerated by a thermal input. The desiccant loading and regenerating is performed in a cycle, allowing for continuous dehumidification.

The two major system types are liquid and solid desiccants. While solid desiccants have a larger established market presence, the liquid-based systems have gained interest in applications for active dehumidification, enhanced evaporative cooling, and indoor air quality. These liquid desiccant systems, also known as open absorption systems, have had limited market presence due primarily to the inefficiency of current regenerating components and difficulties in handling the caustic strong salt desiccant solutions.

Successful completion of Phase 2 is expected to lead into follow-on construction and field trials of alpha LDDOAS prototypes. The specific objective of Phase 2 is to prove the LDDOAS' system operation in the laboratory and determine its value to potential end users. In Phase 2, the project team will design and experimentally evaluate a breadboard LDDOAS test rig rated at approximately 100 CFM capacity (approximately 1/10th scale for small RTUs) using the novel non-corrosive, non-toxic desiccant initially evaluated and characterized in Phase 1.

Results

In Phase 1 of this project an experimental gas-fired liquid-desiccant air-conditioning (LDAC) system was constructed. A fluid was demonstrated to operate as a desiccant over a range of process air dew points (for space conditioning) and could be regenerated at low temperatures (<200°F). The absorption/regeneration tower operated as designed (~0.5-2 lb/hr moisture movement at 50 cfm).

During regeneration, with heated liquid and cool regeneration air, 50% of the enthalpy rise in the air was latent. This result was within the expected order of magnitude.

In Phase 2, the project team initiated upgrades to a one-tower test rig. The single-tower apparatus was fully instrumented to measure temperatures, pressures, and flow across the tower to allow completion of the initial test plan. Single-tower experiments were initiated. The preconditioning system for simulating outdoor air temperature and humidity levels was completed and tested.

Liquid desiccant distribution tests in the single tower were completed. Researchers characterized the desiccant distribution in the tower by varying nozzle configurations for distributing the liquid at the top of the tower to identify the optimal nozzle to use and determine whether tower-wall effects were present.

In 2021, rigorous testing of dew-point sensors concluded that the energy imbalance was not due to instrument accuracy. One theory that emerged regarding the cause of the energy imbalance was the insufficient mixing of water vapor in the air at the exit of the tower. To ensure proper mixing of the air as it exits the tower, a reducer was constructed for the top of the tower to increase velocity and turbulence of the flow. Testing of the modified tower commenced and confirmed that insufficient mixing was causing the energy imbalance.

In 2022, data analysis was completed for regeneration and batch-conditioning tests. A new digital refractometer was purchased for measuring the refractive index of the desiccant solution. The refractometer was used in conjunction with a Karl Fischer titration, and a new correlation was generated that more accurately characterized the strength of the raw desiccant and diluted solution. Various metrics were calculated and plotted to characterize the performance of the liquid desiccant during simulated regeneration and batch-condition tests. These metrics include effectiveness, water uptake, and the difference in vapor pressure between the liquid desiccant and duct air.

The simulated regeneration tests were performed at two different desiccant dilution rates, which was controlled by setting the peristaltic pump at 30% or 50% of operating speed when injecting water into the desiccant. At greater pump-operating speeds, more water would be injected into the liquid desiccant stream before it entered the tower, making for a weaker desiccant solution. This was done to study the change in regeneration performance by the liquid desiccant at varying solution concentrations. The experimental setup was also upgraded to use gear pumps rather than diaphragm pumps to circulate the liquid desiccant, which provided better control of the flow rate.

Construction of a second packed-bed column tower allowed for simultaneous regeneration and conditioning. All major instrumentation was installed for conditioning and characterizing the air stream, including a resistance heater temperature controller, a steam humidifier, a pitot traverse array, pressure transducers, thermocouples, and humidity sensors.

Status

The team completed the final experimental testing. Preparation of the final report is underway.

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UTD Utilization Technology Development

EnergyPlus™ Models for Advanced Gas Space-Heating Systems and Combination Systems

In this project, researchers developed models of advanced gas space-heating and water-heating combination systems in the EnergyPlus building energy simulation engine, with an overarching objective to inform and expand energy-efficient choices for building operators, designers, and other stakeholders.

Project Description

EnergyPlus™ is a whole-building energy-simulation program developed with support from the U.S. Department of Energy (DOE) that engineers, facility managers, researchers, and others use to model energy consumption for heating, cooling, ventilation, lighting, and plug-and-process loads as well as water use in buildings. However, the limited capability of EnergyPlus to simulate advanced gas-heating systems makes it difficult to accurately compare these options with other HVAC alternatives.

Data indicate that current models in EnergyPlus are inadequate for estimating the dynamic efficiency of condensing furnaces, gas absorption heat pumps (GAHP), and combination systems using tankless water heaters. Having no module in EnergyPlus to estimate the performance (or, even worse, to do it incorrectly) significantly limits choices for users to consider advanced, energy efficient systems during initial screenings of HVAC options. This project helps to address these limitations in EnergyPlus and helps to provide decision makers with accurate and reliable simulation tools for advanced residential heating systems, to enable equitable comparison with competing technologies and to advance the integration of gas and renewable energy.

Specific tasks in this project included:

- Developing mathematical models and performance maps for advanced gas space- and water-heating technologies
- Performing a technical and economic potential analysis on the above systems for the U.S. national single-family housing market, and
- Disseminating results through peer-reviewed journal publications which can support direct updates to EnergyPlus.

Daikin VRV System (L) and EC Power 25 kW mCHP (R)

In Phase 1 of this project, researchers leveraged technology-performance data for furnaces and gas absorption heat pumps collected as part of other projects to develop custom modules in EnergyPlus, and then used them to estimate energy savings potentials in several climates and use cases.

In Phase 2, the project team focused on GAHP model refinement, a more expansive market analysis and further functional refinements for combined space- and water-heating systems based on tankless water heaters.

Phase 3 builds on the successes of Phases 1 and 2 by making those results publicly available through updates to EnergyPlus that are supported by peer-reviewed publications. Phase 3 has also analyzed best practices for controlling gas dedicated outdoor air systems when combined with electric variable refrigerant flow (VRF) systems.

Phase 4 focuses on including additional next-generation gas equipment models of emerging gas heat pumps (beyond initial absorption-type), and hybrid gas-electric and integrated systems into EnergyPlus. It also focuses on deploying the results from modeling advanced equipment in Phases 2 and 3 into the capabilities of the residential building rating software used to determine HERS rating index.

Benefits / Market Implications

Through this project, researchers developed EnergyPlus performance data and/or built-in models for advanced furnaces, gas heat pumps, and tankless water-heater combination systems to allow general users to adjust the parameters (e.g., system size, performance curves, or design features). The outcomes of these efforts were published in peer-reviewed publications, public technical reports, and presented at several industry conferences hosted by Purdue University and ASHRAE, with additional dissemination still pending.

The tools developed as part of this project will enable decision makers to objectively evaluate the technical and economic potential of novel gas heating systems across North America.

Technical Concept & Approach

Specific tasks for Phase 4 include:

- Deploying a Generalized Gas Heat Pump Model for EnergyPlus
- Developing and Validating Models for Electric HVAC and Power Generation Systems
- Supporting Gas System Modeling for HERS Index Rating

Results

To achieve the project objectives, current limitations of the furnace, tankless water heater, and heat pump models were reviewed and new approaches for modeling were developed, taking advantage of part-load performance data collected on five condensing furnaces from a single manufacturer and prototype GAHP units.

In Phase 1, researchers leveraged extensive data collected in a Virtual Test Home to validate the EnergyPlus models. Using simulations of modern homes in mild and cold climates, the approach helped demonstrate how a modulating furnace could consistently save 10% on the natural gas consumption annually compared to single- and multi-stage furnaces, and an additional 2% if it is right-sized for the home.

Also, as part of Phase 1, GAHP combination system was modeled using a custom EnergyPlus script and available performance data. An analysis was then performed to compare a GAHP combination system to an electric heat pump with three different water-heater alternatives (gas, electric, and electric heat-pump water heater) with a condensing furnace and a premium water heater as the baseline. It was demonstrated that the GAHP combination systems were competitive with electric heat pump and heat-pump water-heater alternatives in mild marine climates, with respect to source energy savings and operating cost savings ($100-$200 per year). The GAHP combination system was the only option offering energy and operating cost savings in the colder climates.

Major accomplishments of Phase 2 included: 1) development of a whole new mathematical framework for simulating tankless-based combination units; 2) refinement of the GAHP combination model; and 3) public dissemination of the results through conference presentations and journal articles presented in 2020-2021. The major conclusion was that the GAHP is the best and most cost-effective option right now (and for the foreseeable future) for reducing CO_2-equivalent emissions in the majority of most cool- and cold-climate locations around North America.

"Many states require energy modeling before allowing new equipment into energy codes or for incentive programs. But most engineers won't touch a new technology without knowing energy performance. With existing software, gas heat pumps aren't a built-in option. That makes this project critical for market acceptance and transformation."

- Kevin Duell
Lead Engineering Consultant
NW Natural

In Phase 3, the project team developed reduced order models that can be readily integrated with simple energy-savings calculators; used models developed in Phase 2 to improve testing protocols for gas heat pumps; and partnered with an approved EnergyPlus developer to deploy a built-in model for GAHPs and other air-to-water fuel-fired heat pumps. The generalized gas heat pump model is now deployed and publicly available.

Phase 4 started in Q3 2022. EnergyPlus 23.1 was released and now includes the Gas Absorption Heat Pump model as part of the software. In Q3, the team completed validation of the ZNE models based on data collected from CA Habitat for Humanity homes. In Q4, the team completed a preliminary review of all power-generation sub-models in EnergyPlus. In 2023, the team is focusing on validating models for cold climates heat pumps, PV generators, and battery electric storage systems.

Status

A bug was discovered in the battery model of the EnergyPlus, which was validated through troubleshooting with the development team. Phase 4 simulations will be simplified by excluding the battery simulations and picked up again in Phase 5 that started in 2023. The team is now performing case studies of different gas-electric hybrid scenarios.

The team is also preparing a summary of recommendations for improving HERS Index calculations to be included in a future publication.

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Thermoelectric Generator for Self-Powered Water Heater

Researchers are developing a self-powered, gas-fired tankless water heater to save ratepayers money and energy while enhancing resiliency. Hardware testing is being performed to develop the critical components and integrate the design to power a condensing tankless water heater.

Project Description

Many consumers are embracing tankless gas-fired water heaters for their high efficiency and compact size, including significant adoption in Europe. According to Persistence Marketing Research, tankless water heaters sales will grow at an annual rate of 5.3% from 2016 to 2024.

Currently, all gas tankless water heaters require a connection to an electrical supply to maintain operation. Unlike gas storage water heaters, tankless heaters do not hold reserve hot water that can be used during a power outage. However, advances in thermoelectric generators (TEG), low-power components, energy harvesting, and energy storage may make it possible to develop an unpowered gas-fired tankless water heater for the residential market.

In previous efforts, researchers evaluated the potential for thermoelectric concepts for water-heater integration. All of the concepts used a water-cooled TEG device for gas-to-liquid thermoelectric power generation. While difficult to implement in a gas storage water-heater design, the water-cooled TEG concept may be ideal to implement in a tankless water heater where electronics, heat exchangers, and water flow are in close proximity to each other. Components such as the spark ignitor, a gas valve, a flue damper, and energy harvest and storage circuitry may have additional application in the development of a self-powered tankless water heater.

The initial objective for this project was to validate that a Thermoelectric Generator Heat Exchanger (TEG-HX) device can generate enough electric energy to power a tankless natural gas water heater.

In Phase 3, hardware testing was conducted to optimize the TEG-HX design to prove the concept of a self-powered natural-gas-driven tankless water heater with ultra-low emissions (<5 ppm NO_x) and with excess power capability. Three gas-to-water TEG-HX designs were analyzed and tested.

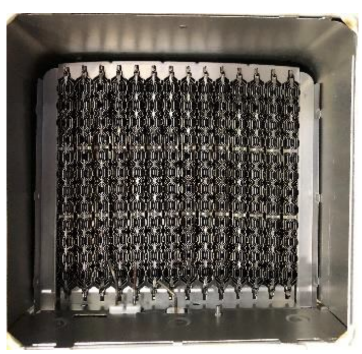
Phase 4 builds upon the hardware testing performed in prior phases to develop the critical components and integrate the design to create a complete alpha working prototype of a self-powered condensing tankless water heater.

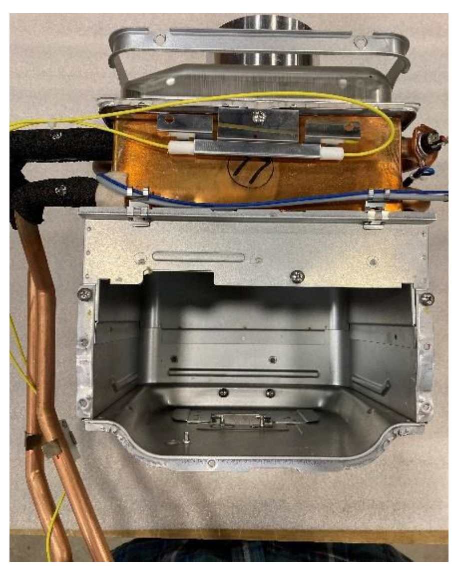
Benefits / Market Implications

A self-powered tankless water heater would preserve a key benefit that traditional gas storage water heaters offer – hot water availability during a power outage.

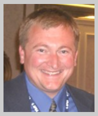
A TEG-HX-based condensing system would provide an enabling platform for higher efficiency self-powered gas appliances and serve end users with greenhouse-gas emissions reductions while still delivering hot water needed in disasters.

A TEG-HX system can also improve the efficiency of traditional storage water heaters by eliminating the energy consumed by the standing pilot light. At 400 Btu/hr, the water heater pilot





Disassembled tankless water heater with the burner pulled out



"Our organization supports the development of self-powered natural gas appliances. The technology is something needed in the market today."

- Chris Latch
Gas & Water Manager
City of Corinth Gas & Water Department

light in a non-powered gas storage water heater consumes about 35 therms per year, or 16% of the total energy consumption of a typical gas water heater.

The novel self-powered tankless water heater offers an identified energy savings potential of 20.9% over typical new natural-gas-driven water heaters and 73.2% over typical new electric water heaters when compared on a source-energy basis – which translates into a total of 0.4 quads savings in primary energy and a reduction of 20 Mt of CO_2 emissions per year in 2030.

Technical Concept & Approach

The key to developing a self-powered tankless water heater is to generate enough energy to power a combustion air blower while harvesting and storing additional power for start-up operations.

The project began with a Phase 1 effort that characterized through technical evaluation both the power requirements and operational constraints of a tankless water heater. Capabilities were demonstrated through numerical and analytical models. Phase 2 validated this capability through technical analysis and benchtop testing. Phases 3 and 4 built upon the knowledge and technology developed in prior phases to develop the critical components and prove the concept that a TEG-HX could power a condensing tankless water heater.

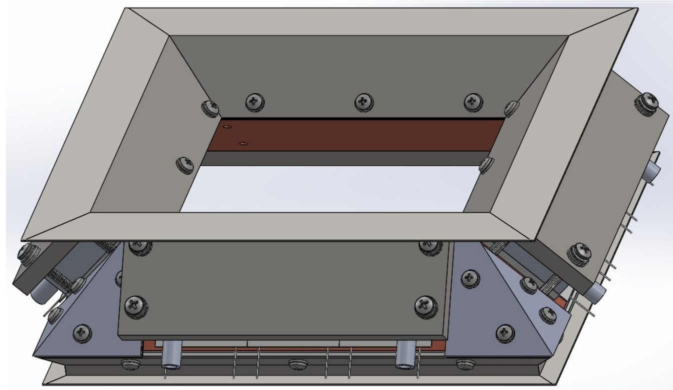
Results

The project team analyzed and tested various TEG heat-exchanger designs and selected the most promising and most efficient design. Researchers were able to achieve more than 25 watts from a single TEG and using the new radiant burner. This showed that more than 10 TEGs can be easily installed in the water heater and provide an excess power of 200 watts – more than is needed to power the water heater.

Researchers designed and tested a TEG-HX with a new radiant burner. Based on the results of experiments and analytical predictions, it was proven that it is possible to achieve an ultra-high efficiency of the tankless water heater.

In 2020, the TEG-HX was optimized to improve performance and reduce the cost to harvest power for self-powered tankless water heater operation and produce excess power. A techno-economic analysis was completed.

In 2021, an advanced radiant burner in combination with a



Thermoelectric generator assembly model for tankless water heater

primary heat exchanger of the water heater was selected for testing. Researchers modified a heat pump for laboratory testing under non-standard conditions in order to confirm its improved performance. The project team developed, designed, and assembled an experimental rig for laboratory testing of the heat pump for the novel tankless water heater. Laboratory testing was initiated.

In 2022, the tankless water-heater unit with the combustion chamber was disassembled and different sections were reviewed to better understand integration approaches. The section around the combustion zone has space, and additional physical space was identified for integrating the TEGs. A solid model will be generated for the integration of the TEG assembly. Currently, three different schemes are being developed for optimized integration of the TEG and one will be chosen based on the feasibility of the approach.

In 2023, a tankless water heater unit with the combustion chamber was disassembled. Different sections of the water heater were reviewed to better understand integration approaches. Certain hardware sections were identified and were reviewed for integrating the TEG assembly. A design assembly and a solid model of the TEG with the water heater was developed.

The project team determined a path forward for integration with the tankless unit and developed models with hardware assembly identification.

Status

The current phase of the project focuses on the development, manufacturing, and testing of an alpha prototype. Researchers will provide an analytical evaluation of the heat pump with tankless water heater and TEG integration.

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UTD Utilization Technology Development

Combination Heating/ Cooling Vuilleumier-Cycle Heat Pump

This project supports the development of an innovative gas-fired Vuilleumier-type heat pump to substantially increase efficiency over current gas heat pumps that operate using vapor-absorption and vapor-compression (engine-driven) cycles.

Project Description

This project supports the development of a gas-fired heat pump based on the Vuilleumier cycle – a closed-loop system similar in nature to the Stirling cycle – that uses a working fluid (helium) driven across several heat exchangers that interact with the environment.

The working fluid flow is driven through two linked displacers located in opposing cylindrical ends known as the "hot end" (where heat input to the cycle occurs) and the "cold end" (where heat removal from the environment occurs). Competitive with an absorption-cycle heat pump, the gas-fired Vuilleumier-cycle heat pump (GVHP) shows potential for a greater coefficient of performance (COP).

When commercialized, the GVHP would represent a step-change in efficiency over the current gas heat pumps that operate with vapor-absorption and vapor-compression (engine-driven) cycles, with a possible cooling COP of greater than 1.0 and a heating COP of greater than 2.0.

Benefits / Market Implications

The technology developer estimates that lifetime fuel savings of a GVHP over a condensing furnace can be as high as $9,760, with the potential for cooling-season cost savings as well. Using a benign working fluid (helium) with cost-effective design to accommodate higher working pressures (~1,450 psia), the GVHP may offer a premium gas heat-pump product with compelling emission and cost savings for gas ratepayers.

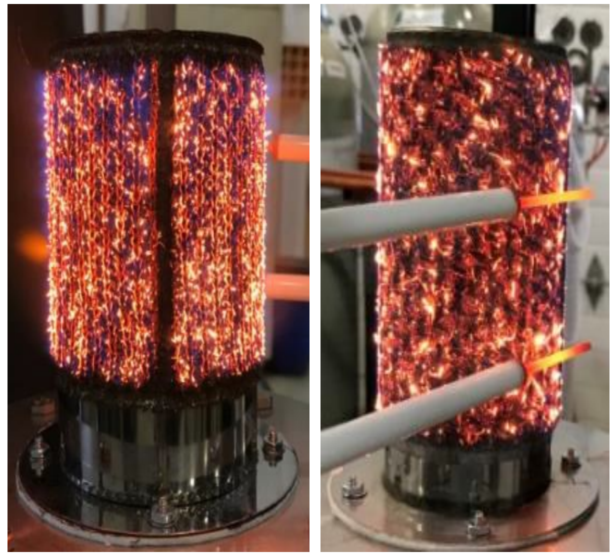
Technical Concept & Approach

Phase 1 efforts focused on helping design, evaluate, and improve the overall performance of the GVHP hot end. The unique operating regime of the system required new burner material, air-fuel mixing, and heat-recovery methods to be assessed, with the project team's recommendations ultimately being integrated into subsequent system prototypes.

Laboratory testing.

"This technology represents a new class of ultra-low carbon heating and cooling appliances. ThermoLift has created a new category of heating and cooling appliances. A single unit (heating, cooling, and hot water across a wide temperature range) that supports the goals of deep de-carbonization through the highly-efficient direct use of energy. This new category of gas heat pump paves the way to use 100% renewable energy sources, including renewable natural gas derived from waste and green hydrogen derived from renewable power."

- Christopher A. Cavanagh
Principal Program Manager - Future of Heat
National Grid



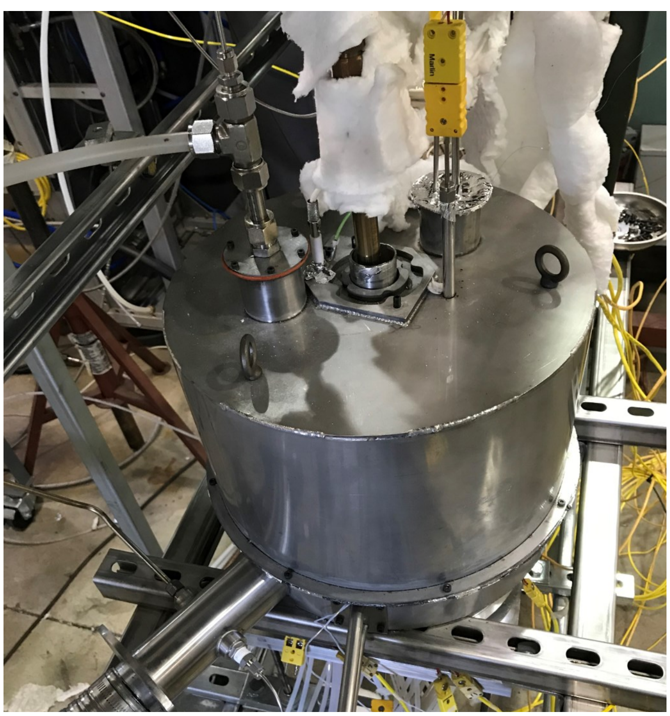
Initial air-preheating test setup with example burners.

In the current Phase 2, researchers provided support on optimizing the design of the hot-end assembly and field certification of the initial prototypes. In addition, an entire pre-production prototype will be laboratory tested using standard rating procedures. This information will be used to assess the energy efficiency and technical potential of the system.

Results

In Phase 1, the project team:

- Identified air-fuel preheat limits for a recuperator that would help the GVHP reach its performance targets
- Defined design guidelines for air-fuel mixing strategies for the GVHP
- Engaged with five burner manufacturers to find a compatible burner for the operating regime



- Validated hot-end heat-exchanger design
- Demonstrated overall hot-end efficiency consistent with initial design estimates, and
- Identified subsystems that needed redesign to reach target performance levels.

Current Phase 2 efforts include:

- Provided technical support to redesign and further optimize the combustion system and novel combustion controls
- Performed a codes-and-standards review to help with field certification of initial prototypes, and
- Testing of the full system prototype is to be completed. In preparation for whole-system testing, a comprehensive test plan for the system was prepared and the test apparatus was constructed.

Status

The research team is currently awaiting a prototype to be provided by the technology developer to complete testing. Testing has been delayed until at least the fourth quarter of 2023.

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Yanmar Gas Engine Heat Pump Field Studies

Researchers evaluated the performance and economics of a Yanmar 2-pipe gas heat pump (GHP) and a Yanmar 3-pipe GHP (the first to provide simultaneous heating and cooling) in Alabama and Georgia, respectively. Researchers obtained key performance data that will enhance GHP energy models and aid facility owner/operators and designers to better evaluate efficient equipment options in order to reduce energy use and operating costs.

Project Description

Natural gas engine driven heat pumps (GHPs) provide high-efficiency heating and cooling while significantly reducing peak electric demand and electricity use, to save energy and reduce life-cycle costs when compared to electric heat pumps or conventional HVAC equipment.

In 2016, Yanmar America Corp. Energy Systems introduced a 14-ton GHP with a 3-pipe heat-recovery variable refrigerant flow (VRF) system, the first GHP in the U.S. market with the capability to provide simultaneous heating and cooling. This option improves the response to building loads by recovering heat from zones in cooling mode (e.g., internal loads) and redistributing it to meet heating loads in perimeter zones.

This technology provides a unique energy-efficient option, and opens up new markets where in the past electric-driven systems were the only options for simultaneous heating and cooling.

GHPs have a significant share of Japanese and European space-conditioning markets, but are relatively new to the North American market. The Yanmar product line includes 2-pipe VRF systems from 8 to 14 tons in addition to the 14-ton 3-pipe unit. As an emerging technology, GHPs face economic and market barriers, including high installation costs (which can be offset by savings in operating costs), the need for additional engine maintenance with limited service networks, and engine emissions (Primarily NO_x).

One of six GHPs installed at the Lawrenceville Public Works facility in Georgia.

For this project, researchers expanded on previous developments with GHPs in laboratory and field demonstrations to evaluate the field performance and economics of the Yanmar 3-pipe GHP. A new phase of the program involves a demonstration of Yanmar's 2-pipe GHP to compare overall performance with the Yanmar 3-pipe system in a similar warm climate.

Benefits / Market Implications

Low gas rates and energy-resiliency concerns are key drivers for the adoption of GHPs to reduce operating costs in areas with high electric rates and demand charges or vulnerable to electrical outages.

Peak electrical demand has been growing in the commercial sector, mainly due to the high cooling requirements of commercial buildings and policies supporting electrification of homes, vehicles and facilities. GHPs offer a cost-effective and environmentally-friendly option to reduce peak electricity demand.

Technical Concept & Approach

Specific tasks included: site selection and development of a field test plan; site monitoring and data analysis to determine the performance, environmental, and economic benefits of GHP installations in commercial buildings.

Results

1. **3-Pipe Gas Engine Heat Pump Field Study:**

For the demonstration, the project team selected the Lawrenceville Public Works (LPW) facility in the service territory of the Municipal Gas Authority of Georgia (MGAG). In 2016, the MGAG launched a GHP incentive program to support market transformation for GHPs. Six GHP systems provide zoned heating and cooling for the Lawrenceville facility.

One of the six GHP VRF systems at LPW was selected to be studied in the demonstration. The GHP outdoor unit and corresponding fan coils were instrumented and energy use and performance was monitored from November 2018 to October

"The Gas Authority recognizes the importance of market acceptance for GHP technologies, which provide energy efficient solutions for customers and reduce carbon emissions. The Gas Authority has supported the testing and installations of GHP technologies including GHP VRF applications for commercial buildings. Through our Emerging Technology Rebate Program, many of our municipal natural gas systems have supported GHP VRF installations in schools and government buildings."

- Rodney Dill
Vice President, Market Development & Communications
Municipal Gas Authority of Georgia

"Modern solutions like engine-driven gas heat pumps leverage our industry's long-standing promise and commitment to deliver affordable, reliable, efficient and resilient energy to the customers and communities we serve. At Spire, we're grateful to Pike Road Schools for partnering with UTD as a host site to better quantify energy consumption, equipment reliability and performance."

- Steve Roberson
Technical Analyst
Spire Energy

2019 to evaluate its performance across the full range of ambient conditions and equipment operation.

Due to the field site's warm climate, the GHP operated in cooling mode for the majority of time, with limited runtime in heating mode. Simultaneous heating/cooling operation occurred only during mild temperatures. Based on this field site, the GHP had lower annual energy costs and reduced peak electric demand compared to equivalent all-electric VRF systems or conventional multi-zone roof top units (RTUs).

Part-Load Operation:

The GHP achieved rated efficiencies that exceeded 1.3 COPg during extended steady-state runtimes; however, overall GHP efficiency was reduced during low part-load operation. Measured seasonal efficiency was 1.18 COPg heating and 0.95 COPg cooling, excluding simultaneous operation. While it is common practice to oversize conventional HVAC equipment to ensure adequate capacity, oversizing GHP systems can impact both heating and cooling performance.

Simultaneous Operation:

Results suggest that 2-pipe VRF systems may in some cases be more cost effective than 3-pipe systems. Fan coil placement and set points may also impact performance in simultaneous operation.

Economic Assessment:

The GHP had lower annual energy costs than an equivalent multi-zone RTU or an all-electric VRF system. Savings in energy costs were driven by reductions in peak electric

One of seven two-pipe GHPs installed at Pike Road School in Alabama.

demand and associated demand charges. Based on the measured performance at this field site, the GHP had lower life-cycle costs compared to an equivalent all-electric VRF with a simple payback of eight years based on regional energy prices. With current incentives ($700/ton), GHPs would have an immediate payback compared to an electric 3-pipe VRF with more than $14K savings in life-cycle costs over the 15-year life of the equipment.

2. 2-Pipe Gas Engine Heat Pump Field Study:

The project team monitored an existing Yanmar 2-pipe GHP installation at a school in Pike Road, AL. Seven GHP units were installed at the school and commissioned in 2017. One GHP system was monitored from November 2022 through October 2023 to collect installed performance data with respect to part-load and ambient conditions, and to quantify the energy use and economics for a Yanmar 2-pipe GHP unit.

The GHP systems were appropriately sized for the facility cooling load and demonstrated excellent cooling performance ranging from 0.8 to 1.7 COPg, resulting in a seasonal average of 1.35 COPg.. Daily average heating efficiencies exceeded 1.0 COPg on days with higher heating loads. This demonstration provided a valuable comparison to the 3-pipe GHP evaluated earlier in the project and also generated another performance dataset for the Yanmar GHP in a warm climate, with both datasets helping to advance the development of accurate engine-driven GHP models in EnergyPlus^{TM} under UTD project 1.21.E .

Status

The project is complete. During the past year, the project team collected and analyzed a full year of heating and cooling performance data of the 2-pipe VRF system. The project team issued a UTD Final Report which assesses the performance and economy of the system. This measured dataset will be incorporated in the development and validation of enhanced GHP energy models for HVAC designers and compliance-based energy simulation.

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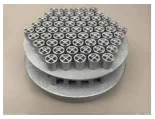
UTD Utilization Technology Development

Advanced Nozzle Burner for Commercial Water Heaters



Researchers are developing and demonstrating an advanced 3D-printed economical nozzle burner for commercial water heaters with high efficiency, ultra-low emissions, good turndown, superior stability, and compactness.

Project Description

Current commercial water-heater burner designs are not able to achieve all the technology targets of ultra-low emissions, high efficiency, good turndown, and attractive first costs. They also often have retrofit-ability limitations and are not scalable.

In Phase 1 of this project, researchers successfully developed and tested a 3D-printed burner by integrating advanced nozzle prototypes with the blower, controls, and fuel inlet of a commercial water heater. In the current Phase 2 of this project, researchers are testing a beta prototype version of this robust, smooth- and safe-operating advanced retention nozzle in a commercial water heater (~200,000 Btu/hr capacity), offering improved efficiency, turndown, emissions, stability, and compactness.

Key performance goals for Phase 2 include:

- Improve efficiency by 2%-4% for the same emissions
- Demonstrate NO_x emission of <5 ppm and CO emissions of <20 ppm corrected to 3% O_2, and
- Achieve turndown of 10:1.

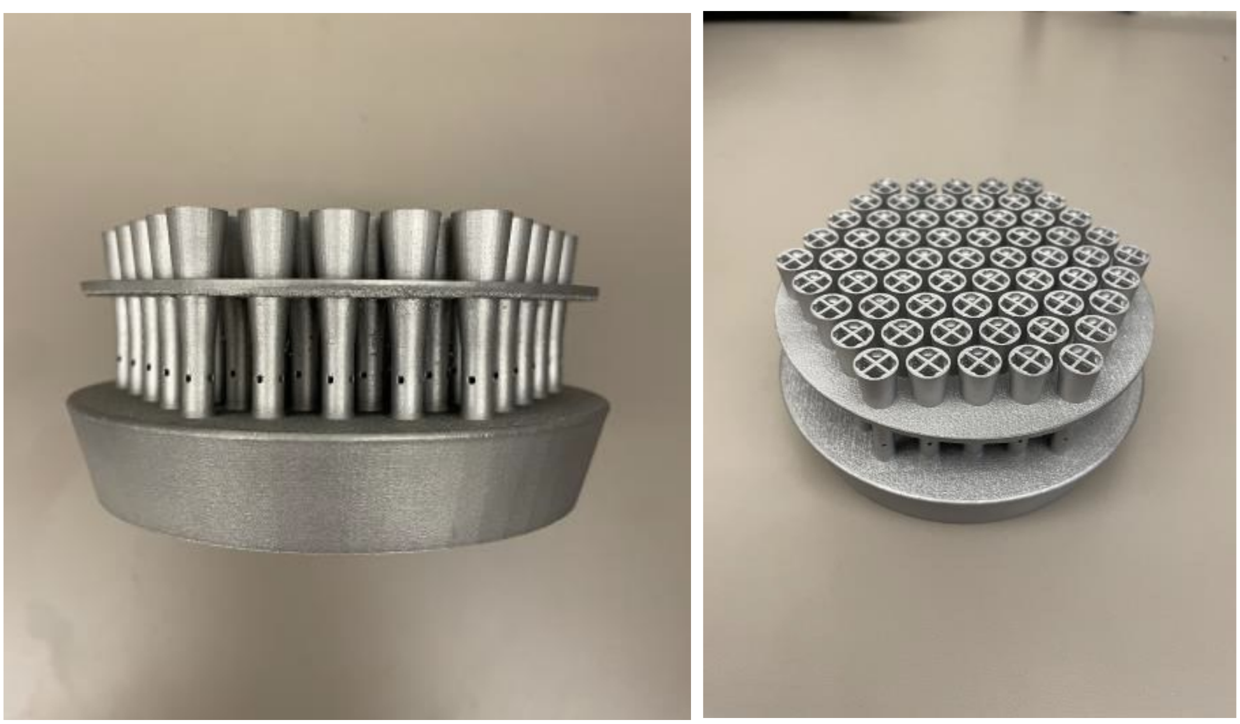
Benefits / Market Implications

Forty-four percent of the 225,000 commercial water heater units sold annually in the U.S. are gas driven, with associated positive impacts on source-energy efficiency. Similarly, data shows that 42% of commercial buildings heat water with natural gas. Low-cost, low-emission, compact commercial gas-driven burners could further reduce source-energy use.

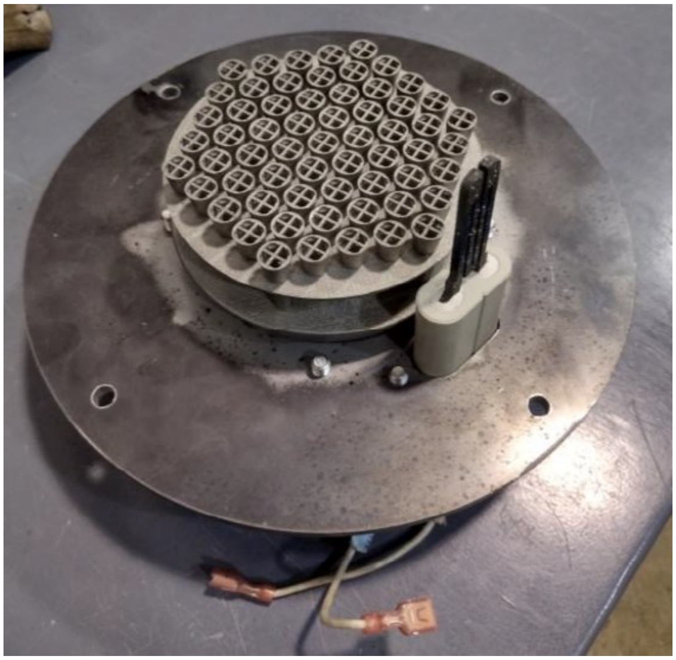
The technology to be advanced in this project can substantially reduce energy consumption in commercial buildings. Of the 40 quads used by U.S. buildings, 9% are used by the water heaters. An average 3% improvement in efficiency will lead to at least 0.12 quads of annual energy savings.

Other benefits of the advanced, patented nozzle burner technology are expected to be:

- Scalable to multiple designs and capacities
- Significant reduction in NO_x emissions >75%, with turndown of 10:1 with CO emissions of <20 ppm
- Simple and robust, with potential lower first costs
- Installer- and manufacturer-focused



3D printed hardware of the β-prototype design



Test setup for 3D printed hardware - β-prototype design

- Reduced weight and size of the water heater; hence, lower cost and easier installation in tight locations
- Improved manufacturing ease and significantly reduced time to market
- Reduced noise (hence, more comfort), and
- Capable of integrating smart controls for smart-building applications.

Technical Concept & Approach

In Phase 2, the project team designed and fabricated prototypes of a nozzle burner. This design considers the key features to be adapted for the prototype (e.g., flame stability within the water heater and smooth ignition). Two to three design iterations were fabricated by Oak Ridge National Laboratory.

After designing the prototypes, researchers will install the burner in a commercial water heater. The dimensions will be matched to have a drop-in design to replace the current burner. The design of the igniter may have to be modified.

The team will perform multiple ignition tests to ensure that the burner ignites reliably and smoothly at variable firing rates. This will determine the reliability and repeatability of the ignition process, even though the water heater usually operates at a constant firing rate. This will provide greater confidence in the ignition process.

After successful ignition testing, performance testing will be conducted. This will help determine the operability and turndown characteristics of the advanced nozzle burner. The testing will be performed for different firing rates and different air-fuel ratios to evaluate the emissions and efficiency characteristics. The firing rate will be varied to ensure operability and oxygen concentrations will be varied for evaluating emissions and efficiency performance.

Results

Researchers designed, developed, and tested a 3D-printed advanced nozzle burner on a benchtop setup with the controls and blowers of a commercial water heater. Multiple design iterations were manufactured to improve operating characteristics and combustion performance and adapt the burner into the water heater for long-term steady and robust operation. Benchscale testing showed the burner can be adapted to a commercial water heater and is able to provide ultra-low emissions of <5 ppm NO_x and <20 ppm CO at 3% O_2 and turndown of at least 8:1.

The novel burner was further developed to provide a drop-in retrofitable design for in-field and new water-heater installations. Design changes were made to the nozzle diameter and the number of nozzles were customized and designed to match the water heater chamber. Multiple design iterations of the advanced nozzle burner were 3D printed. A Phase 1 Final Report was issued in November 2020.

In 2021, the project team reviewed different integration methods for the burner within the water heater. The blower and the burner were and different firing rates were evaluated. The impact of the burner on upstream components such as a premixed air/fuel blower and the combustion dynamics, mixing, and emissions were evaluated.

In 2022, burner designs were further reviewed for adaptation and flame stability within the water-heater prototype. Researchers reviewed various methods for adapting the burner within the water heater. Testing showed that ignition was intermittent and the flame was not stable and, hence, further changes were made to the ignition scheme to ensure that the burner can be retrofit without any other modifications. The emissions testing showed that <9 ppm emissions can be achieved.

In 2023 the β-prototype burner was 3D-printed and the team prepared the test setup for ignition and emissions testing of the nozzle

Status

Phase 2 efforts are continuing. The project team is evaluating performance of the B-prototype nozzle for ignition and emissions.

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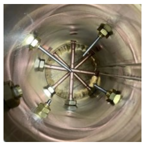
UTD Utilization Technology Development

Mitigating Methane Emissions from Residential and Light Commercial End-Use Equipment



Research is being conducted to quantify the emissions and determine the conditions under which residential and light commercial end-use appliances release unburned hydrocarbons into the atmosphere, in order to identify best practices or design features to reduce methane emissions.

Project Description

Residential and commercial appliances are coming under increased scrutiny due to field-measured emissions of unburned hydrocarbons. However, field-derived emissions measurements are difficult to perform accurately and often lack the data resolution or flexibility to gain a full picture of emission events. This project generates laboratory measurements of methane emissions from appliances with the goal of generating greenhouse gas (GHG) emission factors, understanding the conditions leading to emissions, and identifying best practices or design features to reduce methane emissions. UTD's scientific research can help inform public dialogue on this topic.

In the first phase of this project, the team focused on assessing emissions from tankless water heaters (TWHs), which modulate directly in response to end-user loads. The high-input compact burners in TWHs frequently cycle on and off, which may increase their methane emissions.

In order to maintain outlet temperature stability while handling variable inlet water temperature and flow demands, these units ramp up and down their firing rate quickly, with 20:1 turndown ratios common for products available (which is unusual for most other gas-fired equipment). This is achieved in a number of ways. Staging multiple cassette burners is the most common method. Several burners (~16) are staged in groups, on and off, as sequenced by proportional gas valves. This allows for the highest possible turndown. Another method is use of a single ceramic “plaque” or flat woven/knitted fiber mesh, large enough and with an adequate thermal mass to permit a wide turndown ratio with a modulating gas valve. As the TWH shifts to meet the load, either rapidly staging burners on/off or modulating the single plaque/mesh burner, temporary loss of flame stability and delayed ignition can lead to temporary emission of unburned methane. While this transient effect is present with all cycling gas-fired equipment, TWHs by their nature are constantly adjusting the flame through staging or rapid and drastic modulation. Models from three different manufacturers of TWHs were tested under specific operating conditions and representative use patterns, in order to examine emissions from these various modulating methods.

Phase 2 and Phase 3 efforts expanded this project to examine furnaces, storage tank water heaters, and ranges, which have also been included in various field studies focused on residential methane emission measurements. Phase 4 builds on the work of Phases 1-3 in quantifying and identifying methane emissions in Res/Com equipment, and adds analysis of the effect of hydrogen blending.

Benefits / Market Implications

The results from this study will support the continued improvement of residential natural gas appliances and the understanding of post-meter methane emissions. This includes standard residential gas appliances such as tankless/storage gas water heaters, furnaces, and residential ranges.

Tankless gas water heaters are currently the second most popular type of gas water-heating equipment, representing more than 10% of gas products sold in North America and more than 50% in Europe. The ability to clarify and mitigate the impact of TWHs and other gas appliances on GHG emissions will support the continued improvement of this technology for end users. Any potential restrictions that limit options to

Furnace test bay with final modulating furnace installed for testing.

use this type of high-efficiency device should be based on sound scientific study and consider potential product and technical advancements to minimize and mitigate potential releases.

Technical Concept & Approach

Phase 1 focused on measuring unburned methane release from TWHs, and the results are summarized below.

A laboratory test setup from Phase 1 was adopted for Phase 2 to quantify methane emissions in furnace exhaust. In addition to steady-state testing, a control program was developed to operate the furnaces at a variety of part-load conditions to observe the impact of varying operation on emission profiles.

Researchers will use the laboratory measurements taken in Phases 1-3, supplemented with emission factors from literature where needed, to create a spreadsheet tool to estimate total residential appliance emissions based on selection of appliances in the home and adjustable operating patterns for space heating, water heating, and cooking over a range of climate zones.

In phase 4, the following tasks will be performed:

Task 1: Literature Review and Methods Development

The team will review the current state of knowledge regarding emissions, including learnings from prior phases of this project.

Task 2: Install and Test Res/Com Appliances

The team will install and test space heating and water heating appliances previously tested under Phases 1-3 with hydrogen blends up to 30% by volume to allow for direct comparison with emissions resulting from operation with methane/natural gas.

Task 3: Test Industrial/Large Commercial Burners

The team will also perform benchtop tests of industrial/large commercial burners with hydrogen blends up to 50% by volume.

Results

In Phase 1, researchers completed two tasks: 1) developing the test plan including specifications for the methane-analyzing methodology and 2) procuring and installing both a non-condensing TWH and a condensing TWH in a customized laboratory test rig. Plumbing and system controls were put in place to operate the TWH units. The project team engaged with a major university regarding the test plan as a complement to field sampling of TWHs. Input was also solicited from TWH manufacturers regarding system operation, compact burner modulation/ignition methodologies, and system controls with respect to the emission of unburned fuel.

Researchers developed methods to accurately measure the dynamic emission rate of methane from a modulating TWH and used various dynamic tests to simulate end-user behavior. Three TWHs were tested – representing a range of combustion system designs and the most popular models and manufacturers. The units were tested using steady-state, "step ramp-up", and simulated-use patterns to establish typical methane emissions across products and combustion system designs. Through data analysis, researchers identified tankless designs, features, and operating conditions that can produce methane emissions. A list of recommendations for detection and mitigation of such conditions was developed.

Phase 1 findings showed that the tested TWHs produced measurable methane emissions through "puffing" at ignition/extinction, during modulation (depending on the burner design), during steady-state operation (depending on the burner design and firing rate), and during off periods. Both steady-state emissions and ignition/extinction emissions generally showed similar order of magnitude results as in prior field studies. Phase 1 findings were presented at the ACEEE Hot Water Forum conference on July 22, 2020, and in other venues to university researchers and other organizations.

In 2021 under Phase 2, researchers prepared the testing area and instrumentation for testing furnaces. A number of shakedown tests were performed to address issues with the methane analyzers, instrumentation, control programs, and data acquisition. Furnaces were tested in 2021-2022. Total hydrocarbon emissions data were collected for both steady-state and part-load tests to generate a full picture of the emission profile for typical furnace operation.

In 2023, furnace steady state testing (top) and part load cycling test (bottom) showing seven part-loads ranging from 40-100% with one-hour cool down period in between each cycle. Methane spikes can be seen at ignition and extinction of the burner and is sub-atmospheric during combustion, indicating complete combustion of the gas during steady state operation.

Status

Data analysis of all furnace testing (Task 2 Laboratory Assessment of Methane Emissions) has started. The team also reviewed additional relevant articles that were compiled on specific appliance methane emission measurements as well as end-use emission estimates.

The team has submitted an abstract to a 2024 gas industry research conference to present the findings from Phases 1 and 2. The Final Report for Phase 2 is in development.

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UTD Utilization Technology Development

Economical High-Efficiency Residential Gas Absorption Heat Pump with Integrated Cooling

This project focuses on adding cost-effective cooling to a new low-cost gas absorption heat pump product that currently provides only heating and domestic hot water. An economical, integrated single unit that provides both air conditioning and high-efficiency heating can help more end users benefit from this exciting new product.

Project Description

A gas absorption heat pump (GAHP) can provide low-cost whole-house heating with significant improvements in efficiency over condensing furnaces and boilers. In addition to cost-competitive therm savings of up to 45% over conventional residential gas heating equipment, the GAHP delivers stable, comfortable temperatures without the need for auxiliary heating or backup and is projected to be ultra-low-NO_x compliant with all combustion occurring outdoors. This project builds on other UTD efforts to bring to market a new heating-only, low-cost GAHP for the residential market.

One issue that might limit its adoption is that it currently does not also provide high-efficiency cooling. The economics of the heating-only GAHP (sized at nominal 80 kBtu/h output), with the aggressive equipment cost target of $5,000, are generally suitable in cold climates and for large, single-family homes. However, the economics worsen in mixed or cooling-dominated climates, especially in the U.S. Southeast. As a result, cost-effective cooling is necessary for this product to broadly succeed and serve many ratepayers.

While GAHPs offer high efficiency and low emissions, existing GAHPs commercial products tend to be costly and have seen limited adoption in North America. The approach in this project will advance a new hybrid arrangement, wherein the GAHP would have an electrically-driven compression cycle, and can share internal heat exchangers with the absorption heat-pump sealed system. In this project, a research team seeks to demonstrate an economical GAHP with integrated cooling that could offer a simple payback of less than three years for a hybrid system.

This project leverages co-funding from the Natural Gas Innovation Fund (NGIF) launched by the Canadian Gas Association (CGA) and moves from the development/design stage to a laboratory version of a packaged alpha prototype.

Benefits / Market Implications

The hybrid GAHP with cooling is intended to broaden the energy and emissions savings potential of the GAHP, expanding the benefits of this technology for end users by providing applicability for mixed and cooling-dominated climates.

Of all U.S. single-family homes, 73% have central air conditioning (A/C). Early feedback from contractors and homeowners on the heating-only GAHP is that very few homeowners will permit having two large pieces of HVAC equipment outdoors. The advantage offered by operating with a chilled-water loop for A/C, using the single indoor coil, is that this is not a direct expansion system. This significantly reduces the refrigerant

Prototype GAHP hybrid (left) and paired prototype air-handling unit (right).

charge volume as it is only contained within the hybrid GAHP unit. In addition, many HVAC manufacturers are looking to refrigerants at higher pressures or with moderate flammability, which is challenging for conventional split A/C systems.

Technical Concept & Approach

This project builds upon a gas-fired heat pump water heater (GHPWH) developed and supported in conjunction with UTD project 1.11.H and GAHP under 1.13.F, scaling up the same absorption heat pump technology by a four-fold factor.

Laboratory tests were conducted to estimate the hybrid unit's performance using standardized steady-state testing. In addition to standardized rating tests, an extended 24-hour simulated use test will be conducted in a virtual test home to obtain a complete mapping of performance and evaluate the impact of coincident loads. A purpose-built test-stand, water storage tank, and an environmental chamber will be used to evaluate space heating/cooling loads, domestic hot water loads, and outdoor ambient conditions.

Results

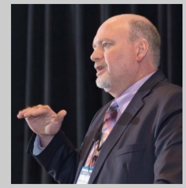
In 2020, the scope of the hybrid GAHP device was defined for the purposes of modeling. A modeling plan (assumptions, boundary conditions, etc.) was developed and simulation was executed. Researchers agreed on the operational parameters of the GAHP hybrid as it pertains to the initial building energy modeling task, using the heating GAHP modeling assumptions developed under prior efforts and absorbing modeled performance curves.

The project team ran models of single-family homes for several representative metropolitan areas, covering multiple climate zones and housing types (size, construction, occupancy) and performing annual energy assessments of hybrid GAHPs. Investigators are considering multiple baseline scenarios (all-electric, high/low efficiency, etc.). This modeling exercise will be extended to key U.S. regions, including: Chicago, Salt Lake City, Fargo, St Louis, Minneapolis, Portland, Rochester, San Francisco, Albuquerque, Atlanta, Los Angeles, and Tampa.

In 2021, the project team made upgrades and additions to the laboratory thermal heat pump test station, developed a test plan, and modified the test stand for the heating-only GAHP.

In 2022, after resolving several installation and unit issues, steady-state cooling tests and heating and dynamic tests were completed. Final results based on testing done by the team were reported to UTD members and also in a technical paper at the 14th IEA Heat Pump Conference held in May, 2023 in Chicago, IL.

"UTD provides an invaluable contribution towards the advancement of innovative, very high-efficiency products within the gas and energy industry. Without UTD's support on numerous projects over the prior 10 years, SMTI would not have been able to prove out and de-risk our family of affordable thermally-driven heat pumps, a critical first step before investors will step in to support commercialization activities. Our Hybrid GAHP/AC heat pump model will help move gas heat pumps from a solid niche to the mainstream HVAC/water heating market."



- Michael Garrabrant
Founder and CEO
Stone Mountain Technologies, Inc.

Key highlights from this test program included defining this alpha prototype's seasonal heating and cooling performance with an AFUE of 121.6% and an estimated SEER of 8. The seasonal cooling performance is lower than the target and is influenced by the compressor selection, this estimated SEER rating would not be acceptable by conventional standards (min. SEER = 13, soon to be increased). For heating operation, the performance degradation is mainly due to the cyclic operation of the hybrid system and the standby electric load. For this first-of-a-kind prototype, the project team have published these key results and findings in addition to modifications/improvements to meet targets. Concerning GAHP emissions, the CO emissions ranged from 11.5 to 101 ppm air-free and NOx emissions were Ultra-Low (7 to 8 ng/J), both of which are already below performance targets.

Status

Phase 2 has been completed. A Final Report was provided to UTD members in November 2022, and the current results were publicly reported in May 2023 as summarized above. The team is now working on Phase 3 which will design, fabricate and evaluate in a laboratory a modified prototype unit which will employ using other low-GWP refrigerants with a goal to increase useful heat recovery within the operating cycle in order increase overall system efficiency.

The project team continues to partner on this project with Stone Mountain Technologies, Inc. (SMTI), the developer of the technology which has made substantial progress commercializing the heating-only GAHP unit. In July 2021, it was announced that UTD member Enbridge had invested CAN $4,000,000 in SMTI. In November 2022, SMTI announced closing of US $15,000,000 in Series A funding. As of October 2023, initial production runs of GAHPs from SMTI's factory were underway.

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Gas Heat Pump RTU Cold-Climate Performance Assessment

This project demonstrated a gas-engine-driven heat pump incorporated in a packaged rooftop unit to quantify its cold-climate performance, reductions in peak electric and peak gas demand, and environmental benefits.

Project Description

Gas-engine-driven heat pumps (GHPs) are an important gas cooling and heating option for commercial buildings when considering electric-demand reduction initiatives. Previous studies demonstrated that GHPs can reduce peak electric demand by 6 kW to 15 kW, compared to electric variable refrigerant flow (VRF) systems, or conventional rooftop units (RTUs), respectively.

GHPs can also reduce peak gas demand. GHPs have high heating efficiency due to the use of engine heat recovery to boost performance during the winter. This increased heating efficiency will reduce peak gas demand, generate energy savings, and reduce full-fuel-cycle greenhouse gas (GHG) emissions when compared to a baseline standard-efficiency RTUs.

Compared to electric heat pumps, GHPs have two key advantages in heating operation for cold climates. GHPs use engine heat recovery to: 1) avoid a defrosting cycle and 2) maintain heating capacity and supply temperatures during very cold ambient temperatures. Electric heat pumps require periodic defrosting at ambient temperatures below 40˚F. Conventional defrosting uses reverse cycling, which results in an inherent energy penalty because it removes heat from the indoor air during the defrosting period. GHPs avoid the need for a defrosting cycle by controlling the flow of the recovered waste heat from the engine and maximizing the heat-recovery process.

A second advantage is to avoid supply temperatures which can result in the "cold blow" effect (delivery of air at less than body temperature) that compromises indoor thermal comfort. GHPs use engine heat recovery to supplement heating output in order to maintain both indoor supply temperatures and heating capacity, which can be a problem with current electric heat pumps. In cooling and moderate heating mode conditions, engine waste heat can also be directed to an optional supplemental water heater, maximizing system efficiency.

This field study quantified the performance and benefits of the packaged natural gas engine-driven heat pump rooftop unit for (PGHP) high-efficiency space conditioning for commercial buildings in cold climates. This rooftop configuration is a unique GHP design with potential for wide adoption and lower installation costs by using the same footprint as conventional packaged rooftop units. Although this model successfully demonstrated high-efficiency cooling performance and reliability in very hot climates, this field study was one of the first cold climate demonstrations of the packaged GHP. The objective of this study was to validate cold climate performance and identify any design changes needed to optimize this technology for cold-climate applications.

This project was conducted in partnership with the New York State Energy Research and Development Authority (NYSERDA) and National Fuel Gas Company, with NYSERDA providing the prime funding for this research.

Image credit: Blue Mountain Energy

Blue Mountain Energy's packaged rooftop gas-engine-driven heat pump.

Benefits / Market Implications

GHPs can provide economic and resiliency benefits for commercial buildings and gas customers, such as life-cycle cost savings with favorable time-of-use rates or electric-demand charges, and infrastructure capital cost savings due to lower peak electric demands.

Technical Concept & Approach

- **Site Selection and Baseline Monitoring**

  Select a site representing a potential end user for GHPs, including facilities such as offices, schools, health clubs, gymnasiums, hospitals, retail buildings, and restaurants. A small gas station and grocery store in Buffalo, NY was selected for this demonstration.

- **PGHP Installation and Demonstration Plan**

  Develop the demonstration plan for the selected site, and then specified, installed, and commissioned the instrumentation and data-acquisition system.

- **PGHP Performance Monitoring**

  Monitor the performance of the PGHP from 2020 through 2021 to determine annual energy use and costs across the full range of operating conditions.

- **Data Analysis**

  Analyze measured data to determine heating and cooling delivered, energy consumption, reduction in peak electric demand, GHG emission reductions, and energy cost savings relative to baseline. Estimate simple paybacks.

- **Innovative Desiccant Proof of Concept**

  Develop at laboratory scale an innovative 3D-printed desiccant wheel with thermo-responsive desiccants to enhance energy efficiency and thermal comfort in buildings. UTD and partners National Renewable Energy Laboratory, Blue Mountain Energy, and TCPoly will design, build, and demonstrate a proof-of-concept prototype. Separating sensible and latent cooling by using desiccants have shown up to 30% savings of primary energy. Compared to conventional desiccant systems, the proposed design has potential to reduce energy consumption by reducing the additional sensible load due to desiccant regeneration.

Results

This field study confirmed significant peak electric-demand reductions, which may qualify for electric-demand response programs or non-wire initiatives. The measured peak demand during cooling was 4.38 kW, a significant decrease (76%) from the 18 kW summer peak demand associated with a conventional RTU using natural gas heating and electric cooling. A comparable electric heat pump would generate 22 kW peak demand during heating operation, excluding any supplemental heating at low temperatures.

The PGHP demonstrated high cooling efficiencies with a seasonal average of 1.19 COPg (Coefficient of Performance on gas use) which aligned with rated efficiencies of 1.12-1.24 COPg reported from laboratory testing. Although the PGHP demonstrated high heating efficiencies in laboratory testing (1.4 COPg at rated conditions), the heating efficiency measured at the field site was lower than expected. Some heating-performance issues were discovered at lower ambient temperatures that will require further investigation by the product design team; this type of anomaly is not unexpected for the first cold-climate demonstration. As noted, a key objective of this study was to identify design changes needed to optimize PGHP heating performance and effectively implement this design in colder climates.

Based on regional utility pricing, the PGHP can reduce energy costs up to 44% compared to conventional and electric heat pump RTUs due to high-efficiency operation, low-cost natural gas, and reduced demand charges. Further cost reduction of the PGHP design is needed to achieve more favorable paybacks. Upstream GHG emissions for the PGHP were similar to conventional and the electric heat pump RTUs based on regional non-baseload power-generation mix; however, engine operation generated additional onsite GHG emissions, highlighting the need for an engine design that can optimize performance while minimizing emissions.

The project team analyzed the experimental NREL data on new thermo-responsive desiccant samples. A computational model was developed to optimize the geometry of the thermo-responsive desiccant channels and the desiccant wheel based on the NREL experimental data.

A conference paper which summarized the results of the rooftop GHP demonstration was presented at the 2023 ASHRAE Winter Meeting on February 5, 2023.

Status

A public summary dated April 6, 2022 of the Final Report for Tasks 1-4 of UTD project 1.18.I is available on the Reports page of UTD's public website.

For Task 6, the project team is waiting to receive NREL's input data for the computational model. The modeled output will then be compared to the measured experimental data.

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UTD
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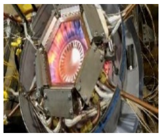
Integrated, Self-Powered, High-Efficiency Burner System



Researchers are developing a grid-resilient, self-powered, fuel-flexible, high-efficiency Advanced Burner Thermoelectric Generator that can be installed in many residential and commercial building space- and water-heating systems to improve their resiliency, reliability, and efficiency.

Project Description

The goal of this project is to develop and demonstrate a laboratory prototype of a grid-resilient, self-powered, UTD-patent-pending, thermoelectric generator (TEG) system integrated into a commercial water heater. Initial development efforts focused on demonstrating this at a 40,000 Btu/h capacity, while current efforts are scaling up development to ~200,000 Btu/h capacity.

The integrated system consists of two key subsystems: 1) a 3D-printed high-efficiency, ultra-low-emissions, fuel-flexible, modulating burner integrated with 2) a commercially-available low-cost, high-efficiency, high-operating-temperature TEG. The project seeks to demonstrate and advance towards commercialization a design that is drop-in retrofittable, self-powered, grid-independent and with fast payback (<2 years). Specific project success goals are to:

- Effectively integrate the TEG system with the water heater to maximize the power output, electrical and controls scheme and water integration
- Demonstrate 200 hours of continuous grid-independent operation via sufficient electrical self-generation (100 We) to exceed power demands for water heating systems
- Demonstrate that the water heater can operate without any external power for a wide range of hot water demand profiles.
- Demonstrate ability to accommodate 5-10% hydrogen blending into natural gas.
- Show how design can be a drop-in solution for a representative product application with no substantial changes to the water heater installation process
- Achieve an expression of interest or commitment from a major manufacturer to advance this prototype towards a commercial product.

Water heater with damper, data acquisition system and water load simulator for testing (left). Programmable water load simulator (right)

Phase 2 will develop a larger-scale system and build upon the accomplishments achieved in Phase 1, which developed and demonstrated the core configuration of the TEG-integrated system.

Benefits / Market Implications

The primary target markets are new and retrofit installations of existing water heaters in the light commercial sector. The global commercial water heater market is projected to grow from \$5.98 billion in 2021 to \$8.69 billion in 2028. The largest shares of the market are in healthcare, restaurants, institutions and offices. A self-powered commercial scale water heater technology would offer a low cost option to continue hot water production during power outages as well use in remote areas and emergency situations without the need for external power. Reliable supply of hot water is essential for many key functions in both residential and commercial sectors, including such as community warming shelters, police and fire stations, urgent care medical facilities, etc.

The technology aims to ensure safe, reliable, and resilient operation and increase integration with renewable energy (RE) sources such as hydrogen produced from RE.

Technical Concept & Approach

In this project researchers will design, develop and test drop-in TEG burner, and develop commercial prototype designs for TEG-integrated self-powered water heater at 40,000 and ~200,000 Btu/hr capacities. The following tasks will be performed in the current phase of the project:

Task 1: Finalize system architecture

Finalize and assess integration of the TEG with the ~200,000 Btu/hr water heater. Review the installation of the TEG and its impact on the operation, reliability, and safety. Perform a trade-off analysis to ensure optimized electricity generation from the TEG. It is important to have a drop-in design with minimum modifications to the heating system. Evaluate the TEG's operational efficiency, location with respect to the burner, and impact of modulation. Miniaturize controls. Optimize integration of the TEG and burner.

Task 2: Integration of the TEG System with WH Controls

Design the controls and optimize the operational performance of the TEG module and integration components. Integrate the module into the water heater to ensure minimum energy usage with the water supply. Accommodate stresses to account for the TEG materials and modules with multiple interfaces being susceptible to failure during thermal cycling. Integrate the system to maximize temperature gradients and achieve maximum power output with minimal design modifications. Perform thermal and emissions characterization with and without the TEG to ensure the TEG does not impact the burner performance. Build and test the TEG module, including heat sink and cooling, with the water heater burner to characterize its operation and fine tune its arrangement and positioning.

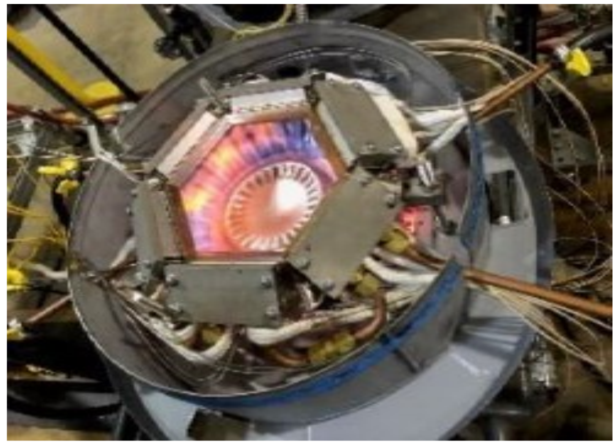
Task 3: Integrate subsystems testing

Integrate the TEG module into the water heater and test over several days of uninterrupted operation at different water load profiles, covering from low to high water demand while ensuring continuous hot water management. Analyze test data to assess integrated system performance against KPIs. Develop designs for TEG integrated self-powered water heaters. Estimate costs of the integrated system towards a commercial prototype and the scope of its potential market.

Results

The team performed a detailed analysis to down-select three different materials for the TEG. In addition, three different water heaters were reviewed.

In 2020, researchers performed Computational Fluid Dynamics (CFD) analysis for the fuel-flexible burner and generated a solid model, which was 3D-printed. Two water heaters were installed in the laboratory for power-consumption and thermal characteristics testing. A test rig was set up for operation with hydrogen including the appropriate interlocks and improved exhaust system. Testing and evaluation of the residential water-heater burner were performed, with temperature, emissions and electrical power demand analyzed. Different TEG integration methods and designs were evaluated. In addition, a preliminary model for hydrogen/natural-gas mixtures was developed for CFD analysis.



TEGs assembled around burner unit

In 2021-2, testing was performed on multiple TEG units of different power levels and physical dimensions to understand the power output. Initial CFD analysis of the burner and bench-scale setup for burner testing was completed. An analysis of an advanced 3D-printed burner was performed for hydrogen testing. Testing with the 3D burner demonstrated <5 ppm NOx emissions. Methods to improve the performance of the burner for pressure drop and air-fuel mixing were evaluated. Researchers also analyzed different single-nozzle burner designs. Further CFD modeling of the burner was completed, and key design improvements were identified and implemented. Testing results demonstrated that <5 ppm NOx emissions can be achieved for the entire firing range and with different levels of hydrogen blends with natural gas.

A Final Report which summarized Phase 1 results was provided to UTD members in October 2022.

In 2023, Phase 2 efforts were launched, and the team reviewed power demand for the larger water heater and started developing an integration design for the prototype larger-capacity TEG and water heater.

Status

The team is currently working on the design to integrate the larger-capacity ~200,000 Btu/hr TEG burner within a water heater, and continuing to discuss and evaluate this technology development with major water heater manufacturers.

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UTD
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Sequestering Non-Condensable Gases for Enhanced Gas Absorption Heat Pump Reliability

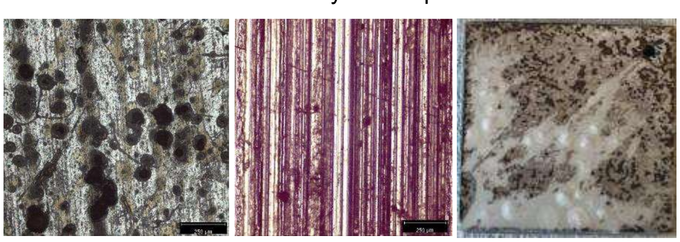
Researchers are developing technologies to enhance the long-term system efficiency, economy, and reliability of any absorption-type heat pump while also reducing maintenance requirements and costs. Plans are to demonstrate the technology in a prototype gas absorption heat pump.

Project Description

A significant factor that influences the cost effectiveness of high-efficiency gas absorption heat pumps (GAHP), which represent the most technologically mature option for thermally-driven heating and cooling systems, is the need for corrosion protection. The ammonia-water or strong salt absorbent/refrigerant working fluids used in absorption cycles typically create high-temperature, high-pH environments that have a tendency to form hydrogen (a non-condensable gas that degrades system efficiency), and can attack steel surfaces, promoting stress corrosion cracking and failure.

To successfully advance the use of GAHPs, it is important to minimize the impact of non-condensable gases (NCGs) on long-duration performance and reliability, and make other cost reductions. The goal of this project is to design and develop NCG isolation (NCGI) modules and provide research and development support to employ novel, low-cost aluminum heat exchangers to increase long-term system efficiency and reliability and safe operation, and reduce the cost of any GAHP. Phase 1 of this UTD project provided co-funding to a prime contract funded by the U.S. Department of Energy (DOE) with the general goal of reducing the cost and improving the reliability of residential and light commercial-sized GAHPs. Specific goals for the current Phase 2 work are:

- Develop a prototype bench-scale NCGI module, and demonstrate its operation in venting and storage modes
- Integrate several NCGIs into operating GHPs
- Demonstrate successful operation, maintaining < 5% loss in COP over simulated one-year of operation.



(Left) *Alloy AA3003 at100x after 60-day immersion in 28-30 wt% ammonium hydroxide solution. The micron marker is 250 µm*
(Middle) *Alloy AA6061 Sample 1 at 100x after 60-day immersion in 28-30 wt% ammonium hydroxide. The micron marker is 250 µm*
(Right) *Alloy AA5052 Sample 2 after 60-day immersion in 28-30 wt% ammonium hydroxide*

Ref: Garrabrant, M., Newland, J., Glanville, P., Spicer, K., and Frankel, G. (2022) Improving Reliability, Weight and Cost of Gas-Fired Absorption Heat Pumps. United States: N. p., doi:10.2172/1886933

Benefits / Market Implications

High-efficiency GAHPs are strategically important to achieve energy efficiency and decarbonization goals. This project seeks to ensure optimum long-term performance, economy, and reliability of these new product categories for end users.

The efficiency of GAHPs that use ammonia-water or strong salt absorbent/refrigerant working fluids can slightly decline over time as NCGs are created within the system. An economical and effective NCGI module will increase the long-term efficiency of GAHPs while simultaneously enhancing their reliability and reducing periodic maintenance expense.

Current GAHP heat exchangers use carbon in part because steel tube/aluminum fin evaporator copper coils are not compatible with ammonia-water solutions. As such, the evaporator coils of GAHP systems are the heaviest and most expensive part of the system. By shifting to an aluminum evaporator (provided that corrosion issues are within control), the GAHP may be significantly lighter and less expensive. The evaporator coil in a standard 80 kBtu/h GHP weighs about 150 pounds; however, an all-aluminum coil could weigh just 25 pounds and might save perhaps $375.

Technical Concept & Approach

Both building on experience with gas absorption heat pumps (GAHPs) and their corrosion control and leveraging technol-

Laboratory setup assembly.

"Succeeding today's gas furnace and water heater are highly-efficient gas heat pumps (GHPs) — the future for space- and hot-water heating. However, to gain customer acceptance, GHPs must be highly reliable, similar to a gas furnace with extremely low maintenance. One of the critical issues for long-term reliability of absorption GHPs is the removal of non-condensable gases. We're very pleased that this UTD-funded technology development, in partnership with U.S. DOE, will further enhance GHP reliability."

- Aqeel Zaidi
Manager, Technology Development
Enbridge Gas Inc.

ogy developments in chemical processing, the team will develop and demonstrate solutions to handle NCGs through isolation, storage, or both. The current project phase will perform the following tasks:

Task 1. Non-condensable Gas Isolation Analysis and Final Design

- Aggregate findings from 25+ GAHP field demonstrations and long-term laboratory testing to further characterize NCG development and the impact/benefits of removal/isolation.
- Finalize the design NCGI module specification, compatible with GAHP units from Robur, SMTI, Vicot and other leading OEMs.
- Finalize the selection and preparation for the H2-selective membranes using a membrane system developed for nuclear fuel applications, building on prior literature survey and bench-scale data collection during Phase 1.

Task 2. Bench-Testing of NCGI

- Perform bench testing on multiple versions of the NCGI module, using a modified NH3/H2O Corrosion Test Station at GTI to provide a simulated environment for each module.
- The NCGI module will be in communication with an NH3/H2O mixture at representative conditions (concentration, temperature, pressure), while a controlled amount of H2 will be fed into the volume to come into contact with the NCGI module to quantify H2 selectivity, transfer rates, and need for module thermal management

Task 3. In-situ GAHP Evaluation of NCGI Prototype

Two evaluations will be performed to frame control options:

- A GAHP will be operate for an extended period of time on an automated test stand for 30 days of accelerated operation exposed to the NCGI module, then the NCGI module is deactivated/removed and the AHP performs a second 30 day period of operation comparing the performance and operating pressures.
- After the 30 day period without NCGI activation, the NGCI will be activated and exposed to the AHP suddenly, with several repeated on/off cycles of the NCGI module to understand the dynamics of intermittent module activation and the short-term impact on GAHP performance.

Results

In 2020 through 2021, the project team completed rounds of corrosion testing with the alloy samples using a custom-built corrosion test stand. In parallel, university researchers initiated atmospheric pressure testing. Testing included bare metal (baseline) and various coatings – in total, 96 alloy and 16 low-carbon steel samples. The project team reviewed the results and shifted towards the next set of alloys for testing. Tests were completed in 2022 and a Phase 1 Final Report was issued. This last round of testing included an evaluation of a range of corrosion-protection solutions for proprietary aluminum alloy coupons from a third party and several baseline coupons. Each coupon test was at two ammonia concentrations, mid (50%-75%) and high (90%-95%), and the coupons were tested in pairs with duplicates for each run – in total 64 test points for this project.

In current Phase 2 efforts, the project team has performed preliminary analysis using corrosion simulation software to evaluate the corrosion mitigation capabilities of degassed water against normal water when mixed with 10% NH3 solution. Unlike as learnt from previous literature, the use of degassed water did not have a significant impact over corrosion mitigation of carbon steel. The dissolved gases in the normal water are helping to reach the safe pH levels where passivation of carbon steel is possible. To better understand this, the project team has decided to perform a few preliminary tests to evaluate the validation of the results obtained from the software.

Status

The project team is making improvements to the testing apparatus, including the pressure test vessels. The project team is also in communication with commercial membrane manufacturing partner, and will identify and purchase 2-3 hydrogen getters after the preliminary tests are completed.

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UTD
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Yanmar Three-Pipe Gas Heat Pump Cold Climate Case Study

Researchers evaluated the performance and economics of the Yanmar three-pipe natural gas-engine-driven heat pump (GHP) in a cold climate. The GHP performance curves developed in this project can help refine GHP models in EnergyPlus™ to better support designers, end-users, and others in decision-making and shaping energy efficiency programs and incentives.

Project Description

Natural gas engine-driven heat pumps (GHPs) provide high-efficiency space heating and cooling using an advanced natural gas engine in place of an electric motor. GHP engines have a demonstrated long life and extended maintenance intervals of about 10,000 hours.

GHP heating output is supplemented by heat recovered from the engine cooling jacket and exhaust, similar to a combined heat-and-power system, increasing overall system efficiency. In contrast, electric-driven heat pumps typically require back-up heating to supplement the heat pump output at low outdoor temperatures.

GHPs combine high-efficiency heating and cooling (1.0-1.4 coefficient of performance – COPg – at rated conditions) to significantly reduce peak electric demand and electricity use with potential savings in operating and lifecycle costs, as compared to electric variable refrigerant flow (VRF) heat pumps or conventional HVAC equipment.

GHPs have a significant share of the Japanese and European space-conditioning markets, and became available in the U.S. in 2016. Yanmar offers a range of GHP VRF (GVRF) systems, from 8 to 14 tons. While most of these products are two-pipe systems that can operate either in cooling or heating mode, Yanmar's 14-ton GHP has a three-pipe heat-recovery VRF system that can simultaneously provide heating and cooling.

Seven installed GHPs at the host site in Dover, DE.

Multiple prior field demonstrations reported significant reductions in electric usage, demand charges, and water use, generating cost savings that more than offset the initial cost premium of GHPs. According to one manufacturer, GHPs reduced operating costs by up to 30% and electricity usage by up to 80% compared to electric heat pumps. UTD project 1.19.F evaluated the performance and economics of Yanmar's three-pipe GHP in a cold climate (Delaware) and built upon a prior field evaluation of the three-pipe GHP in a warm climate (Georgia) in recently-completed UTD project 1.17.G, which reduced peak electric demand by 8 kW (98%) in heating and 10 kW (96%) in cooling as compared to an electric three-pipe VRF, and reduced peak electric demand by 11 kW (96%) in cooling as compared to an electric multi-zone rooftop unit with electric cooling.

Benefits / Market Implications

End users in facilities and markets such as these can benefit from this technology:

- Multi-zoned commercial buildings, such as office buildings, retail, schools, hotels, health clubs, nursing homes, and mid/high-rise multifamily residences
- Facilities that benefit from life-cycle savings, such as commercial offices, government facilities, factories, schools, and other owner-occupied buildings, and
- Electric-grid-constrained markets or regions with relatively high electricity prices and/or high demand charges.

This demonstration will help end users assess the value of gas engine-driven heat pumps while supporting ongoing efforts to refine cold climate performance data in EnergyPlusTM and other modeling software, including through UTD project 1.21.E.

Technical Concept & Approach

The project team identified an existing Yanmar three-pipe GHP installation in Delaware as a demonstration site. Using measured performance data, researchers determined net energy savings and economics based on natural gas consumption, electricity use, and electric demand. Specific project tasks included: site selection and development of a field test plan; site monitoring and data analysis.

Key performance objectives are to: 1) achieve acceptable efficient heating and cooling performance, 2) demonstrate efficient part-load performance, and 3) demonstrate capacity and efficiency under cold ambient conditions.

"Chesapeake Utilities integrated 7 state-of-the-art Natural Gas Heat Pump (GHP) units during the construction of our Corporate site in Dover, DE, more than 5 years ago. Since then, we've not only experienced substantial savings and heightened comfort levels but have also successfully transformed our site into a showcase for the community, highlighting the efficiency of this advanced HVAC technology."

- Shane Breakie
VP of Sustainability and Growth
Chesapeake Utilities Corporation

Results

For the demonstration, the project team selected a multi-story, multi-zone office building located in ASHRAE climate zone 4A. Seven GHP systems provide zoned heating and cooling to the entire facility. Ventilation air was delivered to each zone from an Energy Recovery Ventilator (ERV) unit, which conditioned outside air to space neutral conditions. One of the seven GHP systems was selected to be studied in this demonstration. The selected GHP was a 3-pipe, 14-ton GVRF system with ten indoor Fan Coil Units (FCUs) that supplied zoned heating and cooling to office spaces. The tempered outside air was ducted into the indoor FCU before being supplied into the conditioned space. All of the 10 indoor FCUs associated with GHP-3 were ducted, which allowed for accurate measurement of return and supply air. The GHP outdoor unit and corresponding FCUs were instrumented to monitor energy use and performance. The GHP system was monitored from December 2021 to April 2023 to evaluate its performance across the full range of ambient conditions and equipment operation.

Due to the field site's cold climate, the GHP operated in either heating mode or simultaneous heating/cooling mode for a majority of the time. Cooling operation was extremely limited and only occurred sporadically during the summer.

Part-Load Operation:

The GHP was sized for peak heating loads and predominantly operated in the 25% to 50% part-load ratio range, while ramping up to 60% on very cold days. This sizing strategy is common practice for sizing HVAC equipment and the resulting operation, especially at extremely low part-loads (below 30%) impacted both heating and cooling performance.

The performance data of the GHP was broken down into hourly steady-state values (i.e., when the outdoor unit ran for the entirety of the hour). This eliminated cycling and other ramp-up and ramp-down inefficiencies of the GHP system. The GHP achieved rated heating efficiencies up to 2.0 COPg during extended steady-state runtimes. Steady state efficiencies on days with below-freezing temperatures ranged from 1.0 to 1.32, which were in line with the rated efficiencies. This highlighted that the GHP did not show any drop in performance or capacity during cold ambient days. Measured seasonal efficiency was 1.2 COPg for heating and 0.72 COPg for cooling, excluding simultaneous operation. Unfortunately, reduced efficiencies were seen for cooling due to ERV commissioning issues at the site. The ERV supplied ventilation air at very low temperatures leading to artificial calls for heating even when the outdoor temperatures were high.

Simultaneous Operation:

The GHP system exhibited significant runtime in simultaneous heating and cooling mode. Researchers believe that this was due to a combination of fan coil placement, zonal thermostat set points and ERV supply air temperatures. Daily performance for simultaneous operation ranged from 0.36 to 1.84 COPg.

Comparisons were made between the 3-pipe GHP performance datapoints generated in this project to the results of prior part-load performance curve data by others for the same 2-pipe GHP unit. The project team noted good correlation between the two datasets making it a great candidate to generate a refined performance curve fit for EnergyPlus. The agreement between these datasets also suggested that the performance of a 2-pipe VRF system in heating or cooling operation can be equated to the same 3-pipe VRF system in pure heating or cooling operation.

Status

This project is complete and a UTD final project report is being reviewed and finalized. This demonstration and analysis generated a crucial performance dataset for the Yanmar GHP in a cold climate to support the development of refined GHP models in EnergyPlus in coordination with efforts underway in UTD project 1.21.E, and to support designers, end-users and others in their selections of energy efficient options. Results of this research will be disseminated at the 2024 ASHRAE Winter Conference as a conference paper presentation.

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UTD Utilization Technology Development

Robur and SMTI Low-Capacity Gas Absorption Heat Pump Laboratory Evaluation

This project evaluated the performance of new low-capacity gas-fired absorption heat pumps, specifically the Robur K18 (60 MBH) and SMTI 40K (40 MBH) units, since they may soon enter the North American market. Best operating practices were identified to apply these highly-efficient units in high-performance residential

Project Description

Cost-effective, right-sized, and properly-installed Thermal Heat Pumps (THPs) will be a crucial linchpin for society and end users to meet aggressive energy-efficiency goals. However, an impediment is that most low-load, new-construction residential HVAC systems installed are vastly oversized, often installed with oversizing factors greater than 1.4 dictated by the Air Conditioning Contractors of America (ACCA). Significant improvements in building envelopes (per 2006 and later codes) have also reduced thermal loads, regardless of climate. Many existing homes now would only require low-capacity heating systems, typically under 60 MBH of heating output (MBH = 1,000 Btu/hr).

Low-capacity heating systems are broadly classified as those with a nominal output of less than 60 MBH or lower. These systems typically apply to new construction, with envelopes built to modern codes or retrofits where envelope improvements and other measures are employed. Focus on this low-capacity product category is also essential for the emerging suite of highly-efficient THPs because they will be more expensive than furnaces on a per-MBH basis.

A prototype North American Robur K18 GAHP installed inside a laboratory environmental test chamber

Robur Corporation is one of the most mature manufacturers of light-commercial-sized absorption-based gas heat pumps (GAHPs), with products available in Europe for 15+ years and the U.S. for 10+ years. Robur sells GAHPs direct to consumers through a distribution network. The company has discussed bringing its low-capacity (60 MBH) residential-scale K18 units from Europe to North America. However, greater granularity is needed to develop seasonal performance metrics and identify best practices to optimize its application for the North American market, which predominantly uses forced-air distribution.

In several phases of efforts with the U.S. Department of Energy, the California Energy Commission, and UTD, researchers also provided substantial technical and project support to Stone Mountain Technologies, Inc. (SMTI), to bring a residential-scale ANESI GAHP to market based on the single-effect vapor-absorption cycle. This effort included installing prototypes at eight residential field test sites, with future placements and adding a vapor compression system for cooling in parallel – all focusing on the retrofit size category of 80 MBH nominal.

GAHP systems are very suitable for cold climates due to specific design features and using NH_3 as an efficient refrigerant. Seasonal efficiencies of up to 140% are feasible. These GAHP systems are generally geared towards the retrofit market, replacing furnaces and, to a lesser extent, boilers – including water heaters when deployed as a combination system. Considerable resources have been applied to develop standard-sized GAHPs for light commercial/large residential applications; these efforts include the design and demonstration of SMTI 80 MBH systems and the deployment of commercially available Robur GAHP-A units. A portion of this UTD project seeks to apply and prove out findings and strategies regarding an emerging prototype ANESI GAHP that is half the size – rated at 40 MBH.

In summary, the objective of this project was to evaluate and optimize the performance of low-capacity GAHPs, specifically the Robur K18 (60 MBH) and SMTI 40K (40 MBH) units, when applied to residential combination space/water heating systems (forced-air heating) to fill out the product portfolio and target low-load, new-construction applications. How the

SMTI 40K Hybrid GAHP system installation in HVAC laboratory. (left) The installation of the GAHP in a environmental chamber; (right)

GAHPs perform in, addition to how system parameters are optimally controlled (system modulation, space vs. water heating modes, air handler operation, etc.) was determined in this experimental effort. For GAHP combination systems, a reduction in oversizing factor is recommended relative to ACCA guidelines for gas-fired furnaces.

Benefits / Market Implications

The primary target markets impacted are as follows:

Equipment Type: Air-to-water gas-fired heat pumps, absorption-type (space heat: forced-air or hydronic; water heat**:** DHW via indirect tank)

Application: Residential low-capacity homes and low-rise multifamily

Climate: Heating dominant, but all apply.

The anticipated benefits to ratepayers of developing system-integration strategies to optimize low-capacity GAHP operation in high-performance homes include:

Efficiency: Reduction in gas consumption for space/water heating by 40% or greater, with nominal incremental electricity consumption

Emissions: Reduction in greenhouse gas emissions by 40% or greater while broadly deploying ultra-low-NO_x solutions, and

Health and Safety: Elimination of indoor air quality and venting concerns with combustion outdoors and the broad utilization of natural refrigerants rather than ozone-depleting or high-GWP refrigerants.

Technical Concept & Approach

In this effort, the project team performed a laboratory-based experimental investigation of two low-capacity GAHP systems, with the goals of 1) developing high-resolution performance curves to estimate seasonal performance and develop high-resolution simulation tools and 2) optimizing GAHP performance as a combination system by developing control strategies with off-the-shelf air-handling units and storage tanks, and 3) evaluating GAHP reliability during an extended operation test in an outdoor environment. Comparative performance and opportunities for further product development were highlighted with the GAHP OEM partners.

Through 24-hour simulated-use testing, the researchers strove to optimize the interaction between GAHP and system components (e.g., indirect tank, air handler) to improve daily efficiency to be within 10% of seasonal ratings.

Results

The project team evaluated the SMTI 40K hybrid and Robur K18 GAHPs in a laboratory per the revised ANSI Z21.40.4 method of testing. Test results demonstrated that both technologies can operate within a seasonal AFUE of 120% relative to the U.S. national average climate zone while operating within ultra-low-NO_x and South Coast Air Quality Management District (SCAQMD) emissions limits.

The alpha prototype SMTI 40K hybrid GAHP system was also evaluated with a prototype advanced air handler unit (AHU) in a Virtual Test Home (VTH) in the laboratory. The testing program optimized controls and right-sizing for the subsequent production-version AHU.

Status

Evaluations of the SMTI 40K hybrid and Robur K18 GAHPs have been completed, and the results were very promising. A Final Report was issued to UTD members in March 2023, and overall results were shared with the GAHP OEM partners to help them improve their final product designs, including recommended firmware upgrades. As UTD members and other North American gas utilities support roll-out and deployment of GAHPs, and residential building envelopes continue to improve, the findings of this UTD project will help ensure successful and efficient field deployments of very-high-efficiency, low-capacity GAHPs.

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UTD Utilization Technology Development

BOOSTHEAT Thermal-Compression-Based Gas Heat Pump

Researchers are supporting the development of a high-efficiency thermal-compression-based heat pump product for North America with 1) high-modulation ratio, 2) integration with forced-air distribution, and 3) optional cost-effective cooling. If successful and deployed widely, environmental and ratepayer benefits will be significant.

Project Description

This project addresses the need for cost-effective thermal heat pumps (THPs) that provide next-generation performance of high efficiency, self-power capability, and both high -temperature heat and low-temperature chilling.

Researchers are investigating THPs that use natural refrigerants, but with higher operating efficiencies. One of the primary players in this field is the French company BOOSTHEAT. Through this project, researchers are extending their partnership with BOOSTHEAT (that began with a third-party evaluations of the BH.20 heat-pump boiler) with a product-development program in advance of a North American introduction.

To date, the BH.20 demonstrated a Coefficient of Performance (COP) for gas of 1.90 (low-temperature heating) and 1.63 (high-temperature heating) in third-party testing in Europe, and is capable of delivering heat at temperatures above 150°F. However, as initial testing showed, the BH.20 was very much optimized for the European residential hydronic heating market and, specifically, the low-temperature emitter market. As a result, a direct translation of the BH.20 to North America, with a wider operating envelope of ambient conditions and the requirements of forced-air heat distribution, will not leverage the full potential of this exciting THP.

BOOSTHEAT's core technology is the thermal compressor itself. The balance of the BH.20 is comprised of the common components of a trans-critical CO_2 heat pump (evaporator, gas cooler/condenser, and expansion valve). In this vein, BOOSTHEAT's core technology is not unlike the vapor-absorption and vapor-compression gas heat pumps that use these common components as their core technologies. BOOSTHEAT's thermal compressor is essentially a gamma-type Stirling engine with the power cylinder/piston replaced by inlet/exhaust ports.

An initial evaluation of the BH.20 in 2019 revealed several opportunities to improve performance in North America, which, by and large, were the result of design decisions for the European market and hardware issues in a pre-commercial prototype.

The goal of this project is to help develop a North American THP and investigate other applications for the Thermal Compressor with a focus on 1) high-modulation ratio, 2) integration with forced-air distribution, and 3) optionally adding cost-effective cooling. BOOSTHEAT has partnered with UTD on this project to help pave the way for a North American product. This UTD project will help BOOSTHEAT address key product development needs.

Benefits / Market Implications

Thermal compression-type THPs may offer a 20% or greater improvement in energy/emission reductions versus best-in-class conventional sorption and vapor compression-type THPs.

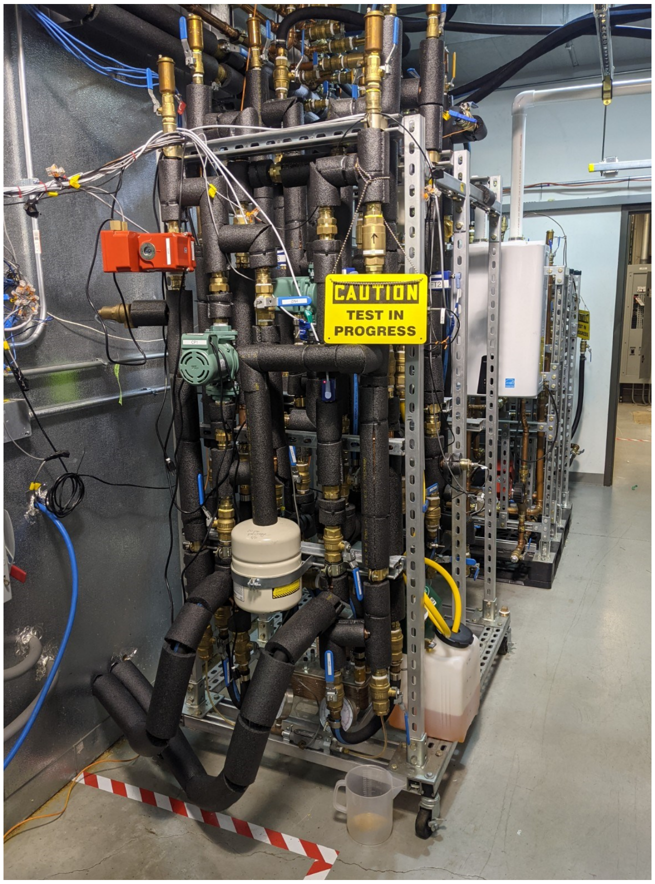
The primary target application markets are:

- **Equipment Type:** Water-to-water gas-fired heat pumps with outdoor heat exchanger (effectively air-to-water)
- **Application:** Residential homes and low-rise multifamily
- **Climate:** Heating dominant, but all climates apply.

Benefits include:

- **Efficiency:** Targeted reductions in gas consumption for space/water heating by 60% or greater, with nominal incremental electricity consumption
- **Emissions:** Expected 60% or greater reduction in greenhouse gas emissions while broadly deploying ultra-low-NO_x solutions and utilizing natural refrigerants, and

If the project is successful, the BOOSTHEAT THP will be better positioned for the North American market and will lead into well-crafted pilot projects. If deployed widely in ratepayer homes, broad ratepayer and environmental benefits can accrue.



Completed laboratory test stand.

Technical Concept & Approach

The project work is broken into two major tasks:

Task 1: Design Improvements to TC-THP

- Install and evaluate performance of an existing 2nd generation GHP with controls modifications designed to reduce cycling losses, improve capacity/efficiency loss with colder ambient/warmer loop temperatures, improve performance when coupled with external AHUs and ISTs, reduce backup boiler operation, and combustion system tuning to meet 14 ng/J NOx emissions
- Develop a comprehensive performance assessment, with steady state, cycling, and simulated use testing protocol originally applied to unmodified *BH.20* baseline and summarize results in Experimental Test Report
- Characterize the thermal compressor to assess its potential use for HVAC/DHW-type applications by testing DHW-only / commercial DHW application, assessing suitability/attractiveness for hybrid-heating application (supplementing a boiler for instance), and assessing suitability/attractiveness for space cooling / chilling application and heat recovery-type applications

Task 2: Technoeconomic Assessment of thermal compressor

- Perform a technoeconomic assessment of the thermal compressor (2nd gen.) vs. alternative THP technologies and electric HP technologies.
- Consider potential commercialization partners in North America for Boostheat's thermal compression technology, and as appropriate provide relevant information or contacts to Boostheat.

Results

Boostheat was recently purchased by a holding company, and as a result their commercialization plans have changed. Boostheat has indicated that they will focus on developing its core technology, the thermal compressor, and will explore licensing and supplier agreements where its thermal compressor could be packaged into a gas heat pump product by others. The new commercialization plans at Boostheat required a pivot for this UTD project, as the system that can be tested is no longer representative of a final commercial product.

Status

In Q1 of 2023, the team prepared a revised scope of work for this project. The revised scope of work will test the existing TC-THP prototype from Boostheat under heating, cooling, and water heater applications for both commercial and residential applications. The scope revisions were accepted and the team is working on securing the TC-THP for testing as well as revising the original test plan.

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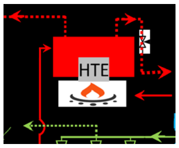
Gas-Fired Binary-Fluid Ejector Heat Pump Water Heater



Research is being conducted to develop and demonstrate a prototype gas-fired binary-fluid ejector heat pump water heater that provides 12,000 Btu/hr (3.5 kW) capacity, achieves a UEF (Uniform Energy Factor) of 1.4 or better, and shows an attractive value proposition for gas consumers.

Project Description

This project involves modeling, designing, building, and testing a prototype of a gas-fired ejector heat-pump water heater (GFEHP). This first-of-a-kind heat pump uses a novel cycle that combines a binary-fluid ejector and sorption subsystem into one high-efficiency cycle. The technology integrates several components that are thermally and hydraulically coupled. The overall objective is to develop and demonstrate GFEHP technology at 12,000 Btu/hr (3.5 kW) capacity in the laboratory and achieve a gas Coefficient of Performance (COP) of 2.0 (equating to a UEF>1.4).This project is taking a ground-up approach for designing and building the novel GFEHP prototype, starting with system specification, modeling, and breadboard prototyping, then culminating in a full system prototype construction and testing.

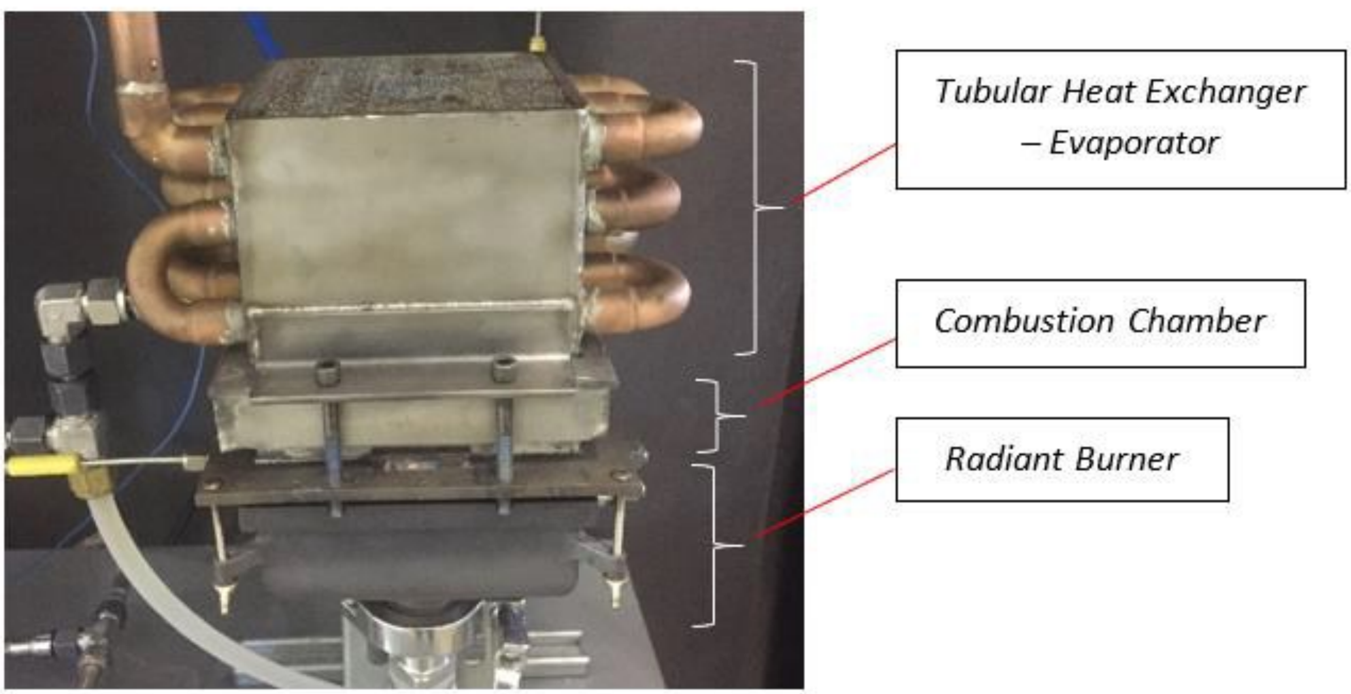
The project is a collaboration among UTD, the U.S. Department of Energy's (DOE) Oak Ridge National Laboratory, the University of Missouri (MU), and ThermAvant Technologies. UTD's funding is being leveraged by approximately $1.9 million in prime funding provided by the DOE.

Benefits / Market Implications

The primary target markets impacted by GFEHP will be residential, multifamily, and light commercial water heating.

The GFEHP has a target gas COP of 2, which translates into an energy factor (EF) of at least 1.4 if the burner is non-condensing and its storage tank is not well insulated. With a well-insulated tank and condensing burner, the GFEHP can have an EF of 1.8. State-of-the-art gas-fired water heaters have a thermal efficiency of 0.98, which translates to a <1 EF.

The GFEHP is expected to be twice as efficient as the state-of-the-art product on a primary energy basis (e.g., tankless water heaters and electric heat pump water heaters). Compared with an electrically-driven vapor compression heat pump water heater, the GFEHP replaces the compressor and the expansion valve with an ejector, additional heat exchangers, and an oscillating heat pipe. A cost comparison indicates that it is possible to meet cost targets of $4,000.



The laboratory-scale heat-transfer system was designed, fabricated, assembled, and tested.

"Innovative next-generation technical solutions like the gas-fired binary-fluid ejector heat pump water heater can double the efficiency of standard water heaters while greatly reducing related emissions. UTD's partnering with the U.S. DOE, MU, ORNL, and ThermAvant brings a strong team to deliver significant efficiency gains from this exciting technology, while ensuring cost-effective solutions for the customers we serve!"

- Steve Roberson
Technical Analyst
Spire Energy

Water heating is a source of significant primary energy consumption in U.S. (second in buildings only to space heating). There are approximately 60 million minimum-efficiency gas water heaters in U.S homes (EF<0.67), responsible for 2.86 quads of primary energy consumption and an annual consumer expenditure of around $32.6 billion. As improving building envelopes reduce space-heating loads and more high-efficiency warm-air furnaces are installed, water heating represents a growing proportion of the residential gas load. The GFEHP technology will provide high efficiency as a retrofit option to all existing gas water heaters and the 9.1 million homes that currently do not use natural gas in water heating but have gas availability. As new houses become more efficient, innovative gas solutions such as GFEHP water heating can provide low-cost, high-efficiency heating options.

Technical Concept & Approach

Specific tasks for this project include:

- **Identify System Architecture and Product Specifications**

  The project team will develop a conceptual design of the GFEHP. Thermodynamic modeling will be used to ensure that the targeted thermal efficiency metrics are feasible. The project team will develop a system architecture that specifies the required components, their efficiency target levels, and how they are integrated.

- **Design, Manufacture, and Test of the Combustion System**

  The project team will develop an ultra-low-NO_x, high-efficiency, low-cost manufactured burner that will be used in the prototype system.

- **Assemble the Prototype Combustion System, Characterize its Performance, and Validate the Model**

  In this task, combustion sub-systems will be integrated with other required components to form a breadboard prototype of the proposed GFEHP. The breadboard will provide valuable information on the characteristics of the GFEHP as a system.

- **Support the Design of an Alpha Prototype**

  The validated system model and information gained from the breadboard evaluation will be used to design an alpha prototype of the GFEHP.

- **Techno-Economic Study**

  The goal of this task is to support commercialization by assessing the value proposition and the potential of a GFEHP water heater. To do so, the first cost at maturity of the GFEHP (based on the alpha design) will be estimated.

Results

In 2020, the project team provided guidance on burner design. Researchers recommended a radiant-type burner, which is the only technology to achieve ultra-low-NO_x emissions without sacrificing efficiency. Other off-the-shelf and prototype burners considered included a metal fiber mesh burner, a permeable metal matrix burner, and volumetric and flat-metal foam burners. Investigators also analyzed the option of using a thermoelectric generator (TEG) in combination with a radiant burner for self-powering of some components of GFEHP.

A report titled *Product Characterization Criteria Brief* was compiled that summarized the applicable efficiency standards and emission requirements for commercialized and pre-commercial gas and electric water heaters. Recommendations related to target cost and physical characteristics of the GFEHP water heater were provided.

In 2021-2022, the project team modified the existing design and test stand to test the system at conditions closer to what would be seen in the full prototype system. A preliminary engineering design of the laboratory prototype combustion and heat exchanger system for the GFEHP was completed.

In 2022-2023, the team designed, built, and tested a breadboard prototype with the anticipation of building and testing an alpha prototype in early 2024.

Status

The team is currently working on finalizing the alpha prototype design.

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Emerging Residential/Commercial Fuel Cells Laboratory Evaluation

Researchers evaluated the merits of residential/commercial-scale fuel-cell systems less than 50 kW and prioritized them in terms of North American market fit and readiness. This will help increase highly-efficient, environmentally-responsible options for natural gas and propane end users in the residential/commercial sector.

Project Description

The micro-CHP (Combined Heat and Power) market in North America has seen a very significant uptick in new products or product positioning. Contributing to the market interest are diverging gas and electricity energy rates, the growing demand for power and energy resilience, and major federal programs and private entities that made advancements in fuel-cell technologies.

The goal of this project was to evaluate the merits of residential/commercial-scale fuel-cell systems less than 50 kW and prioritize them in terms of North American market fit and readiness. Systems were selected for further evaluation in the laboratory to characterize power/thermal capacities, efficiencies, and qualities, as well as modulation and cycling capabilities. Laboratory research on these fuel-cell systems focuses on achieving high electrical efficiencies and near-zero emissions. This research will help increase highly-efficient, environmentally-responsible options for natural gas and propane end users in the residential-commercial sector.

UTD partnered with the Propane Education and Research Council (PERC) on this research, with PERC providing co-funding to UTD.

Benefits / Market Implications

The primary likely end-user applications are:

- Residential and light-commercial applications, especially in areas where net-metering is allowed and in support of Zero Net Energy homes, Zero Energy Ready Homes, and High-Performance Building initiatives/sectors, and
- The California micro-CHP (mCHP) market, with this research supporting possible distributed-generation certification by the California Air Resources Board.

Fuel cells can offer key potential advantages in mCHP applications. The economics of fuel cells are less dependent on the effective use of recovered thermal energy than other mCHP prime movers, such as reciprocating engines, because they have higher electrical efficiencies. They produce more power than thermal energy (high power-to-heat ratio), displacing electricity, which is at least three times more expensive on an equivalent energy basis than natural gas.

Fuel cells can also generate electricity with a hydrogen-rich fuel source, and when pure hydrogen is used, the only by-product is heat and water, thus yielding zero emissions. While most hydrogen is produced from fossil fuels, specifically natural gas, electricity from the grid or from renewable sources also produce hydrogen. As hydrogen blending becomes more prevalent, fuel cells could be an important technology to serve hydrogen-rich on-site power applications.

Historically, the biggest challenges for fuel cell technologies are their high costs relative to other mCHP technologies, fuel-cell stack degradation, and inabilities to modulate or cycle on and off quickly and frequently. These were the prime factors in evaluating and prioritizing fuel cell types that are best positioned for the North American market.

Technical Concept & Approach

Researchers conducted a fuel-cell market landscape assessment. Based on market fit and feasibility, two fuel-cell systems were selected for evaluation. Investigators conducted those evaluations in a fuel cell laboratory designed for tests such as

AISIN SOFCs installation at research laboratory

"Accelerating the availability of small-scale fuel cells will help more of our residential and light commercial customers generate reliable, resilient, low-emission on-site power and thermal energy that can dovetail with variable renewable energy. This UTD research helps speed the transition to clean hydrogen, electrify buildings and helps us reach our decarbonization goals."

- Neil Navin
Vice President, Clean Energy Innovations
SoCalGas

those defined by ASHRAE Standard 204-2020 *Method of Test for Rating Micro Combined Heat-and-Power Devices*. Additionally, the laboratory is equipped with emission analyzers for developing baseline emission rates produced by the mCHP systems.

Specific project tasks included:

- **Fuel Cell Market Landscape Evaluation**

  Researchers evaluated the merits of residential/commercial-scale fuel-cell systems less than 50kW and developed a prioritized list of at least 10 fuel-cell systems.

- **Procure Fuel Cell System and Develop Test Plans**

  Through UTD research project 1.13.D, UTD assisted the consensus development of ASHRAE Standards Committee SPC204. Through SPC204, a formalized Method of Testing was released to the public and will be used as a guide for formulating a rigorous test plan with the fuel-cell manufacturer. The systems are being evaluated on- and off-grid as CHP and distributed-generation devices. The main objective of the evaluations was to assess the performance and endurance of the fuel-cell units as well as their ability to load follow and rapidly cycle on and off operating on pipeline-quality natural gas for validation of the pre-production prototypes.

- **Fuel Cell Test setup, Installation and Testing**

  Test plans were implemented for both fuel cells. The systems were evaluated on a two-week test schedule conducted 18 times across nine months and included polarization mapping, part-load performance, stack durability, stack power cycling, long-term emissions, and stack deep cycling.

- **Data Analysis, Reduction, and Reporting**

  The project team post-processed test data to determine maximum steady-state power and thermal capacities, and assessed transient performance of the system at various loads and conditions. This helped characterize the potential performance of the systems for residential and commercial applications.

The key deliverable for this project was a report that documented the current fuel-cell market landscape for propane and natural gas, and the performance of selected natural-gas fuel-cell systems.

Results

In 2020, researchers completed a micro-CHP fuel-cell market landscape assessment with 16 fuel-cell systems based on technologies identified for residential/commercial CHP applications. These systems were evaluated based on electrical efficiencies, prior interactions with respective manufacturers, successful field demonstrations, and North American market fit. Seven systems were selected for potential further evaluation in the laboratory. Further evaluation was conducted on two systems.

One system is designed to integrate with a boiler as a traditional CHP system where heat is recovered for preheating a small boiler or incoming cold water. It is also designed to operate on or off grid. Results indicate Full load LHV electrical efficiency was about 51% and total LHV efficiency was about 100% or in terms of HHV efficiency, about 90%.

A second system is designed to integrate with photovoltaic panels and battery storage, providing a combination of renewable and fuel-fired electricity on or off grid. This system ultimately could not be evaluated due to high (20 psi) fuel input pressure requirement, which is inadequate for residential buildings per the National Fuel Gas Code (NFPA) 54; and the need for external devices to regulate voltage and control the fuel cell stack power generation functions. The manufacturer has subsequently informed UTD of their progress operating their SOFC on natural gas and hydrogen blends, including in-house testing on low pressure natural gas and anticipated certification.

Status

A review of the market for residential- and light commercial-scale fuel cells and subsequent testing and analysis of promising systems has been completed. A final report has been issued to UTD members, and a webinar which summarized results was given to members in September 2023.

UTD recommends evaluating the second manufacturer's next generation SOFC in the laboratory to confirm performance claims, verify its durability, and understand its responses to operating in a nanogrid environment. Additionally, to advance these technologies from stage 4 to 5, UTD recommends developing next phase projects for beta prototype laboratory evaluations.

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High-Efficiency Combination System Integrating PV and Self-Power

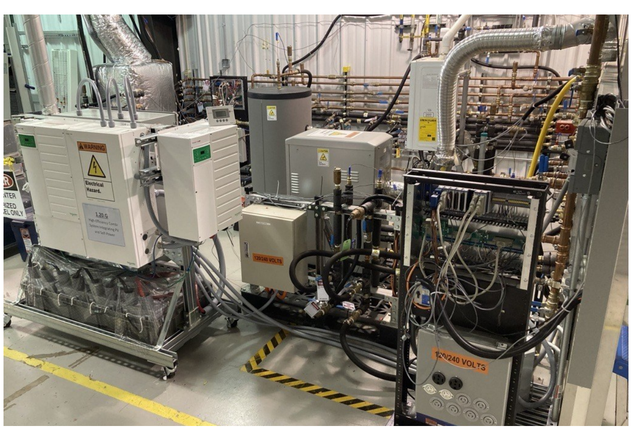
Researchers are demonstrating hybrid residential combined HVAC and water-heating systems that use novel controls to integrate gas/electric systems with micro-combined heat and power, energy storage, and renewable energy in order to increase resilience and reduce operating costs and greenhouse gas emissions by up to 50%.

Project Description

Integrated energy systems (IES) are an emerging approach to provide high-efficiency, self-powered HVAC and water heating by integrating fuel-fired and electrically-powered equipment with distributed energy resources and energy storage. This project is developing and demonstrating hybrid residential HVAC and water heating systems in a laboratory that use off-the-shelf appliances and novel controls to integrate gas/electric systems with micro-CHP (mCHP), energy storage, and renewable energy in order to reduce operating costs and GHG emissions by up to 50% and achieve COPs up to 1.5 while retaining superior resiliency. The initial efforts of this project demonstrated that the integration of a residential scale mCHP system with a tankless combi and an electrically-driven air source heat pump (ASHP) could achieve highly-efficient, self-powered HVAC and water heating. The goals for current project efforts include:

- Develop an ad hoc retrofit solution to replace an AC system with an electric ASHP that is easily integrated with a fuel-fired furnace (existing or new) to achieve COP>1.0.
- Develop an mCHP retrofit solution with an existing furnace and ASHP to achieve self-powered fuel-fired space heating with COP>1.0.
- Integrate a ~5kW mCHP with an air-to-water combi heat pump to achieve self-powered fuel-fired HVAC and water heating with COP>1.5.

UTD is partnering with the Propane Education and Research Council (PERC), which provided co-funding to this project.



Laboratory facility used to demonstrate and test novel integrated energy systems.

Benefits / Market Implications

The target markets to be impacted include, for example:

- Single-family and multifamily residential markets (retrofit or new, including affordable housing markets) where NG/LPG-fueled furnaces and/or ASHPs are used.
- Small commercial applications with moderate HVAC and water heating loads.

Benefits of this project include reducing GHG emissions by: increasing integration of PV renewable energy; using significantly more efficient NG/LPG-fueled equipment; increasing HVAC system operational resiliency for ratepayers through on-site power generation/nanogrids; and the opportunity to rapidly implement the innovations since they integrate and control off-the-shelf appliances in novel ways.

Technical Concept & Approach

Continuing to move from research implementation to technology development, UTD will conduct this project in the laboratory and use Virtual Test Home (VTH) methods for simulated-use evaluations.

The current phase of work will complete the following tasks:

Task 1 – Prepare Overall Test Plan and Procure all Equipment

The team will procure equipment for the ad hoc system, mCHP retrofit and air source heat pump. The Project Test Plan for this project will be developed in order to answer the following research questions:

1. Can an ad hoc retrofit solution to replace an AC system with an electric air-source heat pump (ASHP) be easily integrated with a fuel-fired furnace to achieve COP>1.0.?

2. Can a fuel-fired mCHP retrofit solution with an existing furnace and ASHP achieve self-powered fuel-fired space heating with COP>1.0?

3. Can a fuel-fired ~5kW mCHP be integrated with an air source heat pump to achieve self-powered fuel-fired HVAC

and water heating with COP>1.5?

Task 2 – Develop Cloud-based Smart Fuel Switching Control

BKR Energy has developed an innovative cloud-based smart fuel switching controller that uses data on weather, energy rates, and emissions factors to make fuel switching decisions. Working with BKR Energy, the team will develop control strategies to help answer and achieve the research questions above.

Task 3 – Implement hardware-in-the-loop test protocol

The team will continue to implement hardware-in-the-loop test protocols inside the laboratory. EnergyPlus™ modeling will be implemented to co-simulate building models and hardware interface capabilities. This functionality will enable co-simulation of a building model as the hardware operates, permitting “real-time” interaction between the building model and HVAC system.

Task 4 – Design and Build Residential Hybrid and mCHP IES

The team will design, build and test the ad hoc retrofit solution, an additional mCHP retrofit solution, and an integrated 5kW mCHP with an ASHP system. VTH data will be reduced to 24-hour load versus efficiency profiles. As with all VTH data sets, they will be used to develop performance curves that can be used in building energy modeling software to predict energy, GHG, and cost savings from the various IES systems.

Results

In Phase 1 a residential nanogrid testbed was built and a prototype system achieved key performance markers such as: self-powered HVAC water heating on- and off-grid for superior resiliency for ratepayers; annual hybrid space-heating efficiencies >100%; predicted annual GHG reductions based on IES performance of >30% in cold climates; and annual operating cost savings of >40% in several regions.

The performance of the prototype matched best-in-class advanced combi system performance. More importantly, the prototype has led to development of a full IES where an electric heat pump and onsite power are already installed and the control logic developed for integration.

The VTH performance-based modeling efforts determined that significant energy, cost, and emissions-related savings are possible with the hybrid self-powered system when compared to a traditional 90%-efficient furnace, 0.62 EF water heater, and 15 SEER HSPF air conditioner. Modeled estimates for seven different climates were developed.

Enginuity E-ONE Micro-CHP System (image credit: Enginuity)

Additional findings indicated that specific IES designs (particularly with integrated PV) can achieve self-powered space heating/cooling and water heating at annual COP >1.5 on a source energy basis with 30-50% lower operating costs and similar GHG emissions reductions than with separate code-compliant equipment in various climates.

Researchers also determined the nanogrid system can operate entirely off grid and power the HVAC and water heating loads but with substantial battery storage, thus demonstrating resiliency.

To communicate these important findings and concepts to building HVAC design professionals, results from this project were presented at the ASHRAE 2022 Winter Conference in Las Vegas, NV in January 2022 and the World Gas Conference 2022 in Daegu, Korea in May 2022. Additionally, a paper was presented at the Purdue 2022 Refrigeration & Air Conditioning conference in West Lafayette, IN in July 2022. Two papers resulting from this research were also presented at the ASHRAE 2023 Winter Conference in Atlanta, GA in February 2023.

Status

In 2023 the project team: formalized a Project Test Plan with Enginuity; secured an Enginuity E-ONE mCHP system along with automated electric and thermal load banks in order to perform simulated use testing of E-ONE; and completed modeling of nanogrid systems to understand control options and quantify cost/GHG benefits. The team will install the E-ONE in a nanogrid testbed and begin simulated use lab evaluations.

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Hydrogen-Blended Gas in Residential/Commercial Combustion Equipment

This project is adapting and demonstrating solutions to use hydrogen blends in residential and commercial combustion equipment. Researchers will demonstrate multiple solutions in a controlled laboratory environment and leverage findings from other researchers globally.

Project Description

A number of researchers worldwide are investigating the impacts of hydrogen blending in fossil or renewable natural gas on end-use equipment safety and performance. While hydrogen as a fuel presents a number of challenges to existing combustion equipment, an emerging consensus suggests that low blends (e.g., <20% by volume) are suitable for existing equipment.

Technology demonstrations are under way in Europe, where natural gas is predominantly used for heating. However, renewable energy production is high, primarily since imported natural gas prices are high, and environmental requirements are strict. Through these efforts, several products are undergoing development and demonstration, from domestic boilers to cooking ranges and their associated combustion components, that can safely and efficiently utilize up to 100% hydrogen fuels.

Under Phase 1, this project seeks to build on these European efforts through extended technology transfer, while developing an R&D roadmap for hydrogen-blend-compatible equipment in North America, with an initial focus on >50% hydrogen blending by volume.

The concurrent Phases 2 and 3 of this project seeks to support the potential deployment of up to 30% hydrogen-blended gas in North American buildings by assessing the performance, emission, safety, and qualitative impacts of hydrogen blending on widely-used residential gas-heating appliances. Phase 2 focuses on high load gas appliances such as furnaces and water heaters, while Phase 3 focuses on widely-used but low-load peripheral gas appliances such as gas lights, space heaters, and indoor fireplaces.

Table-top hearth hydrogen-blending test setup

Benefits / Market Implications

This project initiated a significant technology-transfer and research effort with several leading global technologists to demonstrate high-hydrogen-compatible equipment and lay out a path for wider utilization of hydrogen in North America. Subsequent phases of the project are aiming to assess the compatibility of existing appliances with hydrogen blends to quantify net benefits of hydrogen blending at different levels. If successful, broad ratepayer benefits are anticipated to include:

- **Emissions:** Up to 100% reduction in the onsite carbon emissions associated from natural gas consumption, and
- **Health and Safety:** Reduction or elimination of carbon-based emissions, including carbon monoxide and trace contaminants.

Technical Concept & Approach

Specific tasks for Phase 1 include:

- **Test Planning and Equipment Procurement**

  The project team will design, develop, and fabricate a high-hydrogen blending system, including installation and calibration of necessary safety sensors and equipment in consultation with European partners with equivalent test stations.

- **Experimental Evaluation of High-Hydrogen-Compatible Equipment**

  Researchers will install and evaluate the performance, efficiency, and emissions from five or more components. For combustion components, investigators will evaluate the potential for reduced NO_x emissions. Through the demonstration of high-hydrogen-compatible equipment, the project team will additionally evaluate the efficacy of components, including gas valves and meters.

"Clean hydrogen will be key to helping consumers take advantage of the reliability and resilience of the gas system, while aiding us in reaching our decarbonization goals. This project will help assess the compatibility of existing appliances with blended gas and demonstrate the next generation of hydrogen-ready equipment

- Neil Navin
Vice President, Clean Energy Innovations
SoCalGas

- **Roadmapping and Outreach**

  The project team will prepare and issue a *R&D Roadmap for North American Residential/Commercial Equipment Compatible with Up to 100% Hydrogen Content Fuels.* One or more outreach events will be held, targeting interested manufacturers, utilities, regulators, and advocates.

Specific tasks for Phase 2 include:

- **Testing of Standard Gas Appliances Under Rating and Adverse Operating Conditions**

  Working with appliance manufacturing partners, researchers will perform standard rating and simulated-use tests with several typical furnaces and condensing water heaters in "as-shipped" condition to quantify any changes in efficiency and emissions of criteria pollutants for existing appliances when operating on hydrogen blends up to 30%. Additional tests will focus on adjusted appliance tests as well as operating under adverse operating conditions to determine if the use of hydrogen will cause existing appliance to lose compliance with ANSI standards.

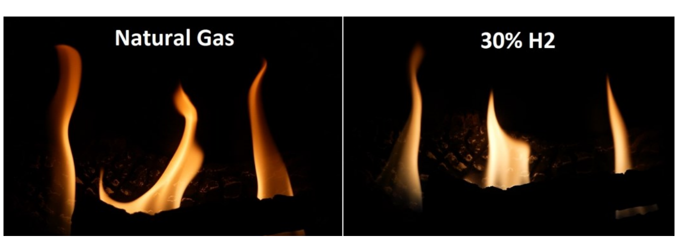
Specific tasks for Phase 3 include:

- **Qualitative Impacts of Hydrogen Blending on Aesthetic Burners**

The team will build a test apparatus for evaluating the qualitative and aesthetic output of fireplaces, radiant space heaters, and gas lights based on changes to flame size, shape, color, luminosity, and radiant output. When possible, small modifications will be considered to improve any of the qualitative features.

Results

In 2020, researchers coordinated with manufacturers of key hydrogen-capable components and combustion systems.



Hearth testing with Natural Gas (left) and a 30% H2 blend (right)

H2 Source and Mixer Undergoing Installation

Within this group, several appliance manufacturers discussed approaches to operating with hydrogen blends, up to 60% in most cases and 100% in some cases. Hydrogen-compatible flow sensors were acquired and project representatives developed a hydrogen/natural gas automated mixing station.

In 2021, the project team developed a comprehensive review of hydrogen demonstrations in Europe and Asia that included end-use customers, including materials from the EU-based *THyGA* project, adapting some of the timely findings for a February UTD member webinar. Additionally, researchers actively coordinated with other North American hydrogen studies and testing efforts.

In 2022, test stands were built and/or modified for standardized testing of furnaces and water heaters. As part of the R&D roadmapping and outreach efforts under this project, the team prepared a summary paper for the *World Gas Conference* held in May 2022. Researchers demonstrated that methane emissions decrease with added hydrogen. The response to results was very positive, in particular with high interest from organizations in Latin America.

In 2023 the team completed commissioning the test stand for Phases 2 and 3, and as of the beginning of Q3, had initiated initial tests with hydrogen blends in a hearth and gas furnaces. Results to date for this project were presented at a seminar at ASHRAE's Winter Conference in February 2023

Status

For Phase 2, rating and simulated use tests are ongoing with the first round of gas furnace tests complete.

For Phase 3 combustion performance and hydrogen compatibility is ongoing and qualitative impact tests will be performed in parallel to compatibility tests. The fireplace test stand facilitates both.

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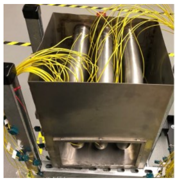
UTD Utilization Technology Development

Membrane-Based Ionic Liquid Absorption Heat Pump for Commercial HVAC



This project developed an innovative thermally-driven cooling technology for commercial HVAC applications. The technology will be demonstrated in a prototype ultra-high-efficiency dedicated outdoor air system. At the core of the equipment is a novel, scalable absorption system centered on a compact membrane-based heat and mass exchanger for retrofit HVAC equipment.

Project Description

Commercial building owners often use natural gas in buildings with forced-air-type HVAC equipment (e.g., rooftop units, or RTUs) as the primary means of heating and cooling. The U.S. Department of Energy's Advanced RTU Campaign estimates that more than 60% of commercial building area is conditioned by RTUs.

For RTUs to process outside air to remove moisture, vapor compression systems must overcool air to saturation conditions. This is a thermodynamically-inefficient process, particularly in dedicated outdoor air system (DOAS) applications in which cooled air is often reheated. The ability to directly remove moisture from air, without cooling it, would enable more efficient HVAC systems capable of separate sensible and latent cooling in locations where latent load constitutes the majority of the ventilation load.

For this project, a research team developed a prototype novel highly-efficient gas-fired absorption cycle which combines dehumidification and heat-pump functions. The system can use ventilation or indoor humidity load for water and/or space heating. Specifically, the system is enabled by:

1. An absorption cycle that allows combined dehumidification and heating
2. Non-crystallizing ionic liquids that allow double-effecting the cycle and operating at elevated temperatures (~160°C) without costly materials
3. Compact membrane-based absorber which contains ionic liquids and directly cooling to provide a high system coefficient of performance, and
4. Novel, highly-integrated, double-effect desorber condenser designed to reduce size, weight, and cost.

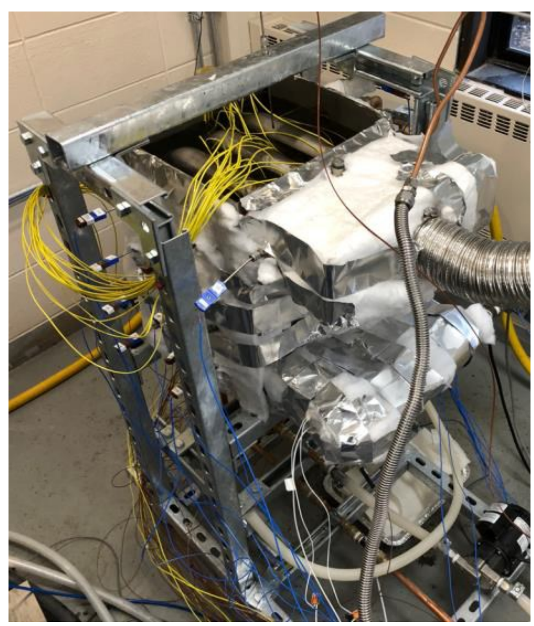
The goal was to develop an innovative thermally-driven cooling technology for commercial HVAC and demonstrate it in a prototype ultra-high-efficiency DOAS RTU. This technology is centered on a compact membrane-based heat and mass exchanger with no desiccant entrainment. The compact size permits easy retrofit into existing building infrastructures. Regeneration of the system is driven by efficient heating (natural gas, propane, waste heat, solar, etc.).

The U.S. Department of Energy (DOE) provided prime funding to the University of Florida (UF) for this technology development effort. UTD partnered with the UF, DOE, and participating OEMs by providing technology innovation support as well as co-funding to DOE.

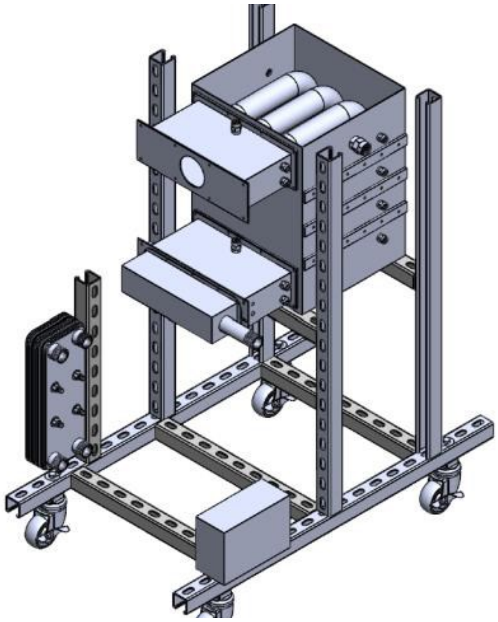
Benefits / Market Implications

End users who can benefit from this technology include those that: 1) use DOAS for dehumidification combined with building zones reheating and/or hot-water supply; 2) handle indoor humidity in tight buildings combined with ventilation air and/or space heating in winter; and 3) handle humidity in indoor pools combined with pool water and/or space heating.

If successful in developing this advanced technology, the project team projects several benefits, including an increase in heat pump energy efficiency, a reduction in peak electrical power consumption, and an increase in the energy efficiency of liquid-desiccant-based latent cooling cycles. Estimates indicate a potential 85% reduction in operating costs.



System desorber testing implementation



System desorber design

Technical Concept & Approach

- **Proof-of-Concept System Integration and Testing**

  Experts provided commercial HVAC advice to the team during the initial product definition, competitive assessment, and determination of operating conditions. Additionally, researchers performed a codes-and-standards analysis to identify any possible non-technical barriers to DOAS RTU system design and deployment. Researchers evaluated the technical feasibility and comparative performance of options for direct and indirect-fired (steam/oil) desorbers. The team designed and fabricated simulators for the desorber(s) to evaluate multiple combustion system design options and performance.

- **System Integration and Testing**

  An experimental test plan was developed, and the team constructed a simulator test rig, procured cost-effective options for the combustion system (burner, gas valve/ controls, ignition system, blower/inducer), and planned shakedown testing. Investigators compared the performance of each system combination in support of meeting performance and emission targets, and made initial recommendations to the project team.

- **System Test**

  With the prototype installed in the laboratory, researchers performed a shakedown to assure the RTU, instrumentation, and controls are all functioning correctly. The ability of the test rig to create and sustain the desired environmental conditions was also be verified.

Results

In 2020, researchers performed initial modeling and analysis to provide insight into fuel/air side impacts on the hot-side components and completed design activities. Simulation using ionic liquid thermophysical properties indicated that a direct-fired desorber/condenser is feasible and worth experimental investigation. The simulations were based on input geometry and heat-transfer parameters, as well as past experience with direct-fired heat exchangers. The overall heat-transfer efficiency from the flue gas to the ionic liquid solution appeared to be very high for all scenarios considered based on results from the simulations. Calculations from first principles yielded maximum potential heat transfer efficiencies in the range 75%-81%.

The codes-and-standards analysis did not identify any possible non-technical barriers to DOAS RTU system design and deployment that could not be addressed.

In 2021, a study was completed regarding the impact of direct firing the desorber, concerning capacity, hot spots (material reliability), and other factors. The project team performed open-air testing of the burners and validated the functionality of the burner ignition and operational controls.

In 2022-23 full desorber tests were completed, demonstrating that a direct-fired design is technically feasible and meets emissions requirements (e.g. Ultra Low NOx), with recommendations for subsequent prototype optimization. The project team publicly reported results of UTD 1.20.I/this DOE project in a technical paper presented at the IEA Heat Pump Conference held in May 2023 in Chicago.

Status

Due to a delay in the readiness of the 1,000 CFM prototype to be provided by other team members, a final report for UTD 1.20.I was issued to UTD members in August 2023 to summarize the results to date. The project team will continue the important work to assemble and test the 1,000 CFM prototype under the overall DOE-funded project, with subsequent reporting to be provided to UTD members. Those findings will also support related efforts in UTD 1.21.I.

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UTD Utilization Technology Development

Integrated mCHP System for Multi-Family Buildings

A project team is cleverly integrating an mCHP unit with best-in-class electric heat pumps, thermal storage, PV and other commercially-available equipment to serve a simulated multi-family application scenario. This advanced system provides annual gas efficiencies greater than 130% for heating, cooling, and hot-water loads, while increasing resiliency and using more Renewable Energy. Gas customers can immediately benefit.

Project Description

This project is demonstrating and optimizing the integration of a near-zero emission (NZE) micro-combined heat-and-power (mCHP) unit coupled with best-in-class electric heat pumps in a multi-family application scenario. By integrating this commercially-available equipment with thermal storage, PV and smart management capabilities, the system can operate as an advanced integrated system to achieve annual gas efficiencies greater than 130% for heating, cooling, and hot-water loads, while providing the high resiliency of on-site power generation, and substantially reducing operating costs and greenhouse gas emissions in cold climate zones.

Specific project objectives are to:

- Integrate communications functions with variable-speed compressor electric heat pump operation and an mCHP system power lead-mode for space heating and cooling.
- Right size thermal storage and manage hot-water production for the mCHP system
- Characterize space and water-heating and space-cooling part-load performance.
- Communicate results to facilitate market transformation.

UTD is partnering on this project with the U.S. Department of Energy (DOE), in which part of this UTD project is supporting a DOE-funded Connected Communities research program that expands DOE's network of grid-interactive, efficient building communities nationwide and enables them to interact with the electrical grid to optimize their energy consumption, which will reduce their carbon emissions and energy costs. UTD is also partnering on this project with the Propane Education and Research Council (PERC), which provided co-funding to UTD.

Benefits / Market Implications

Optimization of an mCHP unit integrated with cold-climate air source heat pumps (ccASHPs), thermal storage management and PV will help increase low-cost, reliable energy solutions for consumers. Applications beyond multi-family housing include multi-unit buildings, low-rise suburban office buildings, smaller strip malls/plazas, distributed thermal microgrids, etc.

NZE buildings are often perceived as feasible only with all-electric HVAC and domestic hot water provided by electric heat pumps powered by on-site PV power generation. However, advanced mCHP integrated systems can provide similar or lower emissions at lower operating costs with superior energy resiliency while directly integrating PV energy. A reliable and

The mCHP integrated system indoor installation.

efficient mCHP system, when cleverly integrated with best-in-class heat pump heating/cooling, can provide numerous benefits. In addition to meeting thermal demands, mCHP can be leveraged to provide clean backup energy to power EV charging stations when PV power is insufficient. Demonstrating its feasibility can inform consumers, homebuilders, manufacturers, and other stakeholders about the benefits for end users and the environment of integrated energy systems.

Technical Concept & Approach

Under Phase 1, this project team will develop a test plan and subsequently build a microgrid testbed to represent a 4-townhome multi-family building. This microgrid testbed will include the Lochinvar 24 kW mCHP with four 3 -ton best-in-class electric heat pumps.

This microgrid will be evaluated using a Virtual Test Home (VTH) load-based evaluation methodology to optimize microgrid integration and control strategies. The microgrid performance will be characterized for building energy modeling to

The mCHP integrated system outdoor installation.

develop sizing guidelines for multi-family building sizing and location, including utility operating costs and region of transmission marginal operating emission rates (MOER). Researchers will quantify the microgrid's MOER and operating cost reduction relative to commercially available all-gas and all-electric baselines. Results will be communicated to industry stakeholders, including building design professionals and hybrid residential HVAC solution manufacturers.

Under Phase 2, this project team will install a PV array and EV charging stations in the microgrid and develop integration strategies to cascade power prioritization, starting with solar, on-site cogeneration, and lastly the grid. An automated load bank will simulate realistic EV charging station loads and capture the effects on the microgrid performance. The project team will also develop performance curves, evaluate microgrid performance with EV charging stations and PV in multiple climate zones, and develop design guidelines.

Results

During Phase 1, the project team developed a test plan and microgrid testbed design, integrated microgrid components, and evaluated its performance over the 2023 heating season in Chicago, IL. The test plan encompassed the microgrid testbed design and component selection. The Lochinvar 24 kW mCHP and four 3-ton ccASHPs were selected for this microgrid. Hydronic integration strategies were developed to leverage on-site cogeneration to prioritize water heating loads while supplementing space heating loads with the ccASHP's heating output. Power integration strategies were also considered to modulate the mCHP as a function of the ccASHP's power demand. The mCHP heat production was designed to be distributed to individual dwellers' indirect tanks and hot-water coils for water and space heating.

To evaluate the microgrid performance, a hybrid approach to couple actual weather conditions with simulated loads was implemented using the VTH test rig and building energy modeling. The simulated loads were crafted to optimize performance via simplified energy modeling. This simplified modeling showed that four-unit townhouse homes with peak heating loads of 60 MBH at design conditions were needed to maximize microgrid performance.

Results indicate that this microgrid can operate at COPs between 1 and 1.8 across the heating season. The resulting carbon footprint rate of the microgrid was an average of 300 lbm/MWh, which is 25% of the national average MOER of the current electric grid and approaches many 2050 emission targets! This project demonstrated that advanced mCHP technologies integrated with best-in-class electric ccASHPs can: operate with only 14% of the net power requirements; reduce electric loads by 27%; reduce installation costs by 43%; and reduce greenhouse gas (GHG) emissions by 47% of fully-electrified multifamily building HVAC&WH systems.

During Phase 2, the project team designed and implemented power integration strategies for PV and EV charging stations. The PV array was sized for 13 kW, and two dual-pole 40 Amp level 2 charging stations were selected. The project team has disseminated the microgrid performance over the 2023 cooling season and is collecting data for the 2023/2024 heating season.

The cooling season evaluation results indicated that the microgrid provides space cooling and water heating with only 13% grid power and efficiencies between 3.0 and 6.0. The microgrid power requirements were heavily managed by solar power generation, with 42% of the net power consumption. Cogeneration, supporting peak cooling power requirements, contributed 14% of the microgrid power requirement while managing all water heating loads. These project results will support analysis within a Connected Communities project awarded by DOE to the Electric Power Research Institute (EPRI).

Status

Phase 1 of this project is complete. A Phase 1 final report was issued to UTD members in July 2023. Phase 1 results were also published in technical paper #AT-23-C062 presented to HVAC system design professionals at the ASHRAE 2022 Winter Conference held in Las Vegas, NV to help accelerate market adoption and transformation.

Efforts currently underway during Phase 2 are to: continue to collect performance data for the 2023/2024 heating season; engage modeling tasks to estimate performance across multiple climate zones in the U.S.; and develop design guidelines as part of the deliverables, which includes a report and another conference paper.

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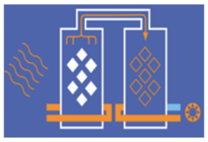
HeatAmp Adsorption Thermal Heat Pump



Researchers are advancing the development of an innovative, high-efficiency, and robust gas-fired thermal heat pump technology by optimizing, designing, building, and testing a cost-effective alpha prototype burner/boiler and combustion system and integrating it into a complete alpha prototype water heater.

Project Description

The technology being developed in this project is based on a proprietary chemisorption sorption system from HeatAmp Sweden AB. The technology is coupled with a novel system integration that is expected to result in a cost-effective, robust, and scalable appliance design with few moving parts.

The Chemisorption unit is compact and efficient and without the corrosion management or sealing requirements of standard absorption machines.

The driving force of the technology is a compact gas-fired heater desorbing the refrigerant, with an efficient integrated backup boiler and a fuel-flexible combustion system projected to be compatible with renewable natural gas and/or hydrogen. Desorbed refrigerant heats the buffer tank, then the refrigerant flows to a receiver/evaporator.

The primary target use is for domestic hot water applications, with options for combined space/water heating or pool-heating.

HeatAmp's cost-effective thermal heat pump (THP) technology has potential for market transformation by virtue of its high efficiency (projected >33% energy/emission savings vs. standard fuel-fired equipment) and the opportunity for increased reliability and operating life relative to other sorption-type heat-pump technologies. Additionally, the scale-up of core sorption heating technology can drive innovative applications in other product categories (e.g., commercial HVAC).

In summary the goal of this project is to advance the development of this cost-competitive, THP technology by optimizing a cost-effective alpha prototype burner/boiler assembly and then evaluating the technology in a alpha prototype of a complete integrated water heater. UTD is partnering with the Northwest Energy Efficiency Alliance (NEEA), which provided co-funding to this UTD project.

Benefits / Market Implications

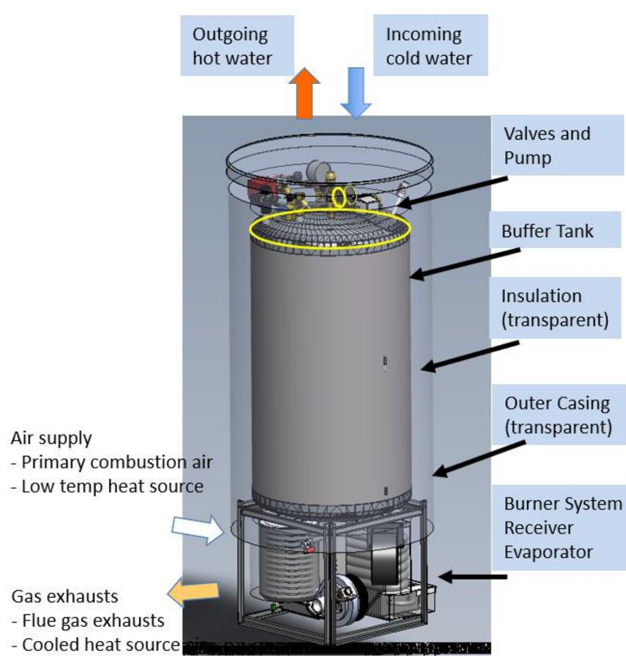
As a competitive addition to the residential-scale THP portfolio, this technology has several potential advantages. The appliance uses a natural refrigerant with zero ozone depletion and zero global warming potential, suitable for all climate zones. Additionally, the sorption components are integrated into the tank, reducing thermal losses and safely isolating the refrigerant charge.

The projected 2030 US residential fuel-fired heating market size is 2.7 Quads/year per DOE's BTO Market Calculator. With a target COPgas of 1.30, this chemisorption heat pump and similarly-efficient products have the potential to reduce US 2030 energy consumption by approximately 830 TBtu/year.

Technical Concept & Approach

With first-cost sensitivity of residential appliances being a major barrier, emphasis is being placed on balancing cost vs. performance in components and in developing a simple overall system. Attention is also being paid to ensuring installer comfort with the new technology, including actual vs. perceived safety implications.

Researchers are developing design/specification recommendations for an alpha burner/boiler, including the combustion system (burner, blower, fuel/air mixing, combustion controls) and boiler module (combustion chamber, heat exchangers, venting/flue, overall burner/boiler controls).



Alpha prototype (XBTI-10) CAD rendering

"Gas-driven Heat Pumps with energy efficiencies over 100% will be key for residential users to reduce energy costs and GHG emissions, but also to meet future energy standards. By maintaining heating appliance capacity we ensure the same end-user experience as for current products. UTD has provided and continues to provide valuable technical support for important developments of HeatAmp's technology including 3rd party support from GTI Energy to accelerate the steps needed to commercialize the technology. "

- Magnus Ekblad
CEO
HeatAmp Sweden AB

The "Alpha" Prototype Set-up for laboratory evaluation

The system will be fabricated and evaluated using bench-scale testing and a simulated load test rig. Performance/emissions/safety testing will be performed (steady state, ramp up/down, etc.), results reviewed, and recommendations for optimized burner/boiler developed.

A final optimized burner/boiler system will then be evaluated within the alpha prototype THP unit. Performance will be analyzed and estimates of manufacturing costs will be generated.

Researchers will compare performance of the THP system to baseline and emerging technologies, as both water heater and whole-house heating systems, using extrapolative modeling to establish the North American technical potential.

In summary, the technical goals are:

- Design and demonstrate a burner/boiler system for the THP capable of >93% effectiveness (>83% fuel to steam), with NOx emissions of 14 ng/J or lower, and successful operation with up to 30% blended hydrogen; and
- Design an advanced sorption-type THP capable of achieving a projected >1.2 UEF (or equivalent) and demonstrating > 1,000 hours of operation in a laboratory test program.

Results

In 2021, the project team held several project meetings to outline the project goals/tasks, finalize the scope of work, and define the partnership. The research team prepared a simplified dynamic modeling of the heat pump water heating design to assess its ability to meet standard and extreme hot-water demands.

After an extensive design process involving HeatAmp and the project team, the burner/boiler testing in the lab indicated that an operating efficiency of up to 96% was feasible, though not at full-fire. The project team has identified design modifications necessary to reach this target at full-fire, which will be explored in Phase 2. NOx emissions ranged from 3 to 15 ng/J, with modifications identified to assure the 14 ng/J target is met at full-fire.

A calibrated simulation tool was developed and used to estimate performance against the standard simulated use test pattern, leading to recommendations for the full "alpha" prototype design and controls strategy.

Burner/boiler system testing completed in 2022-2023 met the targets of 10 kW-13.5 kW firing rate with λ = 1.7, although the team encountered system challenges with flame stability under certain conditions. The project team presented a technical paper at the 14th IEA Heat Pump Conference in May 2023 which summarized this project's technical progress to date.

Status

Design and safety documentation for "Alpha" prototype has been completed and a second "Alpha" prototype has been manufactured and is undergoing testing.

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Technical Support for Residential & Light Commercial Gas Equipment Testing, Performance, and Safety

This project provides support to technical committees that develop, refine, or update codes and standards to improve safety for natural gas end users and increase the energy efficiency, reliability, and resiliency of gas equipment and integrated systems.

Project Description

Advanced technologies are often developed to address problems with existing alternatives in the market; however, new technologies are typically evaluated using existing criteria, which may misrepresent performance and necessitate costly engineering redesign that delays market introduction. In many cases, advanced technologies will not be included in codes and standards unless they are updated. When existing technologies advance from lower- to higher-performance levels, there is often a gap in test protocols and rating procedures to capture the full benefit of the advancement. This project helps address that gap.

Through this project, researchers provide technical support to industry groups and professional societies that develop codes and standards by consensus in open technical sessions. Researchers provide analytical test results, laboratory test results, and field test data to develop and improve test methods to more accurately reflect real-world conditions.

This project builds upon past UTD projects to provide technical information to advance codes and standards such as:

- ANSI/ASHRAE Standard 146-2020 *Method of Test (MOT) for Rating Pool Heaters*
- ANSI/ASHRAE Standard 118.1 *MOT for Rating Commercial Gas, Electric, and Oil Service Water Heating Equipment*
- ANSI/ASHRAE Standard 204P *MOT for Rating Micro-Combined-Heat-and-Power Devices*
- ASHRAE MOT for water heaters, gas-fired heat pumps, furnaces, boilers, combis, and micro-combined heat and power systems (micro-CHP)
- NFPA 54 and ANSI Z223.1 safety requirements for fuel gas piping systems in homes and other buildings
- ASHRAE forums, seminars, and research projects, and
- Mixed-fuel net zero emissions publications and seminars.

Benefits / Market Implications

This project provides information to improve safety for end users and accelerate the use of new advanced gas technologies for space conditioning, water heating, and micro-combined heat and power (mCHP).

These advanced gas technologies can help utilities meet the goals of energy-efficiency programs while reducing individual ratepayer costs. Other important benefits include:

- Expanding customers' competitive choices of product offerings that can save energy and costs
- Ensuring safe and reliable operation of gas appliances
- Developing accurate and consistent equipment ratings for consumers to compare cost, efficiency, and the environmental impact of available products and fuel choices, and
- Expanding choices of product offerings that support ZNE initiatives.

Target markets impacted by this project include current equipment such as furnaces, water heaters and mCHP, as well as new cost effective, high efficiency, gas-fired technologies for all residential and commercial space-conditioning markets, such as gas-fired heat pumps.

Technical Concept & Approach

The project team continues to support the development and consensus review of water-heating and combination system energy codes, as well as methods used to model the performance of new technologies. Examples include:

- The working group for SPC 124 *MOT for Rating Combination Space-Heating and Water-Heating Appliances* is developing a test setup and methodology for testing integrated combination-system packages. The project team was asked to help develop a potential new approach and test protocol based on laboratory evaluations conducted with a Virtual Test Home.
- Project representatives review standards and MOT for space-conditioning equipment, building energy codes, and appliances to identify the testing needed to support appropriate codes for new advanced gas technologies. This task also includes technical support for the consensus updates for ASHRAE 40 and ANSI test methods to reflect recent developments in gas heat pumps.
- A project representative serves as a voting member on ASHRAE technical committees.

Results

Project team members have supported technical discussions on various committees, such as:

- ASHRAE Technical Committee 4.3, *Ventilation Requirements and Infiltration*
- ASHRAE Technical Committee 5.10*, Kitchen Ventilation*
- ASHRAE Technical Committee 6.1*, Hydronic & Steam Heating Equipment and Systems*
- ASHRAE Technical Committee 6.3*, Residential & Light Commercial Forced Air Heating and Cooling Systems*
- ASHRAE Technical Committee 6.9, *Thermal Storage*
- ASHRAE Technical Committee 6.6*, Service Water Heating Systems*
- ASHRAE Technical Committee 6.10*, Fuels and Combustion*
- ASHRAE Technical Committee 8.03*, Absorption and Heat Operated Machines*
- ASHRAE Standards Project Committee 40*, Methods of Testing for Rating Heat-Operated Unitary Air-Conditioning and Heat-Pump Equipment*
- ASHRAE Standing Standards Project Committee 41, *Standard Methods for Measurement*
- ASHRAE Standards Project Committee 118.1*, Method of Testing for Rating Commercial Gas, Electric and Oil Service Water Heating Equipment*
- ASHRAE Standards Project Committee 124*, Methods of Testing for Rating Combination Space-Heating and Water-Heating Appliances*
- ASHRAE Standards Project Committee 154*, Ventilation for Commercial Cooking Operations*
- ASHRAE Standards Project Committee 155p*, SPC 155P Method of Testing for Rating Commercial Space Heating Boiler Systems*
- ASHRAE SSPC 154*, Ventilation for Commercial Cooking Operations*
- Proposed New Standard, Z21.85 - *Alternative Connection Means for Use in Gas Appliances*
- Proposed New Standard, Z23550 - *Safety and control devices for gas and/or oil burners and appliances*
- *Meeting of the Z21/Z83 Technical Committee and, CSA Gas Appliances & Related Accessories Technical Committee Joint Meeting*
- Proposed New Standard, Z23551-4 - *Safety and control devices for gas burners and gas-burning appliances*
- ANSI Z21.40:23/CGA 2.94:23 DRAFT STANDARD, *Performance Testing And Rating Of Gas-Fired, Air Conditioning And Heat Pump Appliances*
- New Edition - ANSI Z21.20-2014 - CAN/CSA C22.2 No. 60730-2-5-14 - *Automatic electrical controls for household and similar use control systems,* and
- NFPA 54/ANSI Z223.1, *The National Fuel Gas Code.*

Status

Representatives participate in relevant technical committees and prepare conference papers and presentations of value to the HVAC and built environments community.

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UTD
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CleanO2 CarbinX™ Carbon Capture

Research is further advancing the performance and applicability of CleanO2's CarbinX distributed carbon capture device by extending operation to higher-efficiency condensing appliances. This builds on prior product development research support including to validate claims of avoided CO2 emissions, and average cost savings and energy savings.

Project Description

This project is advancing the performance of CleanO2's CarbinX™ latest carbon capture device by validating carbon capture and heat-recovery rates in a laboratory test stand, and identifying potential areas for further technical refinement.

This project builds on efforts since 2018 by the research team partnering with CleanO2 under additional separate funding provided by UTD members. The prior research on an earlier prototype identified potential areas for product improvement, such as: addressing the possibility of moisture accumulating in the reaction chamber; optimizing the reaction chamber to maximize carbon capture; adding sensors to indicate progress or completion of reaction process; and easing the process to load the caustic potash and extract the pearl ash.

CleanO2's newest system addresses these areas by: adding moisture sensors and controls to alternate flue-gas and fresh-air intake; using multiple batch reactors in place of one large reaction chamber to improve the carbon capture rate; adding wireless communication to notify the building owner of the reaction progress; and incorporating other improvements.

Current efforts focus on advancing CleanO2's next-gen commercial carbon capture unit (CarbinX v. 4) to apply to higher-efficiency condensing appliances. The team seeks to demonstrate in a laboratory setting carbon capture efficiency ≥50% and payback period ≤5 years. This will enable condensing boilers, water heaters, or other condensing appliances, to provide high-efficiency and low-carbon operation to residential and commercial building operators.

Benefits / Market Implications

Implementing distributed carbon capture technology will reduce greenhouse gas (GHG) emissions in the residential and light commercial/industrial markets while retaining customer choice options to use gas in zero net energy buildings. The team is targeting a 50% reduction in GHG emissions compared with the 20% which has already been demonstrated. An eventual goal may be to reach 100% GHG emissions reduction for future technology beyond the next-gen unit.

This product will save consumers money through fuel savings and pearl ash rebates with an estimated payback period of 4.8 to 7.5 years. The project has a specific goal of a 5 year payback period without a carbon levy, although the technology may also reduce carbon levies owed by customers in jurisdictions that have a carbon-pricing program.

The primary target markets impacted will be:

- Residential and commercial buildings (e.g. multifamily, assisted living, hotels, schools, offices, shopping malls)
- Commercial boilers >250 MBH and <1,500 MBH

Technical Concept & Approach

The current efforts will study and investigate different technologies for improving the carbon capture efficiency and waste heat recovery effectiveness of CleanO2's CarbinX v. 4 prototype. Scaling of the carbon capture unit for larger fuel-

Experimental test stand with carbon capture unit (left), water-heater simulator (middle), and recirculation loop (right).

Interior of reaction chamber after operating unit for a few hours with ~25 kg of caustic potash

> 
>
> *"UTD and its utility members have been essential partners in advancing our carbon capture technology. Their support has helped us to develop a cleaner, more sustainable energy future. We are grateful to their partnership and look forward to continued success in carbon capture and utilization with our disruptive technology along with help from our partners at GTI Energy.*
>
> *- Jaeson Cardiff*
> *Chief Executive Officer*
> *CleanO2 Carbon Capture Technologies Inc.*

fired appliances will also be addressed. The following tasks will be performed:

Task 1: Design Optimization of Carbon Capture Reaction Chamber

• Develop a numerical model of CleanO2's cartridge-style reactors for CarbinX v. 4 using design and performance data provided by CleanO2

• Use CFD to optimize reactor design for improved flue gas flow path and carbon capture efficiency

Task 2: Design Optimization of Waste Heat Recovery System

• Perform modeling of hot water demand for standard installation sites of CleanO2's technology and determine baseline waste heat recovery of current CarbinX storage tank configuration

• Investigate different tank designs and configurations to optimize waste heat recovery while minimizing the CarbinX footprint

Task 3: Advanced Simulated Use Testing of CleanO2's Latest CarbinX Prototype

• Complete baseline testing of CleanO2's CarbinX v. 4 to assess carbon capture efficiency and waste heat recovery using standard draw profiles, such as DOE's Uniform Test Method for Measuring the Energy Consumption of Water Heaters. All testing will be completed with a 500 MBH condensing commercial water heater

• Perform multiple tests at various water heater turndown ratios to determine effect on carbon capture and waste heat recovery performance and extrapolate findings to firing rates >500 MBH

• Test the CarbinX with both natural gas and propane combustion and determine any changes to carbon capture rate and waste heat recovery effectiveness and possible implications on payback period

• In coordination with CleanO2, the project team will modify CleanO2's prototype based on findings from Task 1 and Task 2 in order to evaluate potential additional improvements to carbon capture efficiency and waste heat recovery following the same draw profiles as for baseline testing.

Results

This project builds upon prior efforts by the research team with CleanO2 to support the technology development since 2018. As one outcome, CleanO2 plans to develop and ship a moisture-knockout module that will allow for compatibility for the current system with higher-efficiency condensing appliances.

Major upgrades were made to an experimental test stand to improve functionality and safety. Most of the changes were made to the recirculation/heat rejection loop, which now allows for more efficient charging and evacuation of air. New temperature-limit controllers were installed on the water-heater simulator and flue-gas venting to cut off gas supply to the burner if temperatures exceed a specified threshold. Multiple shakedowns were performed with the water-heater simulator to test for performance stability.

Final tuning of the CarbinX unit, water heater simulator, and heat rejection loops was completed to confirm stable operation of the burner with the activation of the CarbinX inducer. One week of continuous operation of the CarbinX unit has been completed while collecting carbon capture data.

Status

The team is finalizing the commissioning process and will soon begin advanced testing, operation, and further optimization of the CarbinX v. 4 prototype unit.

CleanO2 has commercialized earlier versions of its CarbinX unit; more information is available via its website https://www.carbinx.com. The output of the CarbinX units are sold for example through the website https://cleano2.ca.

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UTD
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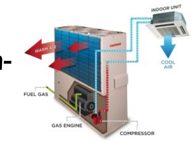
Gas Engine Heat Pump Modeling, Testing, and Implementation

This project is refining gas-engine-driven heat pump performance models based on actual field data for variable refrigerant flow systems operating across a range of conditions. These efforts will optimize benefits for end users through more advanced techno-economic assessments, performance validations and enhanced energy models for system designs as well as compliance-based energy simulations.



Project Description

The performance of all air-source heat pumps – including electric- and gas-engine-driven – varies significantly with ambient temperatures. In addition, the complexity and customized design of variable refrigerant flow (VRF) systems make it costly to accurately measure real-time performance and efficiency. As a result, energy savings are often calculated using simplified energy modeling based on steady-state laboratory data obtained under controlled conditions, rather than actual installed performance.

EnergyPlus™ gas-engine heat pump (GEHP) models were typically based on published electric VRF models adapted to GEHP manufacturer performance data and a limited number of measured datasets. Manufacturers' performance data is typically only available for part-load operation at 60% and above; however, researchers know from previous demonstrations that GEHPs typically operate at much lower part-loads. Furthermore, the measured field data used for the model was from a single installation, corresponding to a limited range of operating conditions.

In summary, a more complete dataset of GEHP measured performance data is required to enhance EnergyPlus models and improve their accuracy to better predict energy savings, greenhouse-gas (GHG) reduction, and economic benefits for facility owner/operators, designers, and others.

Example of a Yanmar Gas Engine Heat Pump being analyzed, with a gas meter to monitor gas consumption

Recently, a number of GEHP equipment options were also introduced to expand the applications for GEHP and/or VRF systems. This project investigates options such as:

- An AHU Integration Kit that incorporates an expansion valve and controller enabling the VRF system to integrate a non-VRF air handling unit (AHU) in addition to, or in lieu of, multiple VRF AHUs
- The Yanmar Hydrobox and Blue Mountain Energy (BME) Sierra AWS System that transfers heating or cooling from the heat pump VRF system to a facility's hydronic heating and cooling system

This project is being done in collaboration with National Research Council Canada (NRCC) and will validate performance for VRF systems across a range of conditions with the goal to support end users with superior analysis tools and information through:

- Enhanced GEHP energy models using measured performance data
- Validation of new methods for testing for new GEHP performance metrics
- Techno-economic assessments to assess best use of new GEHP equipment options.

Benefits / Market Implications

GEHPs are increasingly cost-competitive with electric VRF systems; recent pricing reduced the incremental cost to \$500-\$1,000/ton. Equipment options are expected to expand potential applications to include both hydronic or forced-air installations.

This project provides benefits for ratepayers, society, and the environment such as:

- Expanded options for reducing both gas consumption and electric demand response (approximately 10kW reduction in peak electric demand per unit)

- Targeted 20%-40% savings in energy costs, along with lower life cycle costs
- Reduced GHG emissions via high performance end-use gas equipment that is more affordable and more efficient
- Reduced GHG emissions via high performance compared to conventional HVAC system.
- Improved comfort in multi-zone facilities compared to conventional HVAC system.

Examples of end-users that can benefit include:

- Multi-zone commercial buildings (offices, schools, retail, etc.)
- Markets with electric constraints and/or high demand charges
- Both new or retrofit installations.

This project will also support commercial building designers and owners/operators who use EnergyPlus software.

Technical Concept & Approach

This project will develop enhanced energy models as well as validate new test standards for GEHPs.

Researchers will enhance existing EnergyPlus models. The project team will seek to publish these GEHP models and disseminate them widely. This task includes collaboration with NRCC to share data, validate performance curves, and approve GEHP models for use in compliance-based energy simulation.

The research team will work with manufacturers and testing agencies to validate new GEHP methods of test and compare these ratings to the measured seasonal performance observed in the field. This effort will provide valuable feedback and insight on how well the new performance standard matches seasonal performance, with the long-term goal that comparable GEHP performance ratings can be directly compared to other HVAC technologies, such as electric heat pumps VRF systems.

Technical feasibility and economic assessments will be performed on GEHP options (AHU Integration Kit, Hydro-Box) to determine the potential energy savings of these options, the economic benefit and payback, limitations in performance, and the range of potential applications. This assessment will identify the most promising technologies and application options that warrant further investigation or demonstration. A preliminary technology assessment of current GEHP ancillary products will determine the energy or economic benefits of these options and configurations and estimate the potential market for these applications.

Results

For Phase 1, the project team is developing GEHP performance curves based on four GEHP field datasets in both warm and cold climates. The team is sharing data and collaborating with NRCC staff to develop and validate these heating and cooling performance curves with respect to outdoor ambient temperatures and part load operation. In addition, NRCC is also supporting this effort by monitoring an 8-ton Yanmar GEHP VRF unit installed at their test facility and has commenced data collection.

For Phase 2, the team is monitoring a Yanmar GEHP with an AHU Integration Kit installed at the Middletown Recreation and Community Center in Middletown, CT, to validate performance, best practices, and economic benefits. A successful demonstration of the AHU Integration Kit will support a high-efficiency and cost-effective role for natural gas in space conditioning for commercial buildings.

Status

For Phase 1, the team is working to refine hourly performance curves for the Yanmar GEHP VRF system using four completed field datasets. This series of heating performance curves will be presented at the ASHRAE Winter Meeting in January 2024. The team continues to collaborate with NRCC and Yanmar to enhance GEHP energy models. An updated version of the CSA/ANSI Z21.40:23/CSA 2.94:23 Performance testing and rating of gas-fired air-conditioning and heat pump appliances standard was recently approved and the team will reach out to VRF manufacturers to obtain any available laboratory test data using this updated standard. Additionally, development of the techno-economic assessment of Yanmar's AHU Integration Kit and Hydrobox designs continues.

For Phase 2, the team continues monitoring the system performance of the GEHP and AHU Integration Kit field site in Middletown, CT since April 2023. Based on preliminary results, the system performance approached the rated GEHP cooling efficiency of 1.0 COPg during design day temperatures of 95ºF. Higher cooling efficiencies were observed during periods with greater part loads and more steady state operation. The team will continue to track the system performance during the upcoming heating season.

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UTD Utilization Technology Development

Commercial Heat Pump Water Heater Field Performance Comparison

Researchers will directly compare the performance of commercial fuel-fired and electric-driven heat pump water heater technologies in both a commercial installation and a laboratory using established ASHRAE testing standards to provide end users with validated cost- and energy-savings analyses of each technology and aid customer choice.

Project Description

Commercial water heating end users are seeking higher-efficiency equipment options. Both fuel-fired and electric-driven heat pump water heaters promise efficiencies well above 100%, leading to energy and fuel-cost savings and reduced greenhouse gas (GHG) emissions. In recent years, Stone Mountain Technology, Inc. (SMTI) developed and introduced a gas-fired absorption heat pump water heater (GHPWH). Past projects funded in part by the U.S. Department of Energy (DOE), California Energy Commission (CEC), UTD and others have played important roles in advancing SMTI's product development.

Due to differences in the respective technologies, the standard measure of heat-pump performance – Coefficient of Performance (COP) – does not provide a sufficient metric to compare gas and electric heat pumps. While COP is a good measure when comparing traditional technology of the same fuel, it does not provide a useful comparison when evaluating cost savings or GHG emission performance between electric and gas heat pumps.

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) through EERE's Building Technologies Office provided prime funding for a public sector hot-water "proving ground" demonstration of SMTI's 80 kBtu/hr system at a field site. SMTI's commercial GHPWH and a comparable commercial electric heat pump water heater will be tested using the ASHRAE 118.1 hot-water testing standard for comparable performance testing. This will provide real-world operating data to assess energy and cost-saving potential in order to provide end users with additional scientific data to compare these two technologies, to help inform customer choice with comprehensive data. The field test data will be augmented by laboratory tests.

The Tennessee Department of Environment and Conservation (TDEC) is leading the DOE-funded project, through TDEC's Office of Energy Programs. UTD is partnering with DOE, TDEC, the National Association of State Energy Officials (NASEO), the Tennessee Advanced Energy Business Council (TAEBC), and SMTI by providing co-funding to DOE's prime funding. The Propane Education and Research Council (PERC) is also partnering in this project, by providing co-funding to UTD project 1.21.F.

Benefits / Market Implications

Key benefits that GHPWHs provide customers are to reduce operating costs and energy consumption. Cost savings occur from reduced peak electric demand costs, low gas prices relative to electricity on a per-therm equivalent basis, and overall reductions in energy use. Prior research has shown that total natural gas savings and GHG emission reductions of 16% to 26% (with the potential of up to 53% savings is achievable if the gas heat pump is right-sized) versus conventional water heating technologies. Similar fuel savings are anticipated when fired with propane.

Other important benefits that GHPWHs provide include better cold-weather performance, with ability to operate to -40° F, as well as the resiliency and reliability of the underground

SMTI gas heat pump. (Source: SMTI)

gas delivery system. Propane-fired versions provide options for areas not served by gas distribution infrastructure. Gas heat pumps maintain high efficiency, compared to electric heat pumps, even when ambient temperatures decrease.

New GHPWH product and technologies provide gas utilities and propane distributors with more high-efficiency options to include in their energy-efficiency incentive programs.

GHPWHs can also be beneficial for end users in areas where the electric supply may be constrained, and upgrades to the electric distribution grid may not be feasible within the end-users' timeframe.

The scientific data that evaluates the impact of deploying various types of heat pump water heaters may also aid public dialogue regarding energy efficiency and energy source options.

Examples of gas customers that can benefit include:

- Commercial water heating with a high hot-water use (>1,500 gallons per day)
- Multi-family housing
- Restaurants
- Hotels
- Assisted-living facilities, and
- Health and fitness centers.

Technical Concept & Approach

The project will provide measurement and verification (M&V) support for the DOE-funded field demonstration project. The same models of both the SMTI gas-fired heat pump water heater and a commercially available electric-driven heat pump water heater will also be tested in a laboratory, to provide end users with an additional direct performance comparison.

The research team will:

- Develop an M&V plan and specify instrumentation for baseline and field demonstration of one SMTI 80 kBtu/hr GPWH
- Develop an interface for baseline and demonstration data to provide near real-time access to collected data and analysis
- Collect, monitor, and analyze baseline and demonstration data
- Prepare interim and final field test data analysis report for inclusion in DOE reports
- Assist in report development and disseminating results
- Install and test the SMTI gas pump water heater following ASHRAE 118.1 standard test for water heating with natural gas
- Install and test a commercial electric heat pump water heater following the ASHRAE standard test for water heating, and
- Provide energy and cost-saving analysis based on testing compared to traditional technology.

Results

The host site that was initially planned for this project ultimately declined from participating in this field study, which resulted in a project delay. A new host site, Kings University in Bristol, TN was identified and onboarded. An engineering analysis was performed to validate the applicability of installing the heat pump, and a measurement and verification plan has been developed.

Status

The project team is developing the engineering design, procuring M&V equipment, and planning for installation in December 2023. SMTI's heat pump is scheduled to be installed and commissioned at the host site by February 15, 2024. The heat pump will be installed in parallel to the existing service hot water system providing the opportunity to collect baseline and retrofit data.

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UTD Utilization Technology Development

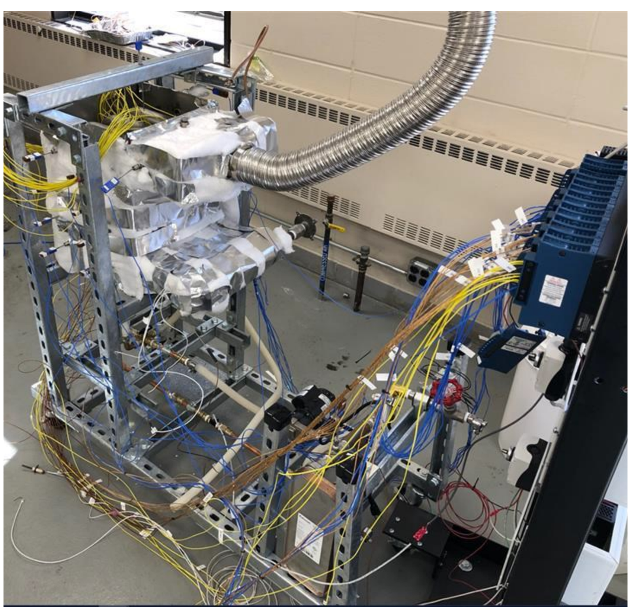
Ionic Liquid Absorption Heat Pump for Commercial Water Heating

Researchers are designing and demonstrating in a laboratory environment an early prototype of a low-cost, ultra-high-efficiency gas-fired commercial heat pump water heater with a novel semi-open absorption cycle that uses a benign ionic liquid and provides integrated latent cooling to further maximize efficiency.

Project Description

In the water-heating industry, significant attention has been given over the past decade to the development of high-efficiency water heaters for residential buildings. Much of this attention has concerned the tankless water heater, electric heat pump water heaters, and even the development of gas-fired heat pump water heaters (GHPWHs). However, hot water in commercial buildings has not received similar levels of attention, where despite greater numbers of residential water heaters sold per year (with approximately 36 times as many residential storage water heaters sold as commercial storage water heaters), commercial buildings can consume 10 to 100 times the hot water as a typical home. Prior research efforts in UTD project 1.16.I demonstrated the potential for high-efficiency GHPWHs using an ammonia/water closed absorption system, which has performance advantages but also some challenges by using ammonia.

UTD project 1.21.I advances a different technology for commercial hot-water applications – a novel semi-open absorption cycle (SOA-GHPWH) that uses a benign ionic liquid and which provides integrated latent cooling to further maximize efficiency. UTD is partnering with the University of Florida (UF), their partner Micro Nano Technologies, and with potential support from a leading commercial water heater OEM. All experimental work will be conducted with natural-gas-fired regeneration; however, findings should be directly relevant to propane-fired regeneration as well. The Propane Education and Research Council (PERC) is providing co-funding to this UTD project.



Desorber Test Stand With Safety Improvements and Insulation

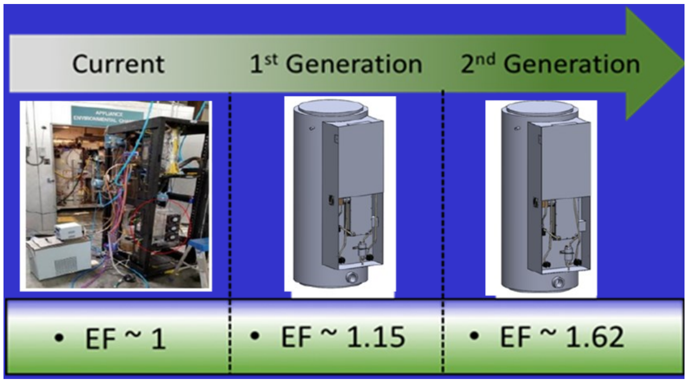
The heat pump design being developed in 1.21.I has several potential advantages over the closed ammonia/water GHPWH. First, the system operates at the atmospheric pressure, thus the lack of up to ~400 psig pressure allows simpler designs and low-cost components – with only small hydrostatic pressures and thin heat-transfer walls, enabling inexpensive low-thermal-resistance materials such as polymers to be used. Second, an inexpensive non-hermetic plastic solution pump is used.

In summary, the objective for this project is to design and demonstrate in a laboratory environment an alpha working prototype of an SOA-GHPWH targeted for commercial water heating applications. The project team will leverage the unique benefits of the GHPWH design, including a) environmentally-benign and safe working fluids, b) supplemental latent cooling via dehumidification, and c) the potential for long-term reliability and avoidance of costly corrosion-resistive materials and approaches. Research work in project 1.21.I is being coordinated with the work in project 1.20.I, which is applying this technology to rooftop units.

Benefits / Market Implications

The benefits that GHPWHs provide customers are primarily higher resiliency and efficiency, and reduced operating cost due to: reduced peak electric demand costs and total energy consumption; the resiliency of gaseous-fuel vs. electric-driven energy delivery; superior cold-weather performance; and lower purchased energy costs on a per-therm equivalent basis. The development of an SOA-GHPWH can provide another robust and attractively-priced fuel-fired GHPWH option for commercial end users.

The current product focus is a 145 kBtu/hr output system with a 100 gallons storage tank and a firing rate of 90 kBtu/hr, which allows this product to have the highest hot-water output in the market while only using a one-half-inch



Conceptual rendering. *Source: University of Florida*

gas connection. The project team's simulations suggest that this GHPWH will have a recovery rate of 220 gallons per hour at 70°F rise. For a system installation with integrated controls, including a conventional water heater in series to support peak demand, the projected economics are very attractive.

For a 5,000 gallon-a-day hot-water demand – typical for full-size restaurants or mid-size hotel, dormitory, or multifamily buildings – the SOA-GHPWH system is projected to reduce natural gas consumption by 5,655 therms (42%), with associated annual operating cost savings of $6,390 ($1.13/therm assumed). The projected cost of the GHPWH system in this example, including the peak demand conventional water heater is $11,950. Thus, the simple payback period is estimated to be 1.9 years. Note that this estimate is conservative with respect to the project, as the GHPWH operation will be more efficient in hot/humid climates and the economic benefit of supplemental dehumidification, reducing overall site HVAC operating costs, will further improve the value proposition.

Technical Concept & Approach

A research team will develop a final design for the SOA heat pump module, including the desorber/condenser, conditioning equipment, combustion system, and other components. The module will then be fabricated and tested.

Researchers will perform a battery of steady-state tests, varying stored water and ambient air dry bulb/dew point temperatures for performance mapping. Ultra-low NOx performance will be demonstrated with simulated thermal loads. Cycling tests will be performed using extended draw sequences, varying the magnitude and clustering of hot-water draws per prior field observations. An optimized control strategy will be identified per cycling tests.

The project team will develop a final alpha SOA-GHPWH testing report, with improvements identified for design, integration, and controls based on test data and simplified simulation of GHPWH dynamics.

A manufactured cost estimate of the heat pump module will be developed and researchers will identify areas for cost reduction in subsequent efforts.

Results

In 2021, the project team continued to refine the product definition and consider codes/standards implications and controls specification options. In addition to defining the concept for the target application, the effort leveraged a parallel commercial HVAC effort using a hospital application to consider deep-dehumidification applications (defined as a separate sensible/latent air-conditioning version) and a compressor-less HVAC version.

The team finalized the design of the desorber, which included shifting the type of overall heat exchanger (HX) design. In addition to these desorber design exercises, the team continued to solicit and evaluate custom premix burner options in open-air testing from multiple burner manufacturing partners.

Final simulations of the desorber design were performed to screen for potential hot spots and other issues. A package of drawings was prepared, bids were secured from local fabricators, and a fabricator was selected.

The desorber setup and testing were completed (with a water boil test and using peanut oil to simulate ionic liquid). These tests yielded results that were used to calibrate parallel computational fluid dynamics (CFD) modeling and a general analytical approach to heat transfer estimated. Results from peanut oil were analyzed and extended to the ionic liquid. Finally, a Multiphysics CFD simulation was performed, where gas phase (flue gases) and shell-side fluid (peanut oil / ionic liquid) were combined for the first time.

Using the data collected, the local heat transfer coefficients were estimated using standard non-dimensional analysis yielding an estimated Nusselt number of 46.3 and HTC of 315 W/m2K, within a 5% error from experimental results.

Progress and results to date from this project were communicated in technical papers that were delivered at the 14th International Energy Agency (IEA) Heat Pump Conference held in May 2023 in Chicago, IL, USA.

Status

The research team completed testing of the desorber, and is preparing to report full desorber test results to UF and other project sponsors. The team will support subsequent analysis and testing on UF's side with updated desorber designs.

The team will also be working to develop a test plan and test rig design to test the 1,000 CFM prototype with UF.

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UTD Utilization Technology Development

Hydrogen Blending End-Use Performance and Safety Field Demonstration

Gas utility personnel and energy researchers are partnering to demonstrate the safety, technical, and performance implications of blending hydrogen into natural gas when used in fuel-fired equipment such as HVAC, water heating, cooking, and hearth products.

Project Description

Blending hydrogen into natural gas for use by existing gas appliances has the potential to reduce NOx and CO emissions into the home while also reducing carbon emissions (depending on the source of the hydrogen). This project seeks to demonstrate the safety and efficacy of a hydrogen/natural gas blend for a variety of end use products including HVAC, water heating, cooking, and hearth products. This project will test multiple retrofit and mitigation strategies. Efficacy will be measured by:

- End user safety and performance
- Estimates of decarbonizations potential
- Reductions of NOx and CO emissions

The results of this analysis will be packaged into best practices for field service technicians during utility blending programs. Outreach will be provided to builders, equipment manufacturers, and code authorities. Best practices will be issued for equipment commissioning for field installers/technicians during utility blending pilots. A methodology to estimate customer decarbonization potential in utility territories will be developed and implemented. Findings will be showcased with trade allies, builders, policy/standards, and other stakeholders.

Benefits / Market Implications

Hydrogen blending into gas grids for use in buildings and industry has distinct benefits:

- It can provide a significant decarbonization/energy storage "win" in the near-term
- This scale up of hydrogen demand further stimulates scale up of hydrogen supply and distribution technologies
- Low concentration hydrogen blending can be a stepping stone towards 100% hydrogen distribution, which can contribute to net zero emissions by 2050.

Hydrogen blending research is being conducted worldwide. Many utilities have recognized the benefit of adopting hydrogen into natural gas pipeline and, with significant efforts on their parts, have initiated hydrogen blending in the field. While other countries have embarked on hydrogen/natural gas blending pilots, such as in the UK, Germany, or the Netherlands, this is only recently happening in the US and Canada, leading governments and stakeholders to drive the development of safety/performance standards for gas-fired appliances, including the identification of suitable hydrogen limits on existing equipment.

This UTD demonstration project can, via outreach and expanding the dataset of operating existing/standard end use equipment on hydrogen blends, catalyze similar developments in the US/Canada while serving to address research gaps and develop best practices for in-field equipment commissioning in blending pilots.

Appliance Samples

Technical Concept and Approach

This effort will focus on assessing the impacts on common, building-owned end-use equipment that are lightly maintained (i.e., in residential or light commercial building applications). Broadly, this project concerns fuel-fired equipment that are inside of the scope of the EnergyStar® program specifications for residential and commercial-sized equipment. Physical testing will focus largely on residential-type equipment (see below), however decarbonization modeling, best practices development, and outreach will concern the full range of building-owned end use equipment.

This project will focus on existing equipment and addressing technical gaps in product development, field servicing, utility training, and stakeholder education, in order to: expand this emerging dataset for a wide range of equipment types at a controlled demonstration for short-term and long-term effects; support the momentum behind utility blending pilots with development of best practices and mitigation techniques; and engage a growing group of multiple stakeholders through in-person and media pathways (OEMs, builders/contractors, utilities, codes/standards bodies).

The hydrogen blending test site will occur at a utility-owned demonstration site located in the greater Las Vegas region.

Under this project, a proposed solar panel-coupled Polymer Exchange Membrane (PEM) electrolyzer with the hydrogen generation capacity of 2 kg/day is going to be adopted to generate and blend hydrogen into the natural gas system onsite. The field testing at the Southwest Gas demonstration site will select 30 representative appliances from the market to conduct hydrogen blending research.

Simulated Neighborhood at Demo Site

Equipment test rigs will identified for this project include:

- Four automated test stands will operate and collect long-term and short-term data from: central warm-air furnaces, wall furnaces, storage-type water heaters, and decorative gas appliances

- Four manual test stands will operate and collect short-term data only from: indoor cooking appliances, dryer/indoor hearth products, space heaters, and outdoor cooking/patio heating appliances

Results

The Blended Hydrogen Field Demonstration Plan was complete and socialized with Southwest Gas (host) and UNLV (partner). This plan would involve both short term (manually-operated) and long term (automated) testing of residential-type equipment with hydrogen blends.

The project team developed safety documentation in preparation for testing, including:

- Job Safety Analyses – Safety documentation for eight test stands, which included process & instrumentation diagrams (P&IDs). These were separately prepared and submitted for automated testing (unattended) and manual testing (attended).

- Manual Testing Protocols – in addition to the *Blended Hydrogen Field Demonstration Plan* which was previously developed and submitted, these protocols spell out how each manual (attended) test will be performed.

With the test rigs largely designed, the team has prepared 'bills of materials' for each rig and has identified prospective models for each of the 30 appliances to be tested. Once aforementioned documentation and agreements are complete, these will be acted upon with procurement in the next reporting period.

Status

The team is moving towards fabrication and deployment of test rigs with plans to initiate testing in early 2024. The project team has also coordinated with partner UNLV on test support and the installation/operation of the 2.2 kg/day hydrogen electrolyzer.

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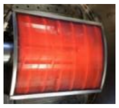
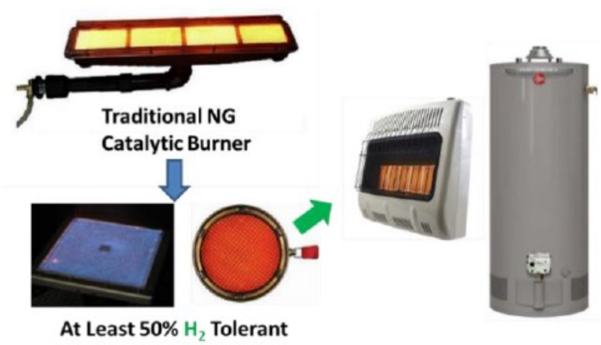
Fuel-flexible Ultra-Low NOx Catalytic Burners for ResCom Appliances



Researchers are developing, testing and demonstrating catalytic gas burners to use a blend of hydrogen and natural gas with up to 50% hydrogen, while achieving low NOx emissions. These advanced burners will enhance the safe, economical operation for end users and reduce GHG emissions by using fuels that contain more hydrogen.

Project Description

This project is developing and demonstrating fuel-flexible hydrogen-natural gas low-cost catalytic combustion gas burners for residential and light commercial applications that can accommodate up to 50% hydrogen while achieving NOx emissions superior to the current state of the art. Specific goals for this project are to demonstrate stable operation while accommodating fuel flexibility of at least 0-50% hydrogen, demonstrate at least sub 10 ppm @ 3% O2 NOx emissions, and quantify performance of the burner operating on different fuel blends.



Improved Catalytic Burners can provide Fuel-flexible Operation

Benefits / Market Implications

The primary target markets impacted will be residential gas water heating and furnace markets (over 61 million households in the US and Canada) and other domestic heaters with heating loads of less than 40,000 BTU/hr (outdoor heaters, etc.). Secondary target markets may include food service combustion equipment, including range top burners and ovens, and light industry heating devices.

Project success will have multiple benefits including:

Saving consumers money: Hydrogen-natural gas burners would expand customer's competitive choices of product offerings (including fuel options from natural gas to H2 blends).

Expanding fuel flexibility of domestic combustion appliances: Ensuring safe, reliable, and resilient operation of end user's equipment and energy delivery systems allows fuel flexible gas burners to come to market.

Achieving superior environmental performance:

- Reduction in GHG emissions beyond current Ultra-Low NOx domestic devices, including storage water heaters and furnaces, by adopting hydrogen in the pipeline natural gas.
- Reduction of NOx emissions under 10 ppm @3% O2, which meets SCAQMD's Rule 1121.
- Expansion of choices of product offerings that support Zero Net Energy (ZNE) buildings.
- Provide scientific data to assess IAQ impacts of adopting catalytic burners in domestic appliances.
- Expand the integration of natural gas with hydrogen/power-to-gas in domestic, commercial, and light industry applications.

Combustion applications are the major appliance types for domestic water and air heating. For example, 32% of the domestic natural gas in California is used for space heating and 59% for water heating. Currently, more than 80% of space heating appliances and more than 90% of water heaters in California are fueled with natural gas.

As decarbonization efforts across North America and Canada, adopting H2-tolerant burners with Ultra-Low NOx performance is of great interest to both gas consumers and utilities.

Adapting natural gas/propane catalytic burners to natural gas/hydrogen mixtures will assist energy transition to renewable hydrogen in residential and light commercial applications. A fuel flexible burner (up to at least 50% H2) which can accommodate varying fuel blends will aid the industry transition as the amount of hydrogen that can be manufactured and injected varies. Over 61 million households in the US and Canada would likely benefit from this alternative option of fuel flexible Ultra-Low NOx device. This project may also help launch a key new product supplier and thus expand consumer choices for Ultra-Low NOx combustion appliances. The research is also expected to help gas utilities achieve their Scope 3 GHG reduction goals, while manufacturers and consumers meet strict NO_x emission regulations (e.g., SCAQMD Rule 1121).

Technical Concept & Approach

This project is broken down into three sequential tasks.

Task 1: Investigate Prototype Burner H_2 Tolerance levels

Conduct tests on at least five current off-the-shelf catalytic burners on various H_2 blending levels to identify the tolerance levels of existing natural gas catalytic burners and examine combustion performance (NO_x, CO, THC emissions, efficiency, etc.).

Task 2: Optimize and Manufacture Prototype Burner

Down-select 2-3 of the most promising tested burners and work with manufacturers to evaluate potential burner redesign or optimization to better accommodate H_2. Manufacture and test the fuel-flexible burners (up to 50% H_2) to meet the sub 10 ppm @ 3% O_2 NO_x target.

Task 3: Adjust and Test the Prototype Burner in Simulated Appliances

Install one or more optimized burners into a storage water heater and a room furnace. Evaluate the appliance performance and conduct further optimization if necessary.

Example Catalytic Burner (Image Credit: Alzeta Corp.)

Example Catalytic Burner

Results

A literature review report of available burners was developed, and updates are being finalized. The review builds on previous studies and other research underway on catalytic burners. The project team has contacted multiple burner manufacturers to secure burners to conduct testing. Three catalytic burners have already been secured to conduct the Task 1 testing on various fuel blends.

Status

The project team is setting up the testing space in an industrial laboratory in order to conduct individual burner testing.

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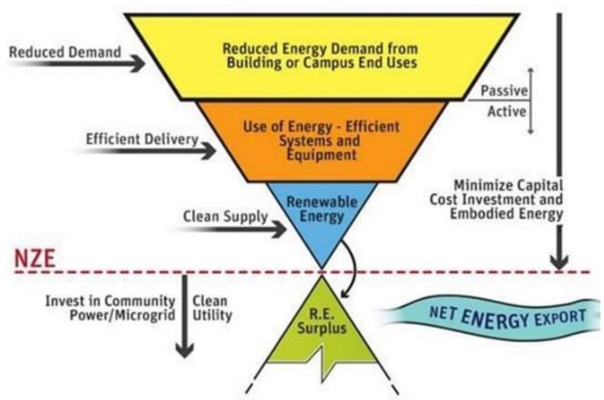
UTD Utilization Technology Development

Deep Energy Customized Affordable Retrofits of Building Envelopes and Mechanicals

Researchers are advancing technologies that can rapidly integrate highly innovative building envelope improvements with next-generation HVAC equipment retrofits to reduce GHG emissions by ≥50%, while providing significant operating cost savings for homeowners, multi-family residences, income-eligible housing, and others.

Project Description

While much greater use of renewable natural gas, hydrogen generated from renewable energy, and other initiatives are key methods to support decarbonization efforts, whole-building decarbonization approaches will be most impactful if they first reduce energy demand through improved passive building envelope measures, especially when coupled with very-high-efficiency next-generation mechanical systems to efficiently use and deliver energy through the building. The image below illustrates one recommended priority of efforts to decarbonize buildings.



Decarbonizing buildings for net zero energy (NZE) Source: Affiliated Engineers, Inc.

The goal of this project is to advance the development and rapid deployment of innovative residential building envelope improvements coupled with directly-integrated next generation, high-efficiency space conditioning equipment to reduce energy use. Improvements will be developed and demonstrated in the laboratory and in field installations using multiple innovative methods. UTD is partnering with a number of entities, including providing co-funding to prime-funded contracts from the New York State Energy Research and Development Authority (NYSERDA) and the State of Illinois Environmental Protection Agency (EPA).

Benefits / Market Implications

Successful commercialization and deployment of the technologies being developed in this UTD “DECARB-EM” project will have a transformative impact on residential energy use. Customers will realize significant cost savings by reducing energy use, while GHG emissions will also be significantly reduced.

The primary target markets impacted will be buildings such as: single-family residences, or low-rise multifamily (e.g. 3 floors), or mid/high-rise multifamily residences (e.g. >3 floors), or income-eligible affordable housing; located in cold climate applications (generally U.S. climate zones Zone 4 and above); using either hydronic and forced air HVAC, and; primarily built more than 20 years ago (since this is the largest building stock by far).

The target is to achieve a 50% reduction in GHG emissions, with significant operating cost savings through reduced loads, higher part-load efficiencies with next generation gas technologies. This project will also expand customer’s competitive choices of product offerings (including fuel options for decarbonization) while also addressing indoor air quality concerns by integrating mechanical ventilation into retrofits.

Technical Concept & Approach

First, laboratory testing will validate a novel distribution system for all heating, ventilation, and cooling designed for an exterior envelope retrofit panel being introduced by Hydronic Shell Technologies (HST). This technology provides ideal distribution for an air-to-water heat pump such as many gas-fired heat pump (GHP) systems, while addressing indoor air quality concerns by providing mechanical ventilation as part of exterior insulated panel retrofits.

Second, the NYSERDA-prime-funded effort will develop a process roadmap to streamline high performance retrofit panels, minimizing on-site disruption for any deep energy retrofits. Performing retrofits in an exterior-only manner that minimizes occupant disruption and eliminates relocation is critical for mass adoption. This UTD project will support that by maximizing offsite construction with digital support tools so that deep energy retrofits can be completed in days instead of weeks, at a more affordable cost. Monitored performance in the NYSERDA project and related efforts at other projects will demonstrate integrated improvements and provide validation.

Third, design guidance will be developed to provide gas-focused solutions that incorporate building envelope and mechanical technologies to deliver deep decarbonization objectives.

Point cloud image result from lidar scan of multi-family building

The following tasks will be performed to achieve the research objectives:

Task 1: Hydronic Shell Laboratory and Technoeconomic Analysis

Perform validation tests of heat transfer for the hydronic shell mechanical distribution system (hydrobox and radiant convectors only), and the system's ability to meet various loads and maintain comfort setpoints in the laboratory using environmental chambers. This will inform GHP design applications for building retrofits.

Task 2: Multifamily Deep Retrofit Mechanical Packages

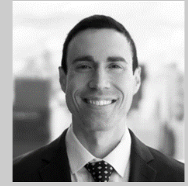
Identify centralized packages of mechanical system retrofits leveraging fuel-fired equipment such as GHPs and install one in conjunction with deep energy retrofits, and measure performance in a baseline year, post envelope year, and mechanical year. This will occur on a multifamily project with NYSERDA funding.

Task 3: Single-Family Deep Retrofit Mechanical Packages

Identify single family mechanical system retrofits to deploy fuel-fired equipment such as an advanced combi, hybrid system, or GHPs in deep energy retrofits, and measure performance in a baseline year, post envelope year, and mechanical year. This will occur on a single-family project with IL EPA funding.

Hydronic Shell envelope/mechanical panel

"UTD provided funding to build and test HST's first prototype panel at GTI Energy, validating our concept at a stage where our technology was too early even for most government grants. It's opened doors to new sources of funding and success in several prize competitions, totaling over $400,000 since testing at GTI began. We're now on a clear path to commercialization that's been enabled and accelerated by UTD's support."



– David Goldstein, Founder and CEO, Hydronic Shell Technologies (HST)

Task 4: Scaling Customized Retrofit Processes

Using findings from prior tasks and co-funded work from NYSERDA and others, develop improvements and identify ways to expedite customization timelines and minimize costs for deep energy retrofits in subsequent field tests which can demonstrate and optimize installation efficiency.

Results

Preliminary modeling on an existing 100-unit building in NY has shown over 70% GHG reductions when the hydronic shell is combined with gas heat pump technology. Results of UTD project 1.22.E were used by HST in its application and successful award in November 2023 to receive a $3 million grant from the Housing Affordability Breakthrough Challenge.

Status

In the current project period, the first stage of evaluation of the Hydrobox system was completed. Installation was completed of all system hardware components in an environmental chamber, along with a hydronic loop, testing and data collection equipment, and controls programming. Data recording has begun. Modeling was done to determine a way to construct a simulated "interior wall" to represent the existing building wall within the HST installation in the environmental chamber. The interior wall will be built and installed after initial heating data collection of the Hydrobox unit and radiant emitters. The team completed shakedown tests for chamber testing and started data collection and submitted abstract proposals to ResNet, ASHRAE, and PhiusCon.

The team also completed lidar scanning of a multi-family building façade for Task 2 as well as installed a tankless water heater that will be the base of a hybrid advanced combi in the single-family home for Task 3 including instrumentation for temperature and water consumption recording.

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UTD Utilization Technology Development

Safe Use of Hydrogen in Buildings

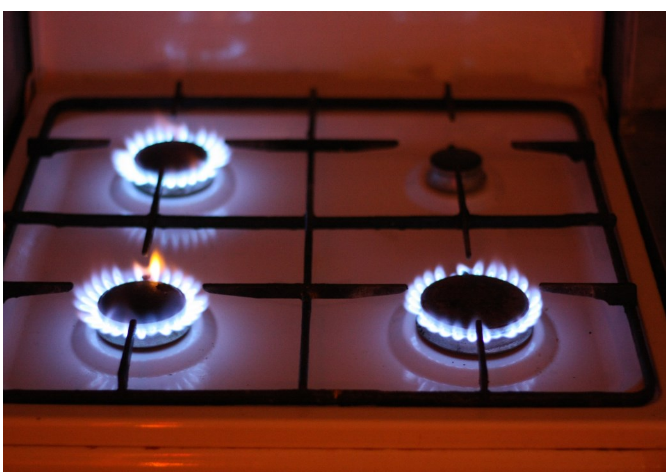
This project aims to address barriers for safe use of higher hydrogen blends (>30%) in residential and light commercial appliances such as hydrogen's potential propensity (in blends with natural gas) of leaking from existing building gas distribution systems and appliance gas handling subsystems, and potential detonation risks.

Project Description

Hydrogen, as a decarbonization means, offers only limited opportunity for GHG emissions reductions at low blends (e.g., up to 12% GHG emission reduction with 30% H2). The carbon reduction potential of hydrogen is reduced further if it is not generated from clean energy sources, if the appliance efficiency is reduced, or if its leak rate is significant in the existing gas infrastructure.

There are ongoing efforts in the industry and the academia to quantify preferential hydrogen leakage. Even if hydrogen blends up to 20-30% are permitted in buildings (currently it is not under NFPA 54), to achieve decarbonization goals of greater than 7-12% on the fuel side, higher concentrations of H2 will be needed. It is well understood that 100% H2 appliances and gas distribution systems need special design considerations and that appliances operating with low blends likely do not need many changes. However, the transition from where no changes are necessary to where significant changes are necessary is not well defined.

This project seeks to enable broad deployment of hydrogen-blended gas by proactively addressing consumer and regulator concerns about its safe use in buildings. To help achieve this, this project will characterize the propensity of hydrogen (in blends with natural gas) to preferentially leak from existing building gas distribution systems and appliance gas handling subsystems. Additionally, this project aims to address barriers for safe use of higher hydrogen blends (>30%) in Res/Com appliances.



A gas range is one appliance that has been shown to be susceptible to flashback and theoretical studies have raised a concern about detonation risk with blends above 45% H2 by volume

Benefits / Market Implications

This project will respond to growing interest and concerns about the use of hydrogen in buildings. With codes and standards revision efforts increasing to enable the safe use of hydrogen in buildings (e.g., CSA formed a committee to enable 100% hydrogen use in appliances), this project will provide timely information to help shape how hydrogen's use will be enabled or restricted in the near future.

The primary target markets impacted will be:

- Those served by low-pressure gas distribution systems (5 in wc – 2 psig), including low-rise residential, multi-family, and small commercial buildings.
- Appliances utilizing premixed combustion systems including gas heat pumps, mCHPs, tankless water heaters, condensing boilers, and ultralow NOx equipment.
- Hydronic and forced air installations.
- Gas-grid supply-constrained markets

Secondary target markets may include large commercial and industrial buildings served by high-pressure gas supply (>5 psig) and large commercial and industrial premix burners.

The development, distribution, and utilization of "Green" and "Blue" hydrogen, produced from clean power-to-gas and methane reformation with carbon capture schemes, respectively, is an important strategic area for society to meet ambitious long-term decarbonization goals.

To that end, society must look beyond small-scale hydrogen blending demonstrations (typically limited to 5-10% H2). However, the use of higher concentrations of hydrogen inside existing buildings and appliances comes with additional questions and concerns. To permit even up to 20% of hydrogen in buildings would require building code revisions (e.g., NFPA 54 – National Fuel Gas Code), and none of the current appliance standards under ANSI Z21 series consider hydrogen specific requirements. This project addresses some of the current knowledge gaps about hydrogen leakage from building gas distribution systems, appliances, as well as potential new requirements in appliance standards for certification for hydrogen operation.

Technical Concept & Approach

The project will investigate the propensity of hydrogen to preferentially leak from blended gas in low-pressure gas distribution systems and appliance gas line connections. Going beyond the distribution system, the study will investigate the potential and risks for leaks inside the appliances, which could pose special risk due to being enclosed and potentially exposed to high temperatures and sparks. In a parallel task, the project team will investigate increasing detonation risks as the level of hydrogen blend increases for use with Res/Com combustion systems.

This project is broken into two tasks:

Task 1: Res/Com Gas Line and Appliance Leakage Assessment

Develop a test plan and an experimental test rig to quantitatively assess the propensity of hydrogen to preferentially leak from building gas lines and appliances. Develop an interim summary of the findings and recommendations on the leak risks and mitigation strategies.

Task 2: Detonation Risk Assessment for Hydrogen-blended Gas

Develop an assessment of detonation risks with increasing hydrogen use in appliances, to be disseminated publicly through peer-reviewed publications.

Results

The research team completed a preliminary literature review on hydrogen-methane-air detonation characteristics with a focus on conditions relevant to the process industry, and conducted a literature review on hydrogen/natural gas mixture leakage research. The team also scouted a location for leakage testing, instrumentation and data acquisition equipment, and sensor products for testing. A test plan for Task 1 has also been completed.

Status

In preparation for testing later in 2023, the team is constructing the test apparatus for preferential leakage testing.

The team has also completed a preliminary literature review on detonation risks with hydrogen-natural gas blends. The team will compile some of the findings with a spreadsheet-based calculator to predict appliance operating conditions under which the risk of detonation increases.

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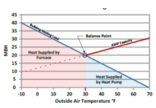
Utilization Technology Development

Hybrid Fuel-fired and Electric-driven Residential/ Commercial HVAC Systems



Researchers are studying emerging or commercially-available hybrid gas furnace/ electric heat pump products in the North American market, in order to evaluate promising hybrid systems and develop installation and operation guides that can help end users accelerate their integration of electricity derived from renewable energy with fuel-fired equipment.

Project Description

This project seeks to characterize the performance of hybrid gas furnace/electric heat pump products and quantify potential energy, operating cost, GHG savings, fuel versus electric space heating contributions, and potential user comfort issues in all seven Building America climate zones. This project will be done in three steps: 1) Conduct a thorough market assessment of emerging or commercially ready hybrid gas furnace/electric heat pump products in the North American market. 2) Select and evaluate three promising hybrid systems. 3) Develop and publish design, installation, and operational guidelines for clean, efficient, and cost-effective use of hybrid forced air heating systems in various climates.

UTD is partnering on this project with the Northwest Energy Efficiency Alliance (NEEA) and the Propane Education and Research Council (PERC), with both entities co-funding this UTD project.

Benefits / Market Implications

Hybrid fuel-fired and electric heat pump systems apply to residential and commercial applications, but the primary target markets impacted by this project will be single-family and multifamily residential new construction and retrofits.

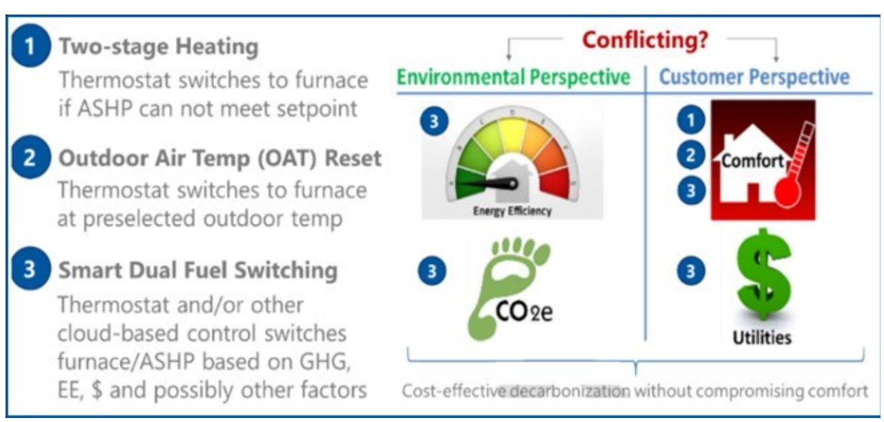
Previous UTD research characterizing the full performance spectrum of fuel-fired residential space heating systems as well as cold-climate and non-cold-climate electric-driven air source heat pump (ASHPs) indicates these systems, if properly integrated and controlled, can generate energy, cost, and GHG savings by 15% to 30%. More importantly, these savings can be realized now, with off-the-shelf equipment that gives customers choices in the fuels they use to heat their homes in a cost-effective, resilient, and environmentally responsible manner.

Driven by ambitious goals to decarbonize the power generation systems, electrification is an emerging trend to switch end-use equipment from non-electric to electric sources of energy. Such societal shifts toward decarbonization coupled with technological advancements and rapid R&D investments have contributed to an expanding North American electric ASHP market, one that may result in dramatic increases in building electric loads. Those loads, combined with the effects of a nascent electric vehicle market, may strain the North American power grid. For example, the 2021 Electrification Futures Study report published by the National Renewable Energy Laboratory (NREL) shows an extraordinary need for new installed power capacity in the U.S. given medium and high electrification load growth scenarios. In this report, new power capacity is predicted to be more than doubled by 2050; to primarily be met using intermittent PV and wind energy resources with very little storage capacity.

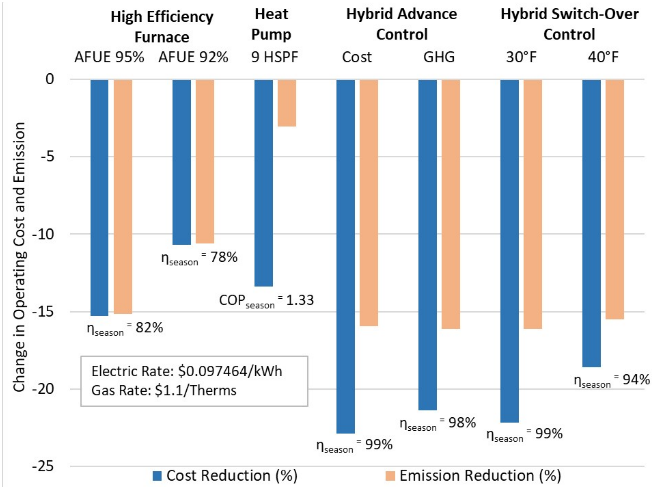
By employing hybrid systems, end users can maximize use of electricity derived from renewable energy while also leveraging the very large underground gas storage capacity in N.A. for peak day energy needs. Hybrid systems also permit end users operational flexibility and enhance operational resiliency.

Technical Concept & Approach

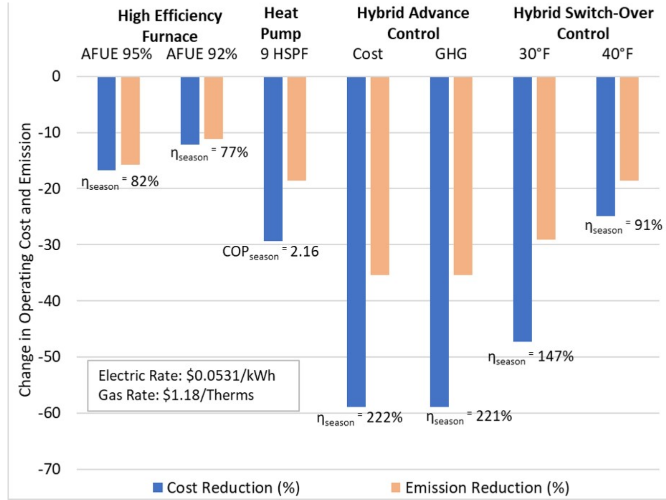
The project team will conduct a thorough market assessment of emerging or commercially ready hybrid furnace-heat pump products in the North American market. Some major manufactures such as Carrier, Daikin, Lennox and Rheem have developed packaged products that include a furnace, ASHP, A-coil and thermostat. However, hybrid systems can also be mix-and-match using a smart thermostat. Moreover, hybrid systems can integrate a cold-climate or non-cold-climate ASHP.



The hybrid control modes



Modeling result of 9 HSPF and 95% AFUE hybrid system compared with 80% AFUE furnace at Rochester, MN



Modeling result of 9 HSPF and 95% AFUE hybrid system compared with 80% AFUE furnace at Seattle, WA

The team will segment emerging and available hybrid products by these various categories. The team will then select three hybrid systems to evaluate in a laboratory. Laboratory research will focus on characterizing the hybrid systems' performance across a range of operating conditions using a lab-based Virtual Test Home methodology. Those performance characterizations will be built into energy modeling software to quantify potential energy, operating cost, and GHG savings. The models will also be used to understand and quantify fuel versus electric space heating contributions. The models will be configured in seven Building America climate zones and consider both natural gas and propane. Finally, the team will work to publish hybrid design, installation, and operating guidelines and disseminate the research material. The project is broken up into three tasks:

Task 1: Market Landscape

Conduct a thorough market assessment of emerging or commercially ready hybrid furnace-heat pump products in the North American market.

Task 2: Laboratory Evaluations

Select one single-manufacturer hybrid system with a non-cold-climate ASHP, one single-manufacturer hybrid system with a cold-climate ASHP, and one mix-and-match hybrid system (i.e. different component OEMs) with a cold-climate ASHP and a third-party smart thermostat. With the selected systems, perform laboratory evaluations and performance characterizations using a Virtual Test Home methodology and develop Energy Plus™ modules specific to the hybrid systems. Then model those systems for energy, operating cost, GHG and other parametric quantifications relative to local code-compliant equipment as well as equipment associated with electrification strategies.

"The annual GHG emissions, operating costs, and source energy consumption of hybrid heating systems will depend on the local climate, regional electric grid fuel mix, system control logic, peak demand periods, and other factors. This project will help the design and contractor community to manufacture and install economical, effective hybrid systems, while enhancing real-time control options for customers to reduce overall GHG emissions, operating costs, or source energy use."

- Thomas Manjarres
Technical Lead – Energy Efficiency Programs
Peoples Gas and North Shore Gas

Task 3: Design Guidelines

Based on the market landscape and laboratory research, the team will develop design guidelines for designing, installing, and operating hybrid systems efficiently and cost effectively.

Results

A market landscape of emerging or commercially ready hybrid gas furnace/electric heat pump products in the N.A. market has been created. A hybrid system has been identified and ordered. Testing infrastructure has been designed.

Status

The project team has finalized a market landscape, and is currently addressing comments and suggestions received from the project sponsors on it. The team has designed and built a thermostat environmental emulator for hybrid load-based testing. The team has obtain a representative hybrid system, built the testing infrastructure, developed a test plan, and will evaluate the hybrid system in the heating season of 2023/2024.

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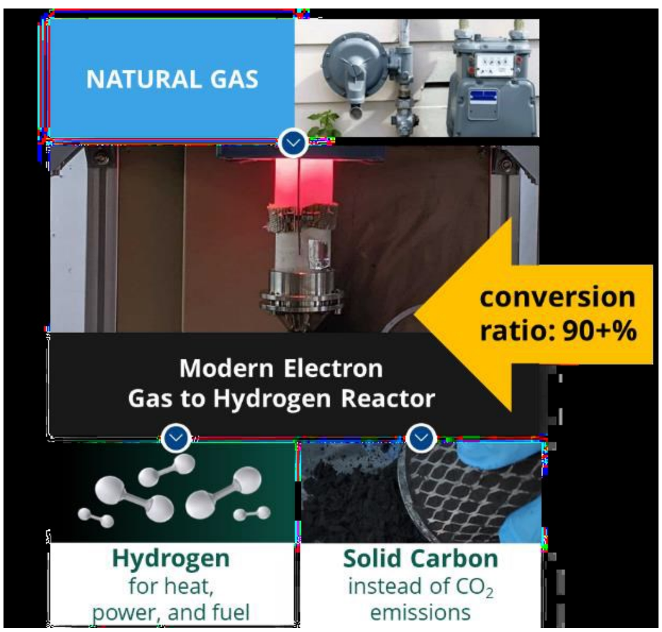
Utilization Technology Development

Emerging Distributed Methane Pyrolysis Technologies

Researchers are surveying emerging methane pyrolysis technologies to produce hydrogen ("turquoise" hydrogen), which allows siting hydrogen generation close to the point of use and potentially very cost-effectively for gas end users to decarbonize their operations.

Project Description

This project is classifying a range of emerging distributed methane pyrolysis solutions as good/better/best fit for gas ratepayers and consumers to decarbonize their operations, by combining application/process modeling with end user demand modeling and technology assessments. The research team initially conducted primary research via direct outreach to the leading technology developers in this space in order to create a landscape survey of options for distributed methane pyrolysis technologies. The survey included a techno-economic assessment (TEA) over a range of applications, with treatment of the underlying conversion process, hydrogen end uses, and handling of carbon outputs. Current efforts are expanding this analysis with additional direct outreach and refinement of the TEA.



Methane Pyrolysis Concept (Source: Modern Hydrogen)

Benefits / Market Implications

The primary target markets are to be determined but are likely to be quite cross-cutting. Initial applications could be commercial or industrial processes or boilers, where produced solid carbon may be readily collected.

With decarbonization pressures on utilities, their customers and society - - coupled with a wave of investments in technologies for hydrogen production, distribution, and use - - it is important to understand the advantages and disadvantages of different approaches for ratepayers to decarbonize their fuels. This need is further accelerated by incentives, such as the tax credits in the U.S. *Inflation Reduction Act (IRA)*, which provide significant tax credits for investments and production of low carbon hydrogen.

Different approaches to distributed methane pyrolysis will have a range of benefits depending on, among other aspects: the scale of their production (10 vs. 100 kg/day) and capacity factors, the ease of carbon utilization/disposal, process efficiency and emissions, and the avoided infrastructure modifications to reach the same overall decarbonization. This project directly addresses UTD goals to reduce GHG emissions while simultaneously accelerating the transition for hydrogen and also leveraging the existing natural gas delivery infrastructure.

Full decarbonization of utility customers, mitigating downstream GHG emissions, is primarily achieved through substitution of delivered natural gas with non-fossil gases, biomethane (RNG), hydrogen, and blends thereof. For instance, in a decarbonization pathways study for natural gas utilities which issued in February 2022, the American Gas Association (AGA) pointed to 59% of total decarbonization by 2050 in one scenario coming from renewable and low carbon gases.

The majority of hydrogen produced today is "gray", that is steam reformation of natural gas resulting in direct emissions of CO2. Some major emerging pathways are "blue" hydrogen, "gray" hydrogen with the addition of carbon capture and sequestration, and "green" hydrogen, hydrogen produced via electrolysis powered by renewable electricity. This research project focuses on "turquoise" hydrogen, a blend of blue and green, which is driven by methane pyrolysis.

Turquoise hydrogen has the distinct advantages over green and blue pathways by a) using a much lower cost feedstock (methane vs. water & electricity) and b) providing an ease of carbon capture via solid carbon, which is approximately 1,000 times denser than atmospheric CO2, sequestering

"Low carbon hydrogen will play an important role in reducing the GHG emissions through deployment in heating, industrial and transportation applications to achieve a sustainable clean energy future. Methane pyrolysis offers a unique opportunity to produce hydrogen by using natural gas as a low-cost feedstock and leveraging existing natural gas distribution infrastructure. We're very pleased to support this project to help increase the awareness of this innovative hydrogen production technology, that could lead to scaling up of this technology."

- Aqeel Zaidi
Manager, Technology Development
Enbridge Gas Inc.

nearly 4,000 times as much carbon. For these reasons, turquoise hydrogen production can be physically closer to the point of natural gas use and can leverage existing gas distribution infrastructure. This has the potential to avoid much of the infrastructure mitigations to accommodate hydrogen-based fuels by utilities, by using methane as a valuable feedstock or providing relative ease of carbon sequestration.

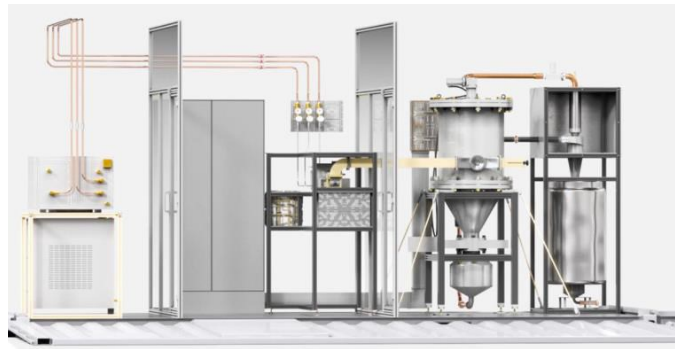
With these advantages in mind, there are a) estimates that turquoise hydrogen will provide more environmental benefits at a lower cost than green or blue pathways and b) that the captured carbon may provide useful revenue streams. This project explores this potential with a techno-economic assessment, while grounding the analysis in technologies currently under development and with considerations of a range of use cases.

Technical Concept & Approach

The project team initially began application/process modeling by defining the approach up through developing a final system modeling plan, to couple with end user demand modeling and identified a range of distributed methane pyrolysis solutions (good/better/best).

This project performed a) a thorough modeling assessment of methane pyrolysis options with application considerations, b) provided analytical feedback to UTD members and select methane pyrolysis partners, c) provided a summary of R&D gaps for methane pyrolysis solutions – conversion technology and carbon handling, and d) a pre-feasibility analysis for a prospective demonstration. This was focused on the five or more application scenarios (e.g. boiler for space heating or industrial drying process) and five or more carbon output scenarios (e.g. disposal to soil, or as feedstock) identified in Phase 1, as reported in Q3-23.

Phase 1 results of this analysis will be used to refine the TEA to update assumptions based on both modeling results and any new information gathered. The project team will also collect data and information from industry scale-up efforts, as experimental and pilot-scale efforts are underway in a range of applications, providing this summary along with modeling results and recommended next steps.



Rendering of the Levidian LOOP Skid – Microwave-Assisted Pyrolysis with Graphene Outputs (Source: Levidian)

Results

The team held information interviews with leading methane pyrolysis technology developers such as Levidian (UK), Molten Industries (US), Modern Hydrogen (US), H Quest (US), and Hago Energetics (US). These developers cover a wide range of pathways ranging from high-temperature thermal conversion (Modern Hydrogen) to use of biogenic catalysts (Hago Energetics), additional level of maturity varies where some are at the bench/lab-scale (Molten) while others have one or more demonstrations active with partners (Levidian).

Status

The project team completed it's initial outreach and engagement with pyrolysis technology developers. Informational interviews were held with Levidian (UK), Molten Industries (US), Modern Hydrogen (US), H Quest (US), Ekona Power (US), Hago Energetics (US) and others. A Final Report for Phase 1 issued in August 2023, and an informational webinar was provided to UTD members in September 2023. Current activities underway in Phase 2 are to perform additional direct outreach to methane pyrolysis technology developers, and further refine the TEA, in order to identify superior opportunities to advance these technologies in end use applications.

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UTD Utilization Technology Development

Triathlon™ 2030 Five-ton Cold Climate Gas Heat Pump

Researchers assisted in developing the prototype design of a new five-ton natural gas engine-driven cold-climate gas heat pump (GHP), which could provide high-efficiency water heating, space conditioning, power generation, and off-grid operation in one unit.

Project Description

Over the last 20 years, there have been several advances in gas-engine heat pump (GHP) design and components, including controls, condensing coils, refrigerants, motors, and fans. This combination of new developments with a proven, high-reliability/low-emission engine provides a low-risk path to developing a high-performance, low-cost heat-pump design.

This effort built on prior five-ton GHP designs first developed in 1995 that used off-the-shelf components, leaving much room for incremental improvement. The most recent design was built and tested in 2015 and optimized for the hot, dry climate of the southwestern U.S. (e.g., Nevada and Arizona). The project achieved its goals for combined water heating, space conditioning, power generation, and off-grid operation: 1.2 cooling Coefficient of Performance (COP); 1.5 heating COP; 80% primary energy savings for water heating; and a five-year payback based on $8,000 product cost and at 1,000 units/year production volume.

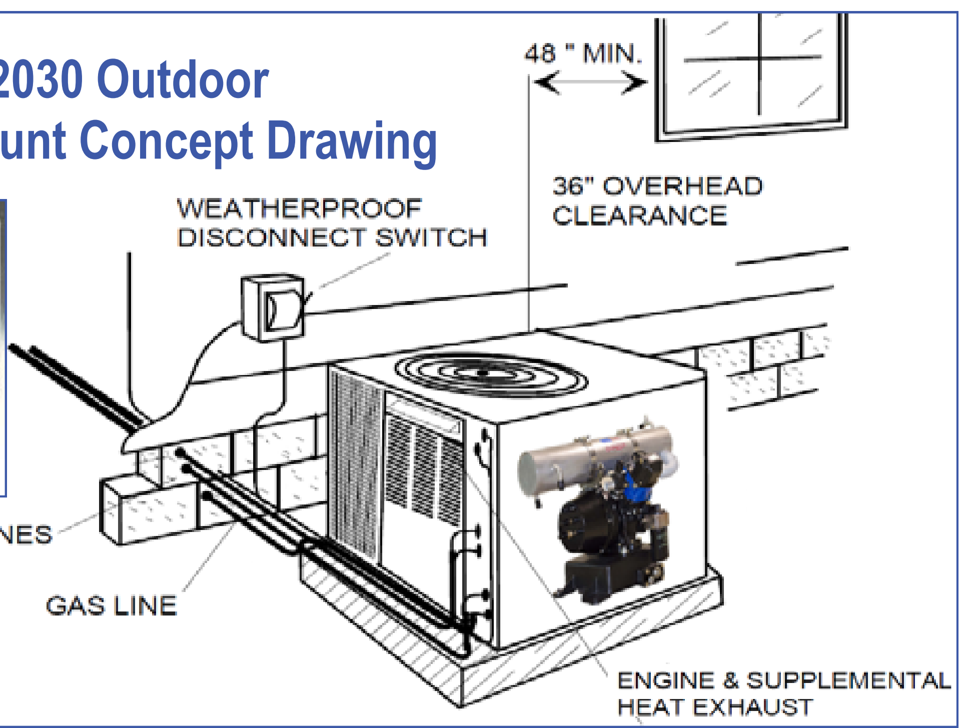
The objective for this current project was to assist in developing and testing a new five-ton natural gas-engine-driven cold-climate heat pump prototype. By providing technical support, UTD researchers supported the efforts of a project sponsored by the New York State Energy and Research Development Authority (NYSERDA) led by Syracuse Center of Excellence at Syracuse University.

Targets of the NYSERDA NextGen HVAC Challenge include lowering energy source consumption compared to current baseline technology, lowering greenhouse-gas emission levels compared to current baseline technology, providing clear peak-demand reduction compared to current baseline technology, and achieving average annual COP >2.0 with emphasis on cold-climate heating capacity and efficiency, with initial product cost targets of <$5,000 per unit based on a production volume of 500 units/year.

Benefits / Market Implications

This GHP can provide the following benefits:

- Achieve high heating efficiency and the ability to operate at significantly lower outside temperatures than electric heat pumps



Triathlon heat pump in 1995.

"A new five-ton natural-gas-engine-driven cold-climate heat pump prototype can meet New York State Energy and Research Development Authority (NYSERDA) NextGen HVAC Challenge as a cost-effective and energy-resilient option to reduce greenhouse-gas emission levels and reduce peak electric demand when compared to current baseline technology. We thank NYSERDA and UTD for supporting the development of this innovative technology, which when commercialized could serve many homes and small businesses across North America."

- James C. Green
President & CEO
Axiom Energy Group

- Expand customers' competitive choices of product offerings and fuel options
- Reduce electrical energy and peak demand for end users
- Improve the use and resilience of the power grid
- Defer investments to increase grid capacity, and
- Avoid rate increases associated with capital projects to increase power grid capacity.

Technical Concept & Approach

This UTD project provided cost share for the Feasibility Stage which the included the development of a prototype design and to model its performance, reliability, serviceability, and cost targets. The Triathlon 2030 design goal focused on space heating and cooling applied to small commercial building load profiles, such as offices, lodging, restaurants, fitness centers, health care, box retail, strip malls, light commercial, and educational facilities.

The Triathlon 2030 was designed to be a reliable, drop-in replacement with a similar footprint to conventional five-ton rooftop units. The major technical design challenge was to redesign and improve engine heat recovery for cold-climate operation. The multifunction power-generation and water-heating capability incorporated in the GHP design will be eliminated to reduce both manufactured and installed cost.

Following the successful proof of concept, NYSERDA had a Go/No-Go option to fund the prototype breadboard development for laboratory testing. Potential follow-on efforts included the prototype development and commercialization, followed by demonstration of four commercialized units. The NYSERDA-funded project team developed energy and economic system models to forecast simple payback, life-cycle costs, utility avoided cost value, source energy savings, and reduced greenhouse gas emissions. The project team also analyzed the New York State Value Proposition to meet NYSERDA goals.

A follow-on modeling study evaluated the impact of eight hybrid gas/electric configurations integrating an electric cold climate air source heat pump (ccASHP) with various forms of gas-fired auxiliary or supplemental heating. The supplemental heating methods included electric resistance heating, a gas furnace, or a compact combined heat and power (CHP) unit.

Results

In Phase 1, the project team developed the modeling approach for the preliminary energy and economic assessment of the five-ton Triathlon 2030 GHP design. Three building types (small office, strip mall, and full-service restaurant) were selected to represent the best applications for a light-commercial five-ton GHP split system. Actual weather data was used for three locations (New York City, Buffalo, and Binghamton). Detailed electric and gas utility rates for each location were updated.

Researchers created Energy Plus™ models to compare energy costs and full-fuel-cycle greenhouse gas emissions between the GHP prototype design and conventional equipment, while considering the current and future power-generation mix and natural gas supply.

Based on modeled results, the Triathlon 2030 GHP concept design met the NYSERDA NextGen HVAC Challenge targets in some cases. As expected, it consistently reduced peak electric demand compared to baseline technologies. In high heating load applications, the GHP high heating efficiency reduced annual source energy consumption along with GHG emissions, but did not reduce GHG emissions at some target NYS applications. With the current configuration, excluding water heating or power generation options, the design was unable to exceed an annual COP >2.0. Without utility incentives, the design will not be able to achieve the three-year payback target.

Of the follow-on models which the team developed for a hybrid heat pump design, the addition of a CHP unit resulted in only slight changes in energy costs or GHG emissions. A hybrid ccASHP/CHP design would not be cost-effective based on energy savings alone, and would require utility incentives for economic viability, as well as the availability of the utility natural gas.

Status

The project is complete and a final report has been issued to UTD members. Further development of this heat pump may occur as additional funding sources are identified.

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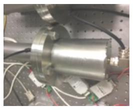
LARGE COMMERCIAL AND INDUSTRIAL, INCLUDING CHP

Field Evaluation of Gas-Quality Sensor



Field evaluations were conducted to demonstrate a new, reliable, low-cost gas-quality sensor that can detect changes in gas quality (heating value, hydrocarbon, and CO_2 concentrations) in real time and provide valuable data to operators and end users.

Project Description

Natural gas is priced by total energy delivered (in Btus or therms). However, Btu content cannot be easily measured, so a common practice is to measure the volumetric flow rate at the point of use, and to determine total energy used by multiplying this number by the average energy content (Btu per standard cubic foot) measured at a central location. While this approach is economical and recognized as sufficiently accurate for billing residential, commercial, and most industrial customers, there are industrial combustion processes (e.g., processes for glass and fertilizer production) and power-generation equipment (e.g., dry low-NO_x gas turbines and lean-burn internal combustion engines) that have stricter limits on gas quality and composition.

Some large-volume end-user applications have in-line equipment to continuously monitor gas quality to obtain measurements that can be readily converted to heating value, methane number, or Wobbe Index. The introduction of shale gas and upgraded biogas from anaerobic digesters into the gas-transmission network is increasing the importance of more accurately and more regularly measuring the heating value of the gas for many of these large-volume customers.

The most common equipment used today for continuously measuring natural gas heating value is the gas chromatograph (GC). Although GCs provide accurate Btu values based on direct measurements and compositional data, they have several drawbacks, including:

- Long response times (often four minutes or more)
- High capital costs (in excess of $20,000), and
- Regular calibration required (a recurring operating cost).

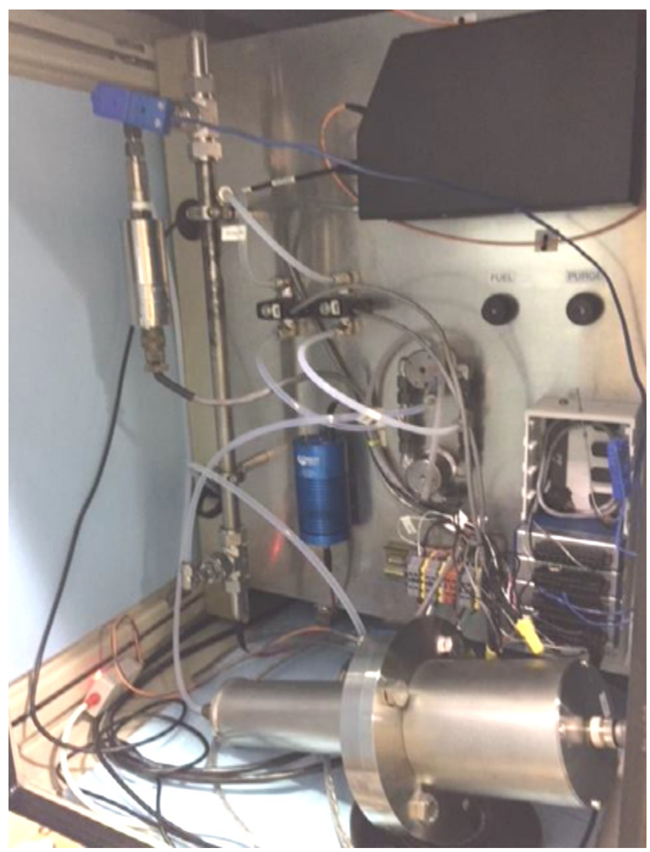
To address the issue, researchers developed and extensively tested in a laboratory a heating-value sensor on natural gas, biogas, and producer gas. The sensor is significantly lower in cost than gas chromatographs and will address other limitations of the GC.

The objective of this project is to continue to develop and demonstrate in actual field-operating conditions a practical, reliable, and low-cost gas-quality sensor (GQS) that can detect changes in gas quality (e.g., heating value, hydrocarbons, and carbon-dioxide concentrations) in real time and provide this data to natural gas pipeline operators, local distribution companies, and end users of natural gas.

The technology development that was advanced in laboratory testing and field demonstrations in this project supported the commercial introduction of the NIRIS NG GQS sensor by licensee CMR Group in 2019. The most recent phase of this project is exploring if the GQS can also measure hydrogen content in natural gas.

Benefits / Market Implications

Gas distribution companies and large-volume gas consumers that are sensitive to variations in gas quality will benefit from the faster, lower-cost new Btu sensor. Industrial customers can operate equipment more efficiently with lower emissions when real-time fuel heating-value data are available. Operators of natural-gas-fueled turbines and internal combustion engines can have enhanced control of equipment performance and protection.



The GQS in laboratory testing prior to the shipment to the field-test site.

Specific advantages of the GQS include:

- The sensor needs to be calibrated just once for the application
- Simple to use; no special training is needed
- Measurements can be taken at high gas pressures
- Measurements can be taken continuously, allowing trending and controls operation, and
- In-line configurations are possible.

Technical Concept & Approach

The GQS uses the infrared light-absorption properties of hydrocarbon gases to measure the Btu content and composition of a natural gas mixture. It has been shown that this sensor technology can be used to measure the air/fuel ratio in air/hydrocarbon gas mixtures delivered to combustion equipment. The accuracy of heating-value measurements made by this new instrument can closely match those of a GC, but at a much lower cost.

Technicians prepared, calibrated, and installed a GQS prototype at a utility site in Tulsa, OK, to monitor the heating value and composition of natural gas for 12 months.

GQS measurements were conducted side-by-side with a gas chromatograph to verify accuracy of the GQS measurements. The gas-quality data can be provided to the pipeline operators and/or end users in real time.

The project team will provide support to the licensee of the GQS technology as production gas-quality sensors move through customer testing and will assess the capability of the GQS to also measure hydrogen content.

Results

Early project activities involved modifying software so that a new spectrometer could be integrated with the concentration determining algorithms. The new spectrometer was capable of reading high wavelength data and therefore was expected to be able to collect carbon dioxide data directly. Software was modified to collect and process this data.

Changes were needed to meet the requirements established by the demonstration site. The project team used a mobile hot spot to collect and transmit data during the demonstration period. Communications with the computer were carried out through an Ethernet cable using the available port on the enclosure.

An experimental apparatus was used to calibrate and test the GQS after upgrades and modifications. In 2017, testing of beta prototypes was performed using 12 gas mixtures with compositions covering the range of anticipated real-world biogas and natural gas. Calibration testing of 10 new prototype sensors from CMR was conducted in 2019.

GQS developments also included:

- The new spectrometer can read high wavelength data and, therefore, collect carbon dioxide data directly. Software was modified to collect and process this data.
- Details of the dimensions, utility requirements, and other aspects of the enclosure (inlet and outlet ports, temperature range, etc.) to hold the GQS for demonstration testing were made.
- The team completed assembling the GQS inside the enclosure. Two sensors were installed. One sensor followed a prototype design using a spectrometer and the other sensor is a commercial prototype built by the commercializing partner and using an interferometer.
- All sensors were installed in enclosures and prepared for testing per safety requirements of the host site.

The project team transferred several beta prototype sensors back to CMR. One sensor was transferred to a U.S. engine company for validation testing. Two sensors were returned to CMR in France so they could be sent to companies carrying out validation testing in real-world conditions.

Data from a demonstration test in Tulsa was retrieved, processed, and shared with CMR. The data showed more scatter than anticipated, which appeared to be a result of temperature variations during the demonstration period. Efforts were made to apply a temperature correction.

Status

Final Reports for Phases 1 and 2 of this project were issued to UTD members in 2021 and 2023.

Phase 3 efforts to investigate adding more capabilities to the GQS are currently underway. CMR will provide the latest version of its GQS unit to the project team for additional testing, including when measuring hydrogen content in gas streams. The project team is currently awaiting this delivery.

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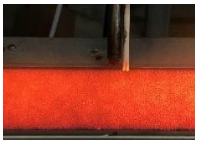
Next Generation Infrared Burner



Researchers are designing, building, and testing prototype high-performance, low-emission gas-fired infrared burners that use an advanced metal foam material to offer end users new high-efficiency products. The project team is collaborating with material and burner manufacturers. Field testing at a host site and durability testing at a laboratory is in progress.

Project Description

Using gas-fired infrared (IR) heaters instead of electric-driven IR heaters can significantly reduce both source-energy emissions and end users' operating costs. The goal of this project is to build on earlier developments to advance a gas-fired IR burner for commercial and industrial use.

Unlike conduction or convection, IR heating transfers heat through electromagnetic radiation (light). As IR light is absorbed by the load material, its surface is heated. This surface-heating phenomenon can be highly efficient by avoiding the unnecessary thermal load of heating surrounding air.

In this project, researchers investigated advanced metal foam IR burners, with better material properties. In the current phase of the project, the research team will design, build, and test in the field a prototype next-generation, high-response, higher-efficiency IR burner.

Benefits / Market Implications

Currently, nearly 75% of the IR-heater market in commercial and industrial applications is occupied by electric units. Development of an advanced gas-fired IR burner that can meet market specifications will increase customer choice and save energy on a source basis in most locales.

Technical Concept & Approach

Specific tasks included:

- **Burner Design**

  The project team designed a laboratory-sized 35,000 Btu/hr burner with sensors, control, and valves with advanced material. This unit has broad flexibility and is well instrumented so a wide range of parametric tests can be conducted and data used to optimize design and operating conditions.

- **Laboratory Testing**

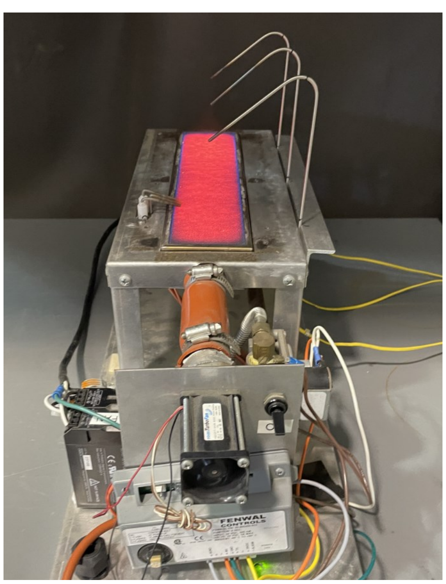
  A range of IR burner tests were conducted to demonstrate safe and stable operation, collect valuable data for burner optimization, and investigate the effect of all independent variables on the performance of the advance IR burner.

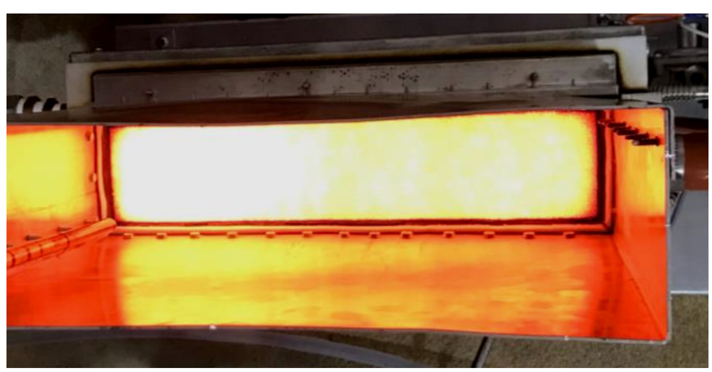
- **Field Test**

  Initial prototypes of a commercially-made product will be tested at a host site.

Results

Researchers selected and tested multiple commercial IR burners to evaluate operational and emissions performance. Different materials and original equipment manufacturers (OEMs) were chosen for the testing to provide a spectrum of performance data. The key performance indicators for the burner testing were to successfully achieve target goals for



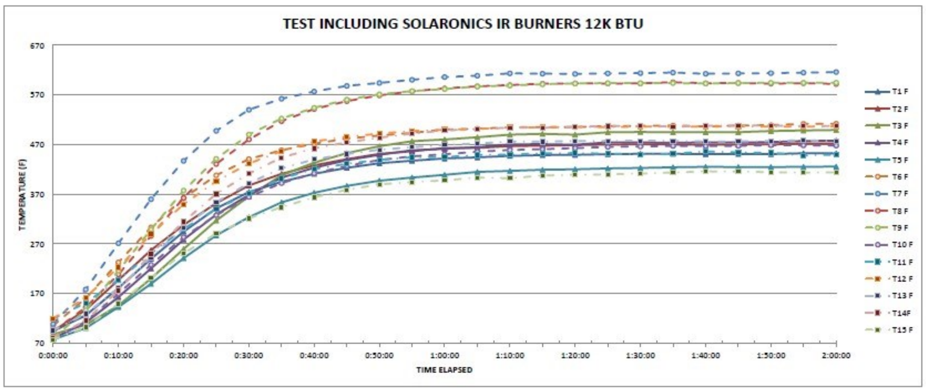


Laboratory testing.

turndown, emissions, start-up and shutdown characteristics, and temperature uniformity.

Testing showed the advantages and key limitations of these burners. The high-throughput burners could provide high output; however, these led to high emissions and potential material degradation. Burner materials such as ceramics led to cracking due to thermal cycling and were difficult to form into different shapes. Other materials such as metal fibers lead to non-uniform mixing, non-uniform temperature profiles, and loss of fiber material due to high-temperature zones.

Metal foam materials testing showed promise in certain aspects, such as adapting to different shapes and layouts, more robust design, and improved thermal cycling characteristics. This material showed the potential to replace a majority of the materials and be able to provide a long-term solution to gas-fired IR.



Emissions and performance testing showed that the non-uniform mixing and high local temperatures led to increased NO_x emissions (>20 ppm @ 3% O2). In addition, the start-up time for a gas-fired IR was high (>7 seconds) with burner material choice making a significant impact.

In 2019, emissions and temperature measurement testing were conducted at different axial locations from the burner surface. A report was issued in July 2019 that summarizes the differences in burner configurations tested.

In 2020, researchers teamed with a burner manufacturer and an advanced material manufacturer to resolve key issues to move the technology to the market. Emissions and temperature-measurement testing were performed at different axial and longitudinal locations from the burner surface. Test hardware was fabricated to reduce air entrainment and provide more data for comparison with previous data.

Burner assembly with multiple IR burners designed for host site.

"This project is evaluating advanced materials for improved performance, increase efficiency, and durability. It is critical to evaluate these materials."

- Tom Martelle
Chief Engineer
Solaronics, Inc.

In 2021, the project team conducted performance mapping of the burner at different axial and radial locations. Testing showed that emissions were below 20 ppm for NOx and CO dropped below 10 ppm, both corrected to 3% oxygen, from about six inches from the surface of the burner. In addition, improvements to the uniformity of the temperature and the oxygen concentration at a given plane (nine inches from surface of burner) were sought. A host site for a demonstration was identified and design criteria for testing was evaluated. A set of prototype burners was fabricated, assembled, and tested at a host site.

In 2022, heat-flux measurements were performed for the different conditions and were compared with the performance of traditional IR burners. The measurements showed this IR burner was in the similar range (8 to 10 Btu/ft2-s) compared to other industrial burner systems in terms of heat released.

In 2023, Solaronics and one of its customers are testing a pre-production version of the new burner at a host site in California and have collected preliminary test results. Simultaneously, durability testing at an industrial laboratory is in progress for multiple hundreds of hours to further evaluate the market-readiness of the material and burner unit. The project team is also setting up laboratory tests to fire hydrogen and has ordered instrumentation and controls to support that effort.

Status

The final report for Phase 2 was released to UTD members.

The project team is continuing to test pre-production versions of the burner made by Solaronics and is separately working to setup laboratory tests to assess how the burner operates when using hydrogen-enriched natural gas.

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UTD
Utilization Technology Development

Recovery of Water from Humid Exhaust Gas to Save Water and Energy

In a field demonstration at a large industrial facility in California, researchers applied a novel new thermal ejector technology using heat pipes to recover useful process water from humid exhaust gas, which in turn can increase overall efficiency.

Project Description

Industries that use large volumes of water to cool natural-gas-fired furnaces could save energy and money if water from hot exhaust gases can be economically recovered and returned to the plant for cooling and other uses. For this project, a research team demonstrated an innovative self-regulated ejector cooling system that generates colder water at a manufacturing plant, which, in turn, can increase overall efficiency.

This effort was conducted in collaboration with the California Energy Commission (CEC) and a leading U.S. drywall manufacturer. UTD provided co-funding to the prime funding provided by CEC.

The thermal ejector technology using heat pipes demonstrated is the first practical technology that can recover room-temperature water that can immediately be returned to a plant and used for process cooling.

Benefits / Market Implications

Operators of drying, curing, commercial cooking, and other agricultural and industrial processes with humid exhaust gases are strongly positioned to realize large benefits from this thermal ejector technology. This technology offers the opportunity to reduce the huge water demand at power plants. Overall, freshwater savings are estimated at one billion gallons per year in California if deployed for example on 50% of applicable industrial and commercial furnaces. Some sites can also save significant amounts of natural gas when warm water produced by a unit displaces ambient temperature waster supplies. Carbon dioxide emissions would also decrease at sites where recovered warm water reduces natural gas demand.

Technical Concept & Approach

For this project, a demonstration of thermal ejector technology with heat pipes was conducted at a major industrial host site in California. The project team attached a demonstration-scale unit to the humid exhaust gas of equipment at the manufacturing facility and recovered water from a portion of that exhaust gas. The demonstration system is based on the laboratory-tested prototype but has production capacity of 700 lb of water per hour (~82 gallons/hour).

Using the remaining thermal energy in the humid exhaust gas from the facility's drying kiln helps to conserve water and enable the plant to receive an added benefit from the same natural gas already being burned in the kiln, thereby also conserving natural gas.

Project work began with modeling and design of the demonstration unit. The unit was designed to recover water from 1 to 2% of the kiln exhaust gas. After modeling and design calculations, a skid-mounted system was designed.

Demonstration testing was carried out over a period of six months. A full set of performance data was collected. The project team developed a technology transfer strategy, including a product-readiness plan.

California host site facility.

Results

The host site provided exhaust gas data for a furnace similar to the one to be used for the demonstration. This data confirmed the anticipated range of exhaust-gas compositions, including water content, to be expected. Additional research focused on modifying and simplifying the demonstration system design. The final system design has one quarter the footprint of the first system design and is much more conducive for further scale-up. In the final system design, no external water is required and the power demand was greatly reduced. Components are reasonable in size because there are no gas -to-gas heat exchangers in the system. In the final design, power demand was also greatly reduced.

The water content in the 256ºF exhaust gas is 43 volume percent (32 weight percent). While the project goal was to demonstrate nominal water recovery of 100 gallons per hour, the amount of water recovered depends on ambient air temperature which changes from day to night and around the year. Measured results averaged 82 gal/h of water recovered. Review of historical weather data showed that although temperature can reach 117ºF on summer days, the average year-round temperature is 73ºF. This data was used to design a demonstration unit producing 82 gallons per hour of water at 73ºF. Water recovery will be lower at higher ambient air temperatures.

A refrigerant recirculates in closed heat pipes to cool the flue gas and to carry the heat up to an upper chamber where it condenses and returns to the lower chamber to recover more heat. Ambient air moved by low-pressure-drop fans is used to extract heat from the refrigerant into the environment. The external power needed is for two water pumps, two ambient air fans, the flue gas blower, valves, and controls.

In 2021, the skid framework and electrical boxes were completed and all components were installed on the skid frame. Wiring and sensors were installed and checked for proper installation and accuracy. The skid was finished, moved to the host site, and connected to the exhaust duct with mechanical and electrical connections. Startup in fully-automated operation was initiated in April 2021.

Automated operation and data collection worked well through the demonstration period. Results confirmed an average water-recovery rate of 83 gallons per hour.

An analysis was made of the full cost of designing and building the demonstration unit used to collect an average of 80+ gallons of water per hour. The total cost of labor and materials was $566,000. A review of this found that careful planning, purchase of low-cost components, and less engineering for the next system of the same size would lead to a cost of $266,000. Over a five-year period, a system of this size would be expected to recover approximately 2.5 million gallons of water. Therefore, the capital cost would be $100 per 1,000 gallons of water. Natural gas savings would lower this to a net cost of $80 per 1,000 gallons of recovered water. Current water costs in the U.S. range from $6 to $20 per 1,000 gallons and are expected to double in the next decade to an average of $30 per 1,000 gallons. This analysis provides guidance on what is needed to lower the cost of the technology.

On an energy basis, the recovery of water at temperatures below 60oF is more than break even. That confirms that lowering the capital cost is key to commercial success. The most expensive component is the heat exchangers.

Status

Both UTD projects are complete. Final reports for UTD projects 2.17.A and 2.20.D were issued to UTD members in May 2023 and July 2023, respectively. A draft Final Report was also submitted to CEC, and CEC will publish the Final Report after it completes its review.

Next steps to promote large-scale commercialization of the technology are being evaluated, and interested end users can contact UTD directly. Results of modeling performed under UTD 2.20.D indicated that a scale-up of the field demonstration unit by at least 10:1 in capacity will likely be needed for the technology to be economically attractive for commercial-scale applications in one key industry application evaluated.

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High-Efficiency Thermo-Vacuum Commercial Clothes Dryer

Researchers are developing and demonstrating at laboratory scale an advanced prototype gas-fired commercial clothes dryer. The technology has the potential to save at least 50% of the energy used in the commercial laundry sector, while also reducing drying time and water consumption.

Project Description

The most common commercial clothes-drying method uses a combination of electrically-driven centrifuge coupled with moisture evaporation by heated air. Research suggests that integrating a thermal-driven ejector vacuum system into a commercial dryer can provide significant performance improvements along with substantial fuel savings and reduced water consumption.

The goals of this project are to develop an advanced clothes dryer concept and demonstrate the technical and economic benefits of an innovative ejector-based technology that can minimize heat losses and accelerate the drying process due to the simultaneous thermal and vacuum effect on moisture removal from the capillary fibers of the laundry being dried.

UTD is partnering with the U.S. Department of Energy (DOE) on this technology development by providing co-funding to a major prime contract award from DOE.

Benefits / Market Implications

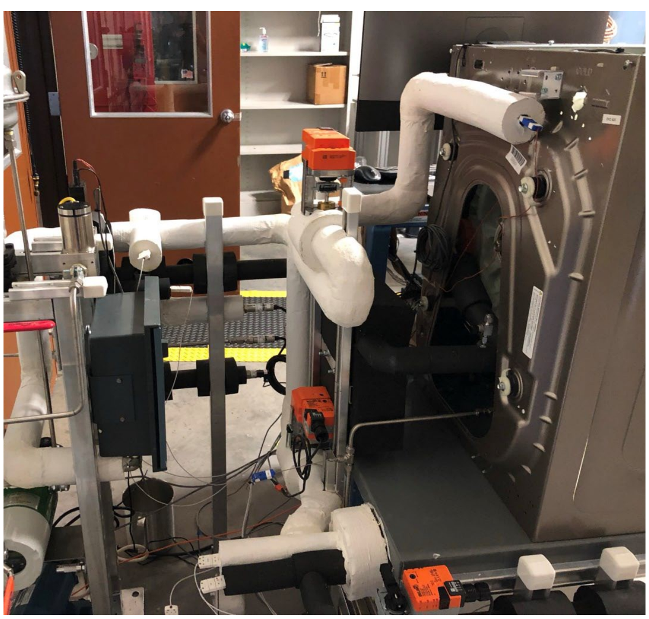
The technology being developed in this project is expected to have the potential to save at least 50% of the energy used for commercial clothes drying, due to its unique approach to integrate heating and vacuum for moisture removal.

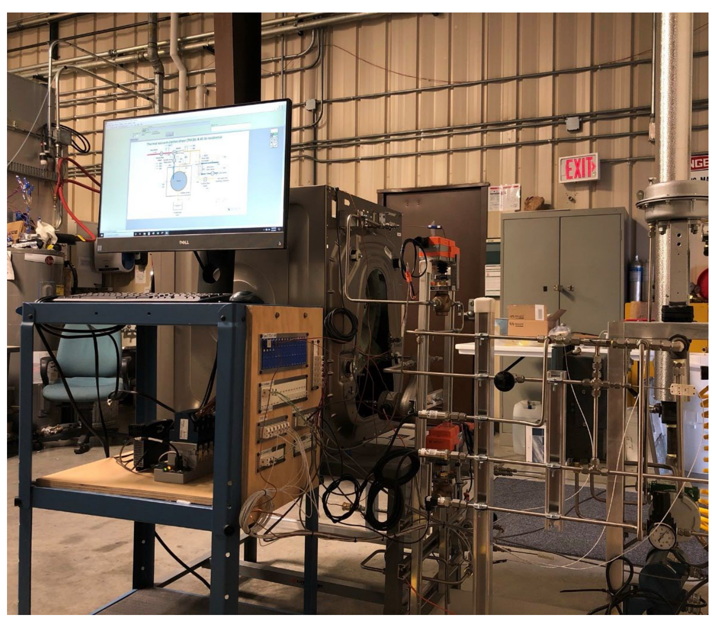
For example, using one thermo-vacuum dryer to produce 50 pounds of dry laundry would save approximately $8,000 per year. The annual savings from the use of new drying technology across the U.S. has a potential to reach over $2.5 billion.

Preliminary estimated benefits of the high-efficiency thermo-vacuum clothes-drying technology are:

- Drying time reduced up to 75%
- Higher Combined Energy Factor (CEF): 5-6 (estimated) versus 3-4 (ENERGY STAR, conventional)
- $6K-8K annual savings (payback period under two years), and
- At least 20% reduction in water consumption.

The primary target markets impacted will be commercial laundry markets, including on-premise laundries, multi-family housing, dry cleaners, industrial, and coin-operated facilities. Special focus is made on “cleanroom” applications, including healthcare and electronic manufacturing.





Photos illustrate the technology prototype infrastructure laboratory testing facilities.
The modified commercial dryer was tested for drying performance evaluation and comparison with state-of-the-art technology.

Technical Concept & Approach

The main element of the thermo-vacuum drying system is an ejector, which simultaneously provides a dynamic vacuum and removes moisture from the drying chamber. The operation relies on the heat circulating mostly in a closed cycle between the steam source, the vacuum ejector, and the drying chamber. This leads to continuous heat recuperation, which makes the process highly energy efficient.

This technology should not require replacing existing laundry equipment completely; it can be used to upgrade existing dryers to a higher performance level. In addition, this technology may allow combining both washing and drying processes in new installations. This will simplify the system design, reduce the cost of the drying process, and, therefore, reduce the operational footprint.

In Phase 1 of this project, researchers performed a commercial market review along with a preliminary cost/benefit analysis and estimated a simple payback period.

In Phase 2, UTD is providing co-funding to a large prime contract funded by the U.S. DOE to: characterize a refined concept and experimentally define the drying curves for three test fabric types; specify key components of the prototype to be tested; develop a test plan and matrix; and identify applicable measurement and verification protocols.

Results

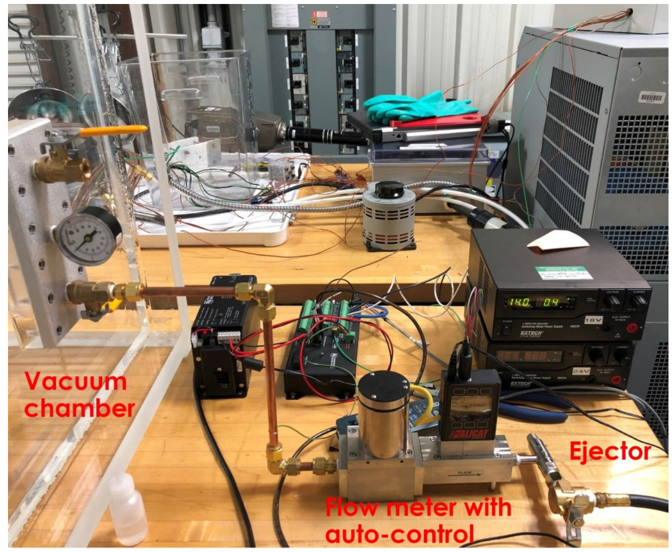
In Phase 1, researchers conducted a bench-scale evaluation of the technology concept and proved its feasibility. A bench-scale system was then constructed by modifying a commercially-available residential clothes dryer with an integrated heat exchanger and steam-driven ejector. Preliminary testing was completed with encouraging results that indicate a possibility of either reduced drying time or increased throughput.

A thermodynamic analysis of the thermal vacuum drying cycle showed that the overall efficiency increases by at least a factor of two. The heat transfer coefficient from condensing steam to the wet laundry through the wall of the perforated rotating drum decreases as drying progresses, but this does not adversely affect the heat and mass transfer process due to a sharp decrease in the heat and mass flow of steam at the final stage of drying.

Bench-scale experimentation for drying of selected fabric samples was conducted. These drying curves serve as a basis for designing prototype units, and help inform the development of refined drying curves.

Commercial product lines were assessed and evaluated, and major equipment OEMs were contacted.

The integrated drying concept was characterized to establish the baseline performance. A benchmark unit for the laboratory -scale testing was defined and specification of key components is in progress.



Benchscale testing.

In 2020, the numerical model of the thermo-vacuum drying process was refined and verified with the initial bench-scale experimental data. The feasibility study and bench-scale evaluation demonstrated the superior performance of the technology and provided promising results for moving the technology forward.

A paper entitled *Thermodynamic Analysis of Thermo-vacuum Clothes Drying Operation* that includes the methodology, model description, and process energy analysis was presented at the 18th International Refrigeration and Air Conditioning Conference in May 2021.

In 2021-22, promising discussions occurred with major equipment manufacturers, which demonstrated significant market interest. In addition, the U.S. Patent Office issued a patent (11,261,560) for the technology in March 2022.

Status

DOE's agency representative has determined that no additional DOE funds will be provided to this project due to limited federal funding availability as well as greater interest in a competing clothes drying approach. The team submitted a Final Report in November 2023 for work completed under Phase 2, and will seek alternative next steps to advance the development and availability of this energy-efficient technology.

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UTD Utilization Technology Development

Capstone C200S Micro-Turbine Laboratory Evaluation

The objective of this project is to evaluate and characterize the performance of the Capstone C200S 200kW Signature Series micro-turbine in order to scale-up the novel, highly-efficient FlexCHP technology to benefit a large number of universities, hospitals, manufacturers, and other end users.

Project Description

To succeed in today's marketplace, combined heat-and-power (CHP) systems must achieve high efficiency and low emissions in a cost-competitive package that is capable of broad deployment throughout existing market segments. The FlexCHP technology developed with support from UTD satisfies these needs for those installations that need 65 kW demand and 80 boiler-horsepower (BHP). The technology can benefit commercial and industrial steam-generation markets because of its ability to achieve high steam-production rates and efficiencies that are unmatched by any other competing turbine-based CHP approach.

The FlexCHP technology uses exhaust from a turbine generator as an oxidant for downstream combustion with supplemental natural gas to generate steam in a firetube boiler. While some competing CHP technologies recover heat from the high-temperature turbine exhaust (~600°F) by delivering the exhaust through a Heat Recovery Steam Generator (HRSG), this approach fails to maximize the quantity of recoverable heat because the exhaust excess oxygen levels are not reduced. The FlexCHP maximizes efficiency by reducing the exhaust oxygen levels from 17.7% in the turbine exhaust to 3% in the boiler stack through supplemental combustion. In comparison to simply delivering the turbine exhaust through a HRSG, the FlexCHP technology provides an efficiency gain of more than 30 percentage points (~60% increase).

FlexCHP is the only CHP technology that demonstrated high steam output and efficiencies of 84% without post combustion clean-up (e.g., selective catalytic reduction or other expensive after-treatment). Further, it is the only technology capable of attaining compliance with air-quality regulations in key non-attainment regions.

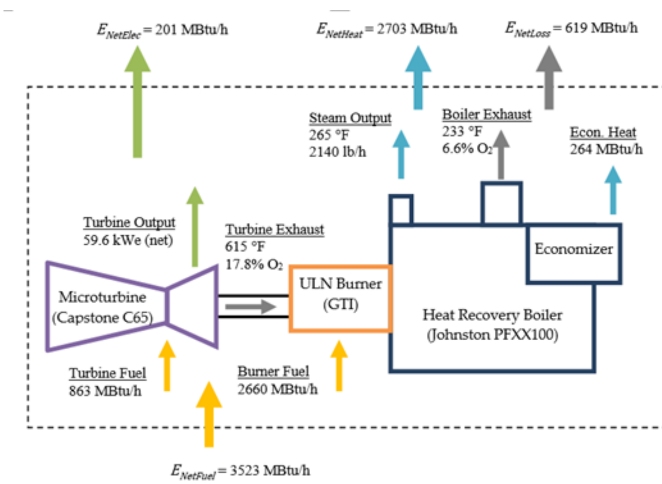
While the FlexCHP systems has been successfully developed and field demonstrated at a capacity of 80 BHP and 65 kW electricity (integration with a Capstone C65 micro-turbine), the economics of the technology favors larger-capacity installations, and thus there is need to develop and demonstrate a scaled-up version. The development of an integrated turbine/burner/boiler product that offers the additional advantage of grid-independence for reliable operation will advance the adoption of CHP solutions if the development team is able to transition from 65 kW to larger units.

The potential customer base for the larger Capstone C200S far exceeds that of the C65, and customers with even higher load demands can be satisfied by coupling multiple C200S units to achieve the required output. The objective for this project is to evaluate and characterize the performance of the Capstone C200S 200kW Signature Series micro-turbine in order to scale-up the novel, highly-efficient FlexCHP technology to benefit a large number of universities, hospitals, manufacturers, and other end users.

Benefits / Market Implications

Successful commercialization and deployment of the FlexCHP technology will have a transformative impact on commercial and industrial steam markets. Rather than purchasing a standard boiler with a conventional burner, end users will have the option of investing in a FlexCHP unit to generate on-demand steam and electricity. Customers will realize significant cost savings through reductions in electricity purchased from the grid. Ultimately, greenhouse-gas and criteria pollutant emissions will be significantly reduced.

For steam boiler customers for whom the price differential between electricity and natural gas rates exceeds a ratio of



FlexCHP system flows

"The FlexCHP system is exactly the type of innovation that Capstone Green Energy is interested in pursuing as part of our energy solutions portfolio. The product will enable customers to maximize the returns on their investments, while also utilizing clean energy."

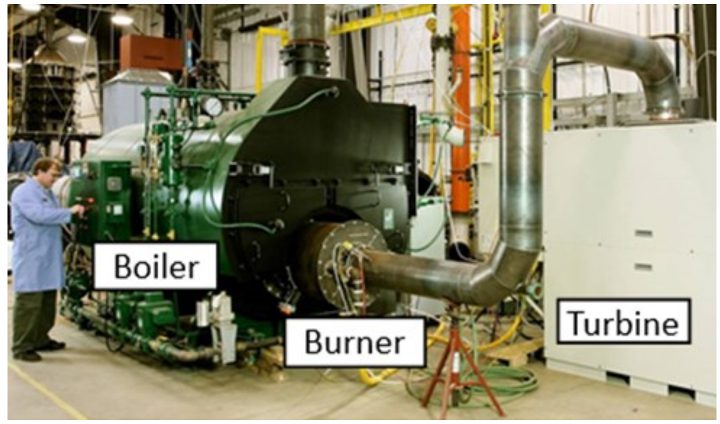
- Don Ayers
Vice President, Technology
Capstone Green Energy Corporation

three years by purchasing a FlexCHP unit, with significant long-term benefit (assuming operation five days a week, 48 weeks per year). For customers paying electricity rates that are six times that of their gas rates (as is the case in key California and the Northeast), customers can achieve payback in less than 1.5 years. As the FlexCHP is deployed more widely and equipment prices are reduced, the economic benefits of the technology will increase further.

As an example, consider a customer with a steam demand of 200 BHP and electricity load of 200 kWe. This customer could install a standard 200 BHP boiler that consumes gas at a rate of 8.5 million Btu/h and purchase electricity from the grid. Alternatively, the customer could install a FlexCHP rated at 200 BHP/200 kWe to generate the required quantity of steam and self-generate 200 kWe of electricity, consuming gas at a rate of 9.3 million Btu/h. If the customer rates for electricity are four times that of their rates for natural gas, on a per-unit-energy basis, the customer could reduce its energy costs by 18% annually by installing a FlexCHP unit. At the same time, greenhouse gas emissions would be reduced by more than 16% based on a source energy analysis of a representative installation site. In addition, the resiliency of electricity supplied to a facility can often be increased.

In 2021, Capstone was rebranded as Capstone Green Energy Corporation and focuses on four key business segments which will align well with increased CHP applications, including the FlexCHP technology.

- Through its Energy as a Service business, it offers rental solutions for its micro-turbine energy systems and battery storage systems as well as aftermarket parts and comprehensive service contracts.
- Energy Conversion Products are driven by the company's industry-leading, highly efficient, low-emission, resilient micro-turbine energy systems offering scalable solutions in addition to a broad range of customer-tailored solutions.
- The Energy Storage Products segment designs and installs micro-grid storage systems, creating customized solutions using a combination of battery technologies and monitoring software.
- Through Hydrogen Energy Solutions, Capstone Green Energy offers customers a variety of hydrogen products, including the company's micro-turbine energy systems.



FlexCHP-65 components

Technical Concept & Approach

Activities in this project fit within a broader research program to develop and demonstrate an advanced FlexCHP technology at larger capacities which is 1) capable of operating on both turbine exhaust gas and air and 2) is packaged as a fully-integrated commercial product across load scales for deployment by the manufacturing partner.

Project efforts focus on logistics, procurement, installation, and testing of the C200S micro-turbine. A test plan was developed to characterize system performance across a broad operating range, and data will be compared to the manufacturer's claims. This will provide insight and knowledge for determining the optimal burner configuration to be used for scaling the technology to larger capacities.

Results

The C200S microturbine was characterized for ambient temperature during measurements, turbine electrical power output; turbine fuel input, and other factors. Flex CHP technology was tested on Simulated Turbine Exhaust Gas (STEG) designed to be representative of C200S microturbine output. Performance was comparable to previous smaller scale tests. The burner was capable of adding significant thermal energy to the STEG while contributing little additional NOx emissions at the stack.

Status

Testing of the scaled up Flex CHP technology on STEG which is representative of the Capstone C200S 200 kW Signature Series microturbine has been completed. The Final Report was issued to UTD members in March 2023. The unit is ready for a larger demonstration project to evaluate the benefits of integrated CHP at an end-user site.

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Low-Emissions Efficient Burner for Ovens and Dryers – Field Evaluation

This project is validating the performance of a novel burner both in a laboratory and at an end-user host site. The goal is to advance the commercial introduction of a new burner that will reduce emissions, energy use, and operating and capital expenses for the many end users who use hot air in their process operations.

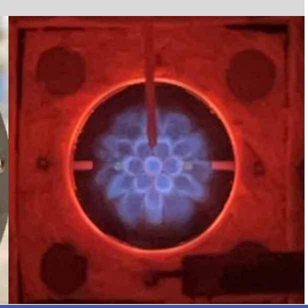
Project Description

Emissions from packaged burners can be impacted by cross-flow or end-flow process air and low-turndown conditions. A new burner with 9 ppm NOx emissions and < 50 ppm CO emissions would be innovative in this industry.

In this project, researchers and manufacturers are advancing and refining a new burner that offers these improvements. It uses 3D printing to manufacture the complete burner assembly as a single-step operation which reduces labor and tooling costs, and to fabricate internal geometries which cannot be achieved via conventional subtractive manufacturing. In addition, there is no need to braze the different nozzles together for further assembly. This innovative approach can simultaneously reduce emissions and equipment costs, and introduce another product in this market to expand ratepayer's choices and options.

The goal of this project is to combine a novel burner technology previously developed with UTD's support with other product design improvements into a 3 MMBtu/hr burner-assembly system to heat process air. Researchers will validate the performance of the burner assembly first in the laboratory and then at an end-user's field host site. In addition to the burner assembly, a cross-flow air-duct assembly provides heated air for simulating process-heating applications. The temperature is controlled by the burner firing rate. In addition, researchers will fabricate, and test the burner for air-heating applications (such as ovens and dryers) using up to 50% hydrogen blends with natural gas. The project team is partnering with a manufacturer of process heaters as it advances this new technology to market.

Sideview and combustion air inlet ends of the fabricated Design II burner section housing the nozzle assembly



Benefits / Market Implications

Leading customer application segments for an improved process heater include automotive manufacturing applications, environmental applications, and food-drying applications such as milk-flash dryers. The technology has the potential to reduce NOx emissions by >80%, CO emissions from 300 ppm to 50 ppm, and blower requirements by 30%, while also increasing efficiency by 4%.

The commercial introduction of a more energy-efficient, low-emission burner that will bring increased competition into this market segment, thereby saving energy and reducing operating costs and potential capital costs for consumers.

Technical Concept & Approach

This project will test the direct and indirect process heating applications with a focus on the burner performance and progress from a laboratory to a host site.

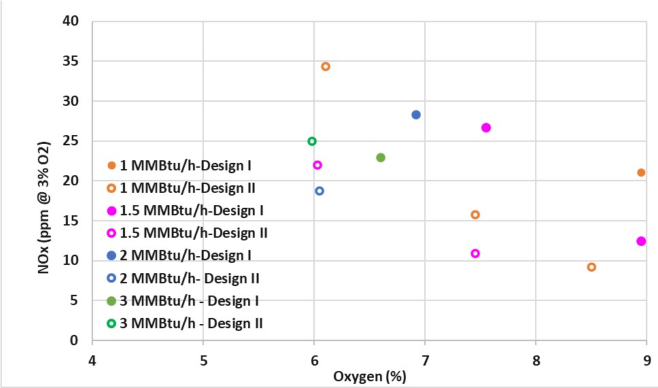
Specific tasks will include:

- **Integrate burner assembly at laboratory**

  Researchers will integrate the burner and the cross-flow air duct. Two blowers are to be installed, one for the burner and the other for the cross-flow air. The fuel and the controls will be linked. Shakedown testing of the complete test setup will be performed for smooth and safe operation. In addition, process parameters and the parasitic loads (e.g., blower, controls) will be discussed with host-site representatives.

- **Evaluate burner performance at laboratory**

  The project team will test the assembled burner to evaluate its performance for key parameters (emissions, turndown, reliable and smooth ignition, and blower-power requirements). After performing shakedown testing of the burner, multiple ignition tests will be performed to ensure the burner ignites reliably and smoothly at variable firing



NOx emissions at the furnace exit at different firing rates for Design I and II burners

rates. After successful ignition testing, the test assembly with the burner will be evaluated for performance and refined.

- **Design and integrate burner assembly at the host site**

  The project team will integrate the burner in a simulated environment process-heating environment similar to the host site. Researchers will generate designs and drawings necessary to adapt the assembly into the host site process. The hardware will take into account the host site equipment, so that minimum modifications will be required when installed at the host site.

- **Evaluate prototype-burner performance at different operating and process conditions**

  Ignition testing will be conducted to ensure that the burner ignites reliably and smoothly. Different process conditions will be tested to ensure all the parameters are covered. The project will further demonstrate and validate burner performance in a laboratory setting, as an important step to help establish a commercialization partner.

- **Develop burner design to burn natural gas/hydrogen (NG-H2) blends**

  Researchers will perform design modifications to the improved NG air-heater burner to enable operation with NG-H2 blends up to 50% H2 to provide greenhouse gas reductions compared to NG alone, while maintaining or improving NO_x and CO emissions, flame stability, and short flame lengths with no adverse impacts on controls, safety, and burner costs.

- **Evaluate NG-H2 burner performance**

  The NG-H2 burner will be tested over the range of 0 to 50% H2 in the fuel in a laboratory. The key parameters will be emissions, turndown, reliable and smooth ignition, blower power requirements, and safety (overheating of burner components, flashback, lift-off etc.).

- **Data analysis and performance assessment**

  Test data will be analyzed from both NG and NG-H2 firing

Simulated test rig for air-heating applications.

and to compare ease of ignition, NO_x and CO emissions, and operating range of flame stability for NG and NG-H2 firing.

Results

A first prototype burner was designed and tested in 2021 to evaluate performance that resulted in lower emissions and good performance in a certain firing range from 1 to 2 MMBtu/hr; however, further improvements were required to achieve the desired for the complete firing range from 1 to 3 MMBtu/hr.

In 2022 and 2023, an improved second prototype burner design was fabricated based on further computational fluid dynamics analysis and when tested on natural gas it demonstrated: operation at up to 6:1 turndown; very low CO emissions of below 10 ppm over the entire range of firing rates; robust ignition and stable flames; and superior NOx performance. Performance testing of both prototype designs were completed with < 9 ppm NOx (corr. to 3% O2) and < 10 ppm CO (corr. to 3% O2) emissions were achieved.

Status

Phase 1 results were summarized in a Final Report to UTD Members that was issued in August 2023. In addition, the project results were publicly communicated in a presentation provided to the American Flame Research Committee in Denver, CO in September 2023.

Discussions with a host site to demonstrate its performance at its location on natural gas are in progress. Separately, additional laboratory testing, evaluation and optimization of the burner to operate using up to 50% hydrogen blended into natural gas remains in progress.

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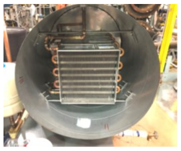
UTD Utilization Technology Development

Sub-Dew-Point Cooling Technology



Researchers demonstrated at laboratory scale a cost-effective and reliable technology to provide deep cooling of water or air to increase the efficiency, lower the cost, and enhance the performance flexibility of residential and commercial appliances as well as industrial systems.

Project Description

Conventional cooling towers typically utilize evaporative heat exchange. In this context, modern cooling towers are close to maximum efficiency by often achieving cooled-water temperatures of 5°F to 7°F above ambient wet-bulb temperature. Advanced cooling techniques with higher efficiencies are being developed; but they require complex retrofits, high energy costs, or a full replacement of the cooling tower with a new unit.

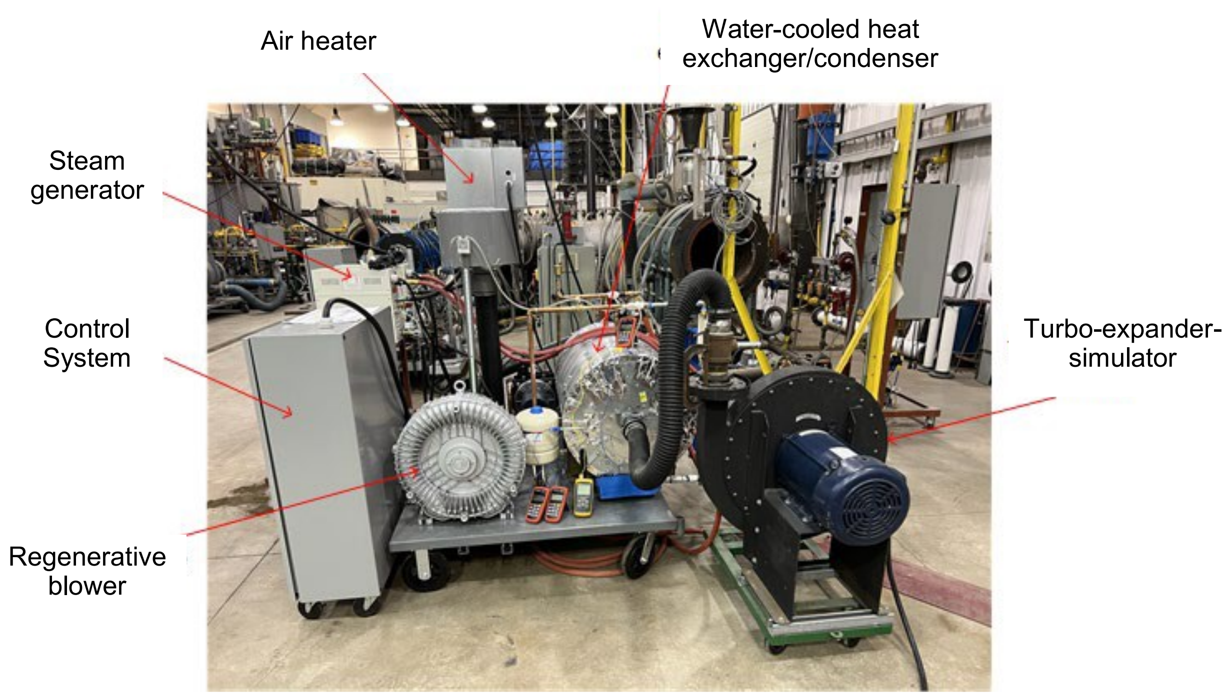
In this project, a research team will demonstrate and characterize the performance of an innovative sub-dew-point cooling-enhancement technology. No drastic modifications will be required to the existing cooling system designs and no new materials must be developed or obtained. Technology enhancements can use commercial off-the-shelf hardware that is packaged as a Pressure Dehumidification System (PDHS) and installed as add-ons or economically integrated with new equipment. These features and flexible application lower the technical risk.

The technology can be driven by natural gas combustion or available waste heat or potentially solar thermal energy to further improve cooling performance and energy efficiency.

The novel sub-dew-point cooling technology (SDPCT) will provide the following advantages:

- Low-cost flexible cooling for residential, and commercial, and industrial applications
- Off-the-shelf components
- High-performance efficiency
- Lower carbon footprint (compared to electrically-powered equipment on a source energy basis)
- High cooling performance due to employing an advanced high-efficiency refrigeration cycle, and
- Further integration of natural gas with renewable natural gas, solar energy, ground-source heat pumps, hydrogen/power-to-gas, or other renewable energy sources.

UTD is partnering with the U.S. Department of Energy (DOE), a leading global heat transfer equipment manufacturer, and university researchers, by providing co-funding to a prime contract from DOE via this project.



Overall view of the PDHS prototype installed and tested in the laboratory.

Benefits / Market Implications

The primary markets that can benefit will include:

- Residential/commercial appliances such as chillers, HVAC, power generators, etc.
- Industrial cooling systems and power plants
- Hospitals, nursing homes, and other life-safety-critical institutions, and
- Distributed power-generation systems.

The modular chiller market (air- and water-cooled) in residential, commercial, and industrial applications in North America is projected to grow from $0.65 billion in 2019 to $0.83 billion in 2024. The natural-gas-assisted SDPCT can potentially replace most of the conventional vapor-compression chillers. Using natural gas in SDPCT could allow for a reduction in cooling costs by 20%-40%. This effort can fill a key technology/program gap for energy efficiency gas utility programs. The SDPCT will also lower electricity consumption and water use in residential and commercial appliances.

Technical Concept & Approach

This project demonstrated and validated the SDPCT performance in a laboratory setting as an important step to advance the technology development.

The project consisted of several tasks structured over a 36-month period, including:

- Concept refinement and performance characterization
- Components design and manufacturing review
- Engineering, purchasing, and fabrication of the prototype
- Assembly, installation, and test plan development
- Data collection and processing, and
- Performance analysis, scale-up design recommendations, and techno-economic assessment.

Deliverables included performance validation of the sub-dew-point cooling system with a capacity of 100 kW (design and performance characteristics).

Results

In 2020, the new SDPCT layout – with a reliable and efficient dehumidification technique based on near-atmospheric pressure regulation – was simulated and evaluated. Initial, boundary, and operational conditions for the pressure dehumidifying system were specified. Nominal SDPCT component boundary conditions in terms of pressures, temperatures, volume, and mass flow rates that support the SDPCT conceptual design were defined.

"The sub-dew-point cooling technology is a very exciting and promising technology! I'm pleased to have contributed my expertise in heat-transfer numerical modeling of its key components. It's really great to see government, universities, manufacturers, utilities, and other researchers partnering together through DOE's and UTD's financial support to accelerate the commercial availability of new energy-efficient technologies for homeowners, businesses, campuses, and industry!"

Sumanta Acharya
Department Chair
Professor of Mechanical and Aerospace Engineering
Illinois Institute of Technology

The overall SDPCT concept was refined based upon numerical simulations of heat-transfer processes and smart fluid flow arrangements. These simulations were conducted to optimize heat and mass-exchange systems and the overall pressure-dehumidifying system.

In 2021, key individual components and advanced techniques were specified. Preliminary design calculations for the follow-on detailed engineering and fabrication of the PDHS prototype were performed. Concept refinement and performance characterization were completed.

In 2022, the PDHS prototype was fully assembled and installed. Testing was performed in the range of three representative climate zones – Baltimore, Chicago, and Dallas.

From the results of the experiments, estimated water savings in the cooling tower exceeded 20%. The reduction in make-up water results in water cost savings of 47.1-59.6 $/MWh. Compared to a baseline conventional power plant design net output increases by about 0.3% for the option without condenser upgrade and about 1% for the case with condenser upgrade at 95°F/35°C ambient.

Status

Testing of the PDHS at laboratory-scale in the controlled environment at an industrial laboratory has been completed. A Final Report for project 2.20.B was issued to UTD members in April 2023. Additional summaries of the results will be available in the Final Report to DOE, as prime funder of this research. Discussions about next steps to advance the technology continue with project partners.

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UTD
Utilization Technology Development

High-Efficiency, Low-Emission Commercial Baking Oven Field Demonstration

A field demonstration is being conducted to validate at least 10% CO_2 emission reduction and 25% NO_x emission reduction in commercial baking settings by applying advanced ribbon burners coupled with optimized combustion controls technology.

Project Description

The gas-fired ribbon burner is a mature, low-cost technology that is widely applied in many industries, such as baking, drying, and surface-treatment applications.

The objective of this project is to demonstrate at least a 25% NO_x emission reduction by optimizing the combustion process in a multi-zoned commercial wholesale baking oven within the environmental jurisdiction of California's South Coast Air Quality Management District (SCAQMD). Carbon dioxide emissions are also anticipated to be reduced by 10% through combustion system optimization.

The project team is demonstrating the performance of a combustion system with advanced ribbon burners and a control system that uses an Integrated Flame Plasma Analyzer to continuously analyze and monitor the air/gas mixture being delivered to the burner to optimize the flame chemistry in each zone of the oven (called an Ecozone). This signal is used as input to operate a gas flow valve to maintain optimal flame chemistry. This ensures that the preset optimum air/fuel ratio is constantly maintained regardless of changes in temperature, humidity, or gas composition.

The advanced ribbon burner configuration to be demonstrated in this project successfully integrates both traditional ribbon and metal-fiber infrared options. Combustion performance is achieved with a simple changeover between infrared and blue-flame ribbon modes. The approach theoretically provides the means to minimize NO_x and CO_2 emissions while operating the burners at the most efficient firing rate possible at every moment of the baking process.

Testing and performance data will be collected over a wide range of operating conditions at a large commercial bakery operated by a leading U.S. grocery retailer to prove the anticipated energy savings and environmental benefits. Testing is being coordinated with a leading burner manufacturer and an independent measurement and verification contractor.

UTD is partnering with SCAQMD and SoCalGas in this effort by providing co-funding to SCAQMD's prime funding.

Benefits / Market Implications

There are more than 3,000 commercial and wholesale bakeries in the U.S., and the U.S. baking industry consumes more than $870 million of energy annually. Additionally, the baking industry in many air-management districts is subject to strict NO_x emissions limits. Offering a technology that promises both energy and emissions reductions is an attractive prospect for the baking industry for financial, environmental, and social reasons.

End users that will benefit include wholesale bakeries using direct-fired ovens and other users, such as for flame treatment, gas-fired drying, process heating, and other industries using ribbon burners and zonal control systems for process heat.

Wholesale bakeries are very energy-intense operations. Energy efficiency is typically low, but upgrades to improve the energy efficiency of bakery systems are often unlikely to occur if they require costly downtime and significant capital investment. The technology being investigated in this project can be implemented without significant change or modifica-

Combi-burners, zone 5 replacement and interior re-firing tion to the oven, the products, or the exhaust hardware. The burner fits in standard oven sleeves and burner plates.

The optimized combustion process demonstration in this project is expected to reduce natural gas consumption by 10%. Additionally, the innovative burners are expected to reduce combustion system NO_x emissions by at least 25%, helping bakeries continue to meet and exceed stringent emissions requirements.

For a bakery that uses 18 MMCF of natural gas each year (such as the host site for this project), this represents almost $7,500 savings in energy costs and 157 pounds of NO_x reductions for the facility.

"We at Flynn feel that utilizing Ecozone technology will be a significant step forward to the real-time control of limiting NO_x emissions from ribbon burners, once deemed a near impossibility. Years of research and development of our sister product line in surface treatment has fueled the continuous technological improvements today. We thank SCAQMD, UTD, and the field host site for their support."

- Travis Eddy
Vice President - Sales
Flynn Burner Corporation

Technical Concept & Approach

Specific project tasks include:

- Host site performance historical assessment and baseline testing data analysis
- Engineering, fabrication, and purchasing of the demonstration system components
- System assembly and installation
- Startup and shakedown
- Data collection and performance monitoring
- Data processing and analysis, and
- Project management, administration, and scheduled reporting.

Deliverables include a presentation of demonstration results and comparative techno-economic analysis for wholesale baking.

Results

Baseline performance testing of the existing baking oven combustion system at the host site was conducted to establish a benchmark for the follow-on performance comparison and techno-economic analysis. Combustion emissions (including NOx and volatile organic compounds) were evaluated by the project team and verified by an independent contractor.

Engineering of the new demonstration combustion system was completed. Components of the demonstration combustion system were then fabricated, delivered, and installed at the host site location, followed by system startup and shakedown. Based on technical issues identified during the system shakedown period, the OEM modified aspects of the burner and then performed laboratory testing.

Two replacement burners were shipped to site for functional testing in the oven. The burners were installed in April 2023, lit, and tuned. Based on this, the remaining burners were modified and prepared for shipment for final testing. Multiple unrelated factors have delayed testing. 1) The test site experienced an additional issue related to the carriage mechanism. 2) There has been high production demand for bread, limiting access for testing, and 3) There was uncertainty how the new SCAQMD ruling for commercial ovens (Rule 1153.1, published 8/4/23) affects testing and the plant's permit.

Status

The oven carriage issues have been addressed and are no longer a limiting factor. High production demand continues, so installation and testing will need to be coordinated with the plant to minimize impact on production. We are coordinating test and permit requirements with SCAQMD so testing can proceed in 2024.

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UTD Utilization Technology Development

Energy Source Options for Industrial and Large Commercial Gas Users

Information is being developed to help end users identify the best opportunities for decarbonization by changing energy sources, using renewable natural gas blends, and/or making efficiency improvements in industrial and large commercial market sectors.

Project Description

This project supports industrial and large commercial end users as they seek to reduce greenhouse gas (GHG) emissions by providing comprehensive new analytical resources. Researchers developed and validated a spreadsheet tool to analyze the economic and environmental impact of fuel-substitution options with related strategies. The tool is comprised of a number of interactive worksheets that allow the user to examine several potential scenarios for carbon-emissions mitigation on both an economic and environmental basis – including changing energy sources, using renewable natural gas blends, and making efficiency upgrades. The initial version of the tool focuses on boilers used for process and/or space heating – one of the largest end-use applications in multiple industries.

The tool will assist industrial and large commercial end users in understanding the tradeoffs for different carbon-mitigation scenarios, accounting for annual energy costs, equipment costs, infrastructure costs, full-fuel-cycle GHG emissions, and the total life-cycle costs associated with GHG-emissions reduction. The tool incorporates baseline natural gas consumption as provided by the end user. The tool can perform qualitative and quantitative evaluations of the carbon-mitigation alternatives and help end users prioritize options that provide the best economics and the most cost-effective reduction in GHG emissions.

The tool allows users to calculate impacts on an individual customer level and could be used to aggregate customer data based on industry SIC code. The carbon-mitigation options evaluated were:

Example of an industrial boiler installation. Image Credit: Hurst Boiler and Welding Inc.

1. Displacing a percentage of the baseline natural gas technology with a commercially-available electric version (e.g., replacing a certain percentage of existing natural gas boilers with electric boilers)
2. Incorporating a percentage of renewable natural gas in the gas supply, and
3. Replacing a percentage of baseline gas equipment with higher-efficiency gas-fired equipment.

The effect of a carbon tax is also included in the analysis, as well as an option to purchase carbon offsets as part of total mitigation measures and scenario options analysis.

Benefits / Market Implications

According to the U.S. Energy Information Administration, the energy use of the industrial sector is projected to grow nearly twice as fast as that of other end-use sectors through 2050. Industrial applications account for the second-largest share (35%) of energy consumption in the U.S. (26.3 quads in 2019) behind only transportation. Twelve percent of that (3.2 quads) is from electricity while 40 percent (10.5 quads) is from natural gas. Natural gas provides well over 50% of the energy consumption in specific industries. Solutions are needed to bring down the carbon intensity of the industrial sector as governments set economy-wide decarbonization targets. Decarbonization pathways need to be weighed carefully – trying to apply a one-size-fits-all approach could lead to increased costs, reduction in manufacturing productivity or quality, and even increased GHG or CO_2 emissions.

This project provides end users and local utilities with insights regarding their decarbonization options such as for:

- Industrial and commercial process-heating boilers
- Water heaters for hospitals, nursing homes, and other life safety-critical institutions
- Food processing facilities (vegetables, grains, etc.), and
- Process facilities with steam demands.

Commercial and Industrial Boilers

Industrial — **SIC#35 Industrial Machinery & Equipment**

	#Unit	Average Capacity (MBH)	Annual Gas Use (MMBtu)
Natural Gas Baseline	4	30,000	841,000

Fuel Options

	Input Mix (%)	Input Efficiency (%)
Natural Gas Baseline		82
Replace with Electric Boilers	10.00	98
Renewable Natural Gas Blend	16.00	
Replace with High-eff Gas Boilers	20.00	93
Purchased Carbon Offsets for	0.00 (%) Industry Baseline CO2eq	

Energy Source Options Boiler Energy Screen

Options for reducing emissions in the industrial sector include improved energy efficiency, deploying new manufacturing techniques, switching to lower-emitting fuels, and integrating combined heat and power or carbon capture and storage.

Technical Concept & Approach

Project deliverables will include an industrial and large commercial market assessment tool with a techno-economic analysis of available technical alternatives and energy resource options. This assessment can support roadmap analyses for greater decarbonization in challenging industrial and large commercial end-use sectors. Co-funding support for some phases of this UTD project was also provided by Energy Solutions Center, Inc.

Results

In 2020, a Microsoft Excel spreadsheet tool was developed and initial analysis was performed for specific UTD members who provided industrial boiler data. This allowed for an investigation of the tradeoffs between equipment costs, customer electric electricity infrastructure costs, CO_2 emissions avoided (or added), and the costs associated with CO_2 emissions reduction their service territories.

In 2021, a database of industrial energy consumption data was analyzed for key end-use applications, and was used to prioritize the industrial technologies based on geographical locations that were linked to individual funders' service territories. The total industry consumption was analyzed for nine different census regions. A database of 77,000 data points was used to categorize the energy use for each of the nine census regions based on five selected subsectors (i.e., food processing, process heating, space heating, etc.). Each of the five selected subsectors was then divided into 18 key technologies to better understand the overall spectrum of end uses and to identify the technology consuming the highest amount of energy under each of the key subsectors, with a geographical indicator.

Researchers performed a market assessment and techno-economic analysis of possible energy source options and electrification scenarios for a spectrum of industrial and large commercial subsectors and end-use applications.

In 2022, the spreadsheet-based tool was transitioned to an online platform. Several GHG reduction pathways for process-heating segments were identified and evaluated on a preliminary basis, including net-zero carbon alternative fuels, renewable energy options, energy efficiency improvements (waste-heat recovery), electrification, hybrid energy sources, and system optimization and control. For Phase 2, the team focused on expanding this tool to include boilers.

In 2023 the team started working to expand the tool to include furnaces and ovens as part of Phase 3.

Status

Phase 1 and Phase 2 of the project have been completed. The Phase 2 final report was released in March of 2023. The team has started software development and is working to identify end-user sectors of furnaces and ovens to include in the tool.

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High-Hydrogen Burner for Commercial and Industrial Applications

Researchers are designing, fabricating, and testing an advanced fuel-flexible, high-hydrogen/renewable natural gas burner for commercial- and industrial-scale furnaces. Input from two national laboratories and from representative end users will help ensure that the final prototype burner meets performance requirements.

Project Description

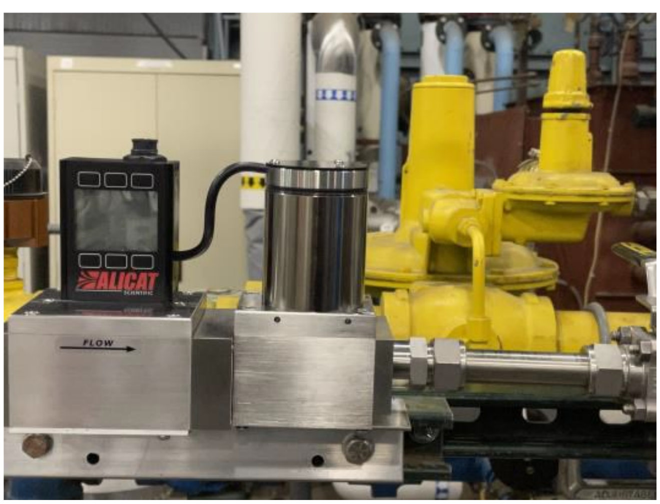
Hydrogen gas (H_2) is being pursued as a sustainable energy carrier and the blending of H_2 into the existing natural gas pipelines as a means of increasing the output of renewable energy systems by converting photovoltaic energy to H_2. Demonstrations of relatively low concentrations of H_2 (less than 5%-15% by volume) are under way across the world. Natural gas blended with renewable hydrogen can provide a stable, low-emissions, energy-efficient long-term solution.

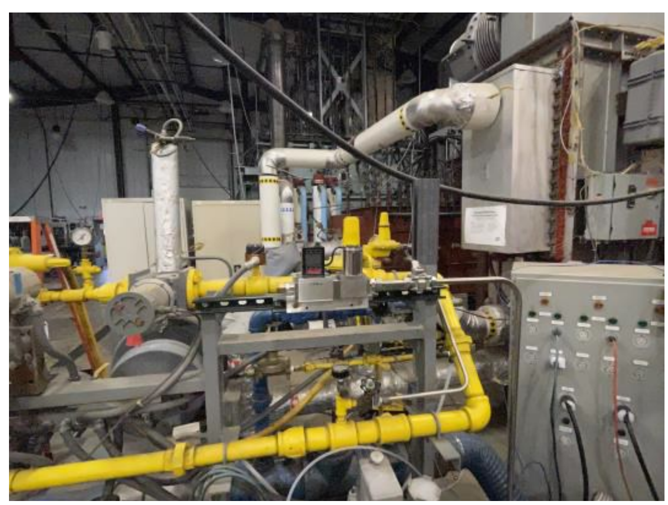
Greater reductions in greenhouse gas emissions will occur when higher concentrations (50+% hydrogen) can be used. There is wide agreement that the industrial and large commercial sector is particularly challenging to electrify, and certain industries may significantly benefit from using gas with high-hydrogen content (up to 100% hydrogen). But researchers note that there are significant differences while operating H_2 as compared to pure natural gas. The addition of H_2 increases the flame speed significantly, which can increase the risk of flashback (flame propagating into the upstream mixing region). As the H_2 addition increases, the flame speed also increases, leading to impact on the combustion systems. And in order to match the heating value, the volume of H_2 required is nearly three times that of natural gas. Current commercial burners cannot operate stably with high H_2 due to fluctuation in composition and combustion characteristics.

In earlier UTD-funded efforts, researchers successfully developed and bench-scale-tested a new 3D-printed burner design capable of operating efficiently and robustly. This project will demonstrate a scaled-up burner in a laboratory with high hydrogen (up to 60%) to evaluate the technology with Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), and two leading large gas users.

The innovative 3D-printed burner design is anticipated to provide greater fuel flexibility with high turndown and ultra-low emissions. This design has the potential to enable the use of fuel gas containing high hydrogen without extensive modifications. Example potential applications include process reheaters, heat-treating furnaces, and mini-mills that currently use large amounts of natural gas.

Testing demonstrated stable and robust performance that provides superior air/fuel mixing, uniform cross-sectional flame temperature profile, and over 6:1 turndown. The burner is fuel flexible, allowing the use of a wide variety of conventional and recycled combustible gases, including hydrogen. With the inherent internal recirculation of cooled products, the design reduces NO_x emissions to <5 ppm and minimizes cross-sectional temperature and velocity gradients at the burner exit. The burner design ensures a robust flame and eliminates potential for flashback and flame propagation into the air-fuel inlet region.





Installed H2 flow meter for testing with higher H2 and all parts ordered for assembly

In this project, a research team will design, develop, and test the advanced fuel-flexible burner in a laboratory environment furnace to evaluate and compare the burner performance with corresponding state-of-the art natural gas burners.

Benefits / Market Implications

Blending of hydrogen into natural gas can present some challenges to various end-use applications in terms of efficiency, process control, or pollutant emissions. A burner capable of handling variable and high H_2 gas concentrations can provide a long-term and sustainable solution.

Adoption of high-hydrogen gas concentrations may first occur in selected single-site users or clusters of large-demand end users, with industrial users being prime candidates since fewer, larger burners need to be changed out.

Technical Concept & Approach

The following tasks will be performed in the current project:

- **Design and Develop a High Hydrogen Burner**

  A research team will design and develop a high-hydrogen burner by modifying and adapting the natural gas design. The project team will use Computational Fluid Dynamics (CFD) and chemical kinetics (with ANL) to adapt and modify the design by evaluating mixing and flame characteristics with H_2.

- **Setup a Test Rig and Perform Burner Testing with Natural Gas**

  A laboratory test rig will be developed to operate with natural gas and installed with the required flow controllers and instrumentation. Researchers will test a natural-gas-fired burner to evaluate its performance for various key parameters as a baseline for comparison with H_2. After performing shakedown testing of the burner, performance testing will be conducted. The key parameters will be emissions, turndown, blower power requirements, and heat-transfer characteristics. This will help determine the operability and turndown characteristics of the natural gas burner. The testing will be performed for different firing rates and different air/fuel ratios to evaluate the emissions and efficiency characteristics.

- **Fabricate and Install Burner for Hydrogen**

  The project team will generate burner and assembly-design drawings to install the burner assembly into a laboratory furnace. The components for the burner and its assembly will be fabricated with ORNL.

Air-fuel skid assembly for H2 operation

- **Evaluate Prototype Burner Performance**

  Ignition testing will be performed to ensure that the burner ignites reliably, repeatedly, and smoothly. The different process conditions will be tested to ensure all the parameters are covered.

The target outcome is to provide a laboratory-proven prototype burner assembly that is ready to be field tested at two industrial user host sites in California. Actual field testing of the prototype will be separately funded/authorized.

Results

In 2021, the project team evaluated the testing apparatus and instrumentation required to perform hydrogen testing. A flow meter, controls and other equipment for high-hydrogen testing were ordered.

In 2022, the flow meter was installed in the air/fuel train setup. Flow meter shakedown testing was performed to ensure safe and reliable operation. Design changes to the burner were reviewed using CFD analyses.

In 2023, assembly of the air-fuel skid for H2 operation was completed. Job Safety Analysis (JSA) and Standard Operating Procedure (SOP) were updated to perform H2 testing and to ensure smooth and safe operation with hydrogen.

Status

The team is currently testing with NG-H2 blends is in progress for ignition, operability and performance up to 3 MMBtu/h firing capacity.

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UTD Utilization Technology Development

Field Demonstration of Energy Recovery from Brewing/Distilling Operation

This project is validating an innovative waste-heat-recovery technology at two micro-breweries. The process will economically recover heat from brew kettles and re-use it for water heating in order to save energy and reduce CO_2 emissions by up to 25%.

Project Description

This project is developing and demonstrating a Waste Heat Effective Transfer (WHET) energy recovery technology in brewing/distilling operations to validate the technology as a robust and reliable operation where waste heat is available and water heating is needed.

The innovative WHET technology combines commercially-available technologies into a simple, reliable, compact, and inexpensive system to economically recover and reuse low-level waste heat. Previous waste-heat-recovery systems have been large, complex, and often too expensive to be deployed because payback times from natural gas savings were too long. WHET systems can operate efficiently and economically at virtually any scale in any industrial setting where waste heat is available and there is a need for hot water or heated water entering a boiler.

The WHET process is designed to be inexpensive, easy to install, and nearly invisible to the plant operator. Simple payback periods are expected to be under five years.

The process consists of several key components:

1. A heat-exchange module made with fluted, flared, or spiraled copper tubing (to yield enhanced heat transfer rates) is installed in the flue containing low-temperature (under 400°F) exhaust gas. This commercially-available tubing provides excellent heat transfer in minimum space and with minimum pressure drop.
2. The flow rate of water through the tubing is controlled by temperature of the exhaust gas and water before and after the heat exchanger. The controller logic is critical because many processes are carried out batch-wise, and the water flow rate must be regulated to avoid extracting too much heat from the exhaust gas and producing problems with condensation in the flue. A flow control loop with valves is used to mix the heated WHET product water with plant water in a water heater or a working process needing heated water. The controller balances available waste heat with facility hot water needs.

Researchers will validate the WHET technology at two micro-breweries. The WHET process will economically recover heat from brew kettles and use that heat for water heating. This approach will provide sufficient operational flexibility to match variations in facility operating load. The goal is to achieve a 15% to 25% recovery of heat from the brew kettles, or 60% of the available waste heat in exhaust gases. A second goal is to reduce CO_2 emissions by up to 25%.

UTD is partnering with the California Energy Commission (CEC) in this project by providing co-funding to a prime contract funded by CEC.


Installation of the heat exchanger in the boiler room (left) and the tank (right) in one of the micro-breweries

Benefits / Market Implications

The current project focuses on demonstrations in breweries and distilleries, a growing market need. In California alone there are now nearly 1,000 brewery license holders and nearly 100 distillery license holders.

The need to heat water, brew, and distill leads to a large energy footprint for brewing and distilling. Energy costs and potential savings are high, although savings as a fraction of total cost are low because the cost of high-quality grains and other raw materials is high. While the percentage of total operating cost savings is low (estimated 25% savings in the 2% -4% of total operating costs related to energy), the total energy saved for brewing and distilling can be large.

The WHET technology also holds the promise of achieving superior environmental performance, including a 25% reduction in greenhouse gas and NO_x emissions. The technology recovers low-level waste heat and uses it to reduce the natural gas needed for water heating. The approach is practical, flexible, and less expensive than other approaches.

The primary target markets impacted will be: 1) breweries, 2) distilleries, 3) commercial cooking facilities, and 4) laundry facilities. Secondary target markets may include industrial processes using hot water, boiler applications in which preheated boiler feed water saves energy, and chemical processes requiring hot water.

Technical Concept & Approach

Perform the following tasks:

- **WHET System Design and Fabrication**

  Individually design WHET systems for the two brewery demonstration sites to match their batch operating practices. Fabricate heat exchangers from extended-surface copper components. Assemble the WHET systems in California and install them at the demonstration sites.

- **WHET Demonstration Installation and Baseline Testing**

  Install the WHET systems at the two micro-breweries. Collect baseline data to determine waste heat available from the brew kettles and the quantity and conditions of hot water used during the brewing cycle. The data provides a baseline to determine energy savings achieved with the WHET system.

- **WHET Demonstration Long-Term Testing**

  Perform at least 12 months of WHET demonstration testing at both breweries. Parametric tests will be carried out to optimize WHET energy savings. Operate the WHET system at optimized conditions for a long period of time. Gather data on temperatures, flue gas volume, water temperatures, and water flow rates. Monitor energy requirements for hot-water heating to determine WHET system energy savings.

- **Performance Monitoring and Evaluation**

  Analyze all collected data, conduct all analyzes, and report results to sponsors.

Results

In 2021, the project team focused on obtaining equipment and components, selecting and then working with the installer, and planning for the first installation. One of the originally-planned brewery sites announced that they were closing. The project team then secured a new, second demonstration location while moving forward with setting up the first demonstration in Sacramento, CA.

In 2022, the project team organized the first installation of the WHET system. This included securing delivery of the water storage tanks, controls components, and other parts. Other activities included locating and negotiating with a reputable installer and finalizing plans for installation. The first system is now in place and is undergoing shakedown testing while brewery baseline data is being collected. Preparations are under way to install the second system.

In 2023, the second demonstration site was forced to close. The team found a replacement demonstration site. The team worked work with local contractors and completed the installation process for the second installation during the third quarter of 2023. Baseline testing has been completed at the second site and both sites are now in demonstration mode. The project team will be monitoring the performance of the demonstration systems for a minimum of 12 months.

Status

The team is focused on completing demonstration testing and processing the resulting data.

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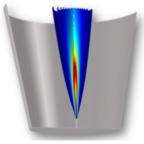
Zero-Emission Processes with Carbon Recovery



Researchers are advancing the development of a new synthetic air-combustion process that simultaneously improves industrial boiler or furnace efficiency when using natural gas – while also lowering CO_2 emissions and providing a means to capture or convert CO_2 to valuable products.

Project Description

Synthetic air combustion (SAC) is a form of oxygen-fired combustion that offers the benefits of lower fuel demand and decreased emissions. Oxygen firing, however, produces a much higher flame temperature than air firing and requires complete rebuilds of equipment and using a new refractory – all of which is costly.

The goal of this specific project is to advance the development of a new SAC process that simultaneously improves industrial boiler or furnace efficiency when using natural gas, while also lowering CO_2 emissions and providing a means to capture or convert CO_2 to valuable products. Laboratory tests will be conducted at industrial conditions. Testing will help compare calculated and experimental results when using SAC to typical air-fired combustion.

This UTD project builds upon an earlier-stage R&D project to explore potential benefits of SAC, which began in 2020 and was funded by UTD members.

Benefits / Market Implications

This project will help utilities and their customers address methane-emission and greenhouse-gas-reduction goals or pending legislation related to emissions of CO_2

SAC can be applied to a very wide range of industrial processes. While some processes will benefit more than others from adoption of SAC, the technology can reach all industrial sectors across the country.

SAC is compatible with a wide range of fuels, making the use of renewable natural gas (RNG), biomethane, and hydrogen-enriched natural gas.

SAC offers natural gas end users a path toward a lower-carbon world. Important benefits of SAC are the ability maintain the existing industrial furnace and boiler infrastructure and to achieve real cost savings that make SAC a practical way to operate in a reduced carbon world:

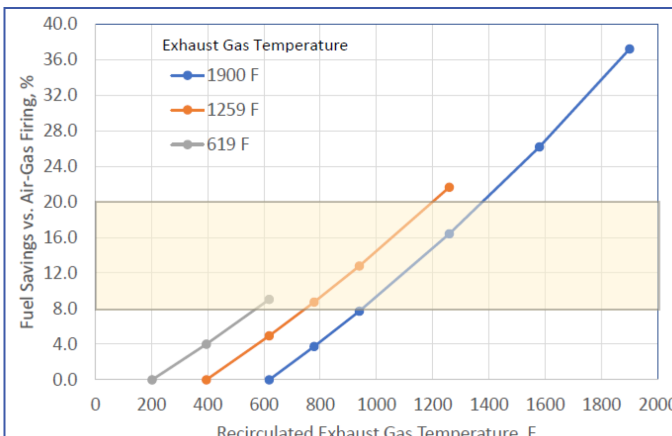
Benefits to end users and the environment are targeted to include:

- Reduction of CO_2 emission by >8%. When add-on technologies such as reforming or bi-reforming are included, SAC provides the enabling technology to provide 100% elimination of CO_2 emissions
- Reduction of natural gas consumption by >8%
- Near elimination of NO_x emissions
- CO_2 can more easily be converted into a number of valuable chemicals, or recovered and sequestered
- Improving product throughput and quality through greater combustion control (targeted 10% increase in furnace throughput with higher product quality)
- Retaining customer choice for gaseous fuels, including RNG, biogas, natural gas, and blended fuels, and
- Higher flame stability.

The primary target markets impacted will be:

- Industrial furnaces
- Process heaters, and
- Stationary boilers.

Secondary target markets include a wide range of industrial processes that generate hot exhaust gases.



The figure above shows the results of mass and energy balances illustrating fuel savings provided by the SAC process as a function of exhaust-gas temperature and recirculated exhaust-gas temperature. Within the range of most industrial process operations and the range of currently practical gas recirculation temperatures (up to 1,200°F), calculations show natural gas savings of 8% to 20% can be realized.

Technical Concept & Approach

This project takes a deeper look at SAC by examining the practical aspects of the technology, the economics and environmental benefits, and the linkage to renewable sources of oxygen. Researchers are conducting laboratory SAC tests with heated synthetic air containing a simulated flue gas of carbon dioxide and steam.

Specific activities include:

Modeling of Industrial Combustion Processes Focusing on SAC

The project team will carry out combustion and thermal modeling of common industrial-combustion processes with air and synthetic air at a range of conditions. The results will be used to determine the economic and emissions benefits of the SAC process. The effort will also evaluate SAC in combination with renewable oxygen production and carbon capture or carbon conversion to products technologies.

Synthetic Air-Combustion Testing

A series of tests will be carried out on a laboratory furnace. Synthetic air containing oxygen, CO2, and steam will be provided to the burner at a range of temperatures simulating recirculated flue gas. Data will be collected on temperatures, efficiency, flame properties, and emissions. Results will be compared with results when firing the same burner under air and ambient synthetic air conditions.

Data Processing and Modeling of SAC Efficiency and Emissions

Comparisons of flame properties, combustion stability, efficiency, and emissions will be made between tests with the industrial burner when fired with air, ambient synthetic air containing oxygen and CO_2, and heated synthetic air containing CO_2 and steam.

Results

The team first conducted synthetic air combustion tests using synthetic air containing oxygen and carbon dioxide at ambient temperature. Results confirmed that burners run well on synthetic air. With CO_2 alone, NO_x is low, but CO is high under certain firing conditions.

In an effort to reduce CO, the team tested a preheated synthetic air containing steam and CO_2 at elevated temperatures. Testing found that the burner was stable when firing with synthetic air and heat release was similar to firing with air and natural gas. NO_x emissions dropped to near zero. CO levels were significantly lower than when firing with synthetic air containing only CO_2, but CO levels were still well above the levels obtained with air firing. The CO level could be lowered to the same levels as obtained with air firing by increasing the oxygen to natural gas ratio from 2.07 to 2.20.

The team calculated conditions for the parametric synthetic air combustion tests with synthetic air containing oxygen, steam, and CO_2. The results indicate a small amount of CO_2 dissociation is occurring in flames, and the CO is elevated because a large fraction of the inlet gas to the burner is CO_2 when firing with synthetic air. To avoid the need to use high levels of excess oxygen, burners may need to be designed to change mixing patterns so CO_2 dissociation is avoided.

Several possible paths were identified to incorporate CO_2 capture. The major routes include:

Membrane separation of CO_2 from other exhaust gas components followed by compression

A large number of membranes including size exclusion, thermophilic, and graphene oxide membranes are under development by many organizations. This path may prove to be an attractive route for CO_2 separation from SAC exhaust gases.

Sorbent recovery of CO_2, removal of water, and compression

Solvent recovery of CO_2 from exhaust gas using amines and other chemicals is the most studied and most mature approach. This approach is fairly complex. The project team will evaluate this approach, although other approaches appear more promising.

Cryogenic recovery of CO_2 as dry ice followed by compression

Thermodynamic calculations have shown the cryogenic path is too energy-intensive to be attractive.

Removal of particulates, NO_x, and SO_2, followed by catalytic removal of oxygen from the exhaust gas and then followed by compression of CO_2 with integrated H_2O removal.

A potentially attractive path is to start with removal of the trace components using traditional gas processing technologies. Then the oxygen must be removed, and this can be accomplished using thermal oxidation. This path is attractive because no membranes or sorbents are required.

Status

The team is working to define the form and extent of layouts, mass and energy balances, and economics to be used to compare CO_2 capture approaches before beginning detailed analyses for the selected CO_2 capture approaches.

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UTD
Utilization Technology Development

High-Efficiency Crop-Drying Process

Researchers are developing a high-efficiency, low-labor crop-drying process that can be retrofitted into existing farm operations to save energy and improve product quality. The project team identified two crops of higher market value, prepared a preliminary design, and is advancing product development.

Project Description

Sun drying is the simplest and least expensive method of crop drying, but it is almost impossible to manage the drying conditions and control the quality of the dried product during the drying process.

The agriculture industry has employed a number of drying methods and techniques to improve crop drying in order to reduce spoilage, increase the marketability of product quality, and to get to the market as fast as possible.

The Thermo-Vacuum Drying (TVD) process that was developed and initially demonstrated in previous UTD project 2.17.B can improve operating efficiency and product quality and reduce greenhouse gas emissions to contribute to decarbonization targets. This technology was applied to rotary drying in bulk food drying operations in that UTD project and may have application in a wide spectrum of crop drying at low temperature to preserve quality and prevent spoilage.

TVD is an ejector-based technology that uses a motive force to create a dynamic vacuum to remove moisture from the product being dried. The removed moisture is then condensed and captured for reuse. That motive force can be pressurized air or steam. One of the key challenges was to remove moisture evaporated from the drying air at sub-atmospheric pressure with cost-effective dehumidification techniques.

The objective of this UTD project is to advance the development of the TVD process so that it can be retrofitted into existing farm operations. In addition, the project outcome may help secure follow-on external funding from governmental agencies for subsequent larger-scale field demonstrations.

Benefits / Market Implications

Development of advanced low-temperature crop-drying methods can reduce primary energy consumption by 10% to 15%, increase the drying rate (resulting in a reduced drying time by 25% or more), and improve product quality.

This technology can be applied to a variety of markets, including:

Traditional Markets – Fruits, Herbs, and Nuts

- Dried fruit was a $9.8 billion market in 2018, dominated by grapes, dates, prunes, apricots, cranberries, and figs.
- Fruit drying has two main forms of product: semi-moist (20% to 25% moisture content) and dried fruits (15% to 20% moisture content).
- Dried herbs was a $4.1 billion market in 2018 and is expected to grow to $6.1B by 2026.
- Nuts are a $37.5 billion (2018) worldwide market. .

Emerging Market – Large-Scale Biomass Gasification

- Utility-scale production of renewable gas from woody or leafy biomass and other biomass feedstocks is being considered. Efficient, economical methods to remove moisture from this feedstock at large scale will be an important need as new sources of large-scale renewable gas are considered. Relevant context includes major project development announcements during 2023 by SunGas Renewables and similar entities.

Thermo-Vacuum Dryer of 100 tons per day capacity in previous UTD project 2.17.B.

Technical Concept & Approach

The project team is comprised of a primary technology developer, an ejector system designer, and a marketing and technical support expert.

Tasks were performed over a nine-month term, including:

- **Crop Selection and Characterization**

  The project team identified, characterized, and selected two high-value crop-drying markets to evaluate. Crop-drying specifications were developed. Researchers characterized the performance of current drying methods and techniques (including typical equipment in use) and analyzed the opportunity for a TVD process.

Tasks performed over a nine-month term included:

- **Crop Selection and Characterization**

  The project team identified, characterized, and selected two high-value crop-drying markets to evaluate. Crop-drying specifications were developed. Researchers characterized the performance of current drying methods and techniques (including typical equipment in use) and analyzed the opportunity for a TVD process.

- **Commercialization Scale-Up Planning**

  The project team selected and analyzed the most-promising solutions and developed a preliminary design for high-efficiency drying of the selected crops. A preliminary economic analysis of most feasible and workable designs was also conducted.

Results

Two high-value crop types were identified and prioritized for further evaluation – tree nuts (almonds, walnuts, and pistachios) and field crops (alfalfa and hemp).

Almonds - This is a $5.5 billion market with 78% of the world's supply grown almost entirely in the state of California. Current on-ground harvesting relies on sun and air drying; however, insect infestation, microbial infection, and dust generation is moving the industry to consider off-ground harvesting methods.

Walnuts - U.S. production is valued at $1.3 billion. Walnuts require drying within 48 hours of harvest to stabilize product quality, shelf life, and increase prices paid by packagers. Because most walnuts are harvested in an 8-10-week window, walnut hullers have an immediate need to accelerate current batch-drying times and dry at lower temperatures to preserve product quality.

Pistachios - U.S. production is valued at $1.9 billion. Pistachio huller needs include accelerating the drying process, drying at lower temperatures, eliminating the need for silo drying, and developing an added-value market in cattle feed from dried green waste (hulls).

Thermo-Vacuum Dryer of 100 tons per day capacity in previous UTD project 2.17.B

Alfalfa - Alfalfa is the fourth most widely grown crop in the U.S., with an estimated annual value of $11.7 billion dollars. The primary benefits of dehydrated alfalfa pellets as a high nutritional, low-cost feed supplement include ease of storage and handling. This has led to increased demand among beef, dairy, and pork producers domestically and internationally.

Hemp – The current value of the hemp market is $824 million (2022). Cost-effective and efficient drying technology has the potential to significantly improve drying time at lower temperature to improve product quality and increase oil output.

Other drying opportunities exist for co-products of existing crops. These include dried distiller grains (DDG) and brewers spent grains (BSG). Based on the project findings, the project team drafted a TVD design layout for a follow-on technology prototype demonstration.

Status

Product development efforts are currently in progress.

The timing to fabricate the prototype equipment and select the final site for the technology demonstration will depend on when a primary supplier to the project provides key contract deliverables.

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UTD Utilization Technology Development

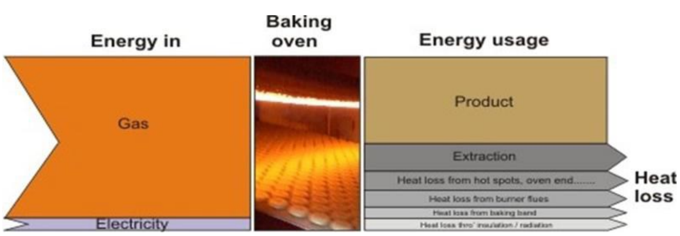
Ribbon Burner Performance With Hydrogen-Blended Gases

Researchers are evaluating the performance of traditional ribbon burners when operating with hydrogen and hydrogen-natural gas blends, with hydrogen content in the gaseous fuel from 0% to 100%. This research supports decarbonization efforts by end users in the baking, heat treating, and similar industries.

Project Description

The goal of this project is to evaluate the performance of traditional ribbon burners when operating with hydrogen and hydrogen-natural gas blends in the range of hydrogen content in the gaseous fuel from 0% (natural gas only) to 100% (hydrogen only), in order to prove technical feasibility and identify the optimal performance along with possible design gaps. The data and correlations obtained will serve the project team as a basis for developing innovative decarbonization concepts and hardware that will integrate green hydrogen production (zero carbon).

Pita bread baking oven interior



Energy input/output of traditional ribbon burners

Benefits / Market Implications

Deep-decarbonization policies are being expanding across the continent. That's why low-carbon, carbon neutral or zero-carbon solutions are of industry's great interest.

The primary target market is industrial wholesale baking. The baking industry is a huge business. It is projected that the revenue of bread and bakery product manufacturing in California will be approximately $5.82B by 2024. Government regulations continue to challenge the industry. The Environmental Protection Agency, the Food and Drug Administration, SCAQMD, and other entities oversee the operations of bakeries and issue new rules and regulations.

In addition, if many customers demand "climate-smart bread," then bakeries would have to prove that their bread production uses less energy than the average loaf and emit less harmful emissions. The current carbon footprint of the average wholesale bakery results in a range of 977-1,244 g CO_2 eq. per loaf of bread.

Some of the baking applications, such as a pita bread production for example, are very hard to be electrified because it requires a flame presence, so fuel substitution is a likely viable option for pita bread baking.

Potential secondary target markets for further consideration include surface treatment and material thermoforming

Ribbon burners are widely employed across wholesale baking industry and estimated to produce over 39,000 tons a year of NOx annually in the United States. Specific burner type and firing rate depend on the product baked (bread, crackers, tortilla, bagels, etc.). Implementation of the appropriate fuel-switching technology may significantly reduce carbon footprint as well as improve energy efficiency of the operations.

Technical Concept & Approach

Ribbon burner performance will be evaluated based on a test matrix including fuel consumption, combustion emissions, temperature profile, and flame characteristics. Operation of the burners (flame shape and color, combustion and ignition stability) will be observed in the range of the hydrogen natural gas blends of 0-100%.

The project is broken down into 3 major tasks:

Task 1: Lab-Scale Test Rig and Fuel Supply Setup

Construct a test facility to analyze the selected ribbon burners' performance in a controlled environment. This includes:

- Select type and size of the ribbon burners to be evaluated.
- Assemble the components of the ribbon burner combustion system along with the control, measurement, appropriate ignition, and flame safety
- Setup a gas blending system or purchase the required hydrogen-natural gas mixture
- Develop safe operating procedure for test firings
- Startup and shakedown of the test rig (ready for data collection)

Task 2: Test Matrix Development and Performance Data Collection

Collect the data of the selected burners in the range of the hydrogen-natural gas blends of 0-100%. This includes:

- Develop test matrix and select appropriate measurement protocols
- Collect the performance data (fuel consumption, combustion emissions, temperature profile, flame characteristics)
- Observe the burners' operation (flame shape and color, combustion and ignition stability)
- Reduce the raw data for the follow-on analysis and representation

Exterior of an industrial demonstration oven

Task 3: Data Analysis and Final Reporting

Analyze all project findings and report them to project funders. The work effort includes:

- Performance data on ribbon burner heat release and emissions in a range of tested hydrogen content
- Recommendations for H2-retrofit in industrial bakery settings and for a follow-on demonstration.

Ribbon burner test setup in laboratory

Results

The type and size of the ribbon burners were selected to evaluate the performance of burners with a mixture of hydrogen and natural gas. A test rig was set up to analyze the selected ribbon burners' performance evaluation. Ribbon burners were tested with mixtures of 0-100% hydrogen and natural gas.

Performance data (fuel consumption, combustion emissions, temperature profile, and flame characteristics) were collected for selected ribbon burners (Task 2). The analysis of experimental data on the tested ribbon burner in the range of the tested hydrogen content was carried out (Task 3).

Selected burners with different geometries have been successfully demonstrated to operate stable, without flashback at fuel hydrogen content up to 95% by volume. With 100% hydrogen, flashback and/or false triggering of the flame sensor is observed.

Status

Based on test results and discussions with a leading manufacturer of ribbon burners, the ribbon burner geometry was modified to burn hydrogen. Prototypes of the modified burners were manufactured and shipped to the team for testing. Further testing and development continues in an industrial research laboratory.

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UTD
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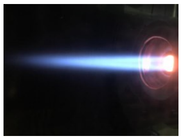
High Performance Adjustable Port Burner



Researchers demonstrated that an innovative prototype adjustable port burner can provide superior ability to operate on varying mixtures of Hydrogen Enriched Natural Gas (HENG) safely and reliably with minimal emissions (O_2 , CO_2 , CO, NO_x).

Project Description

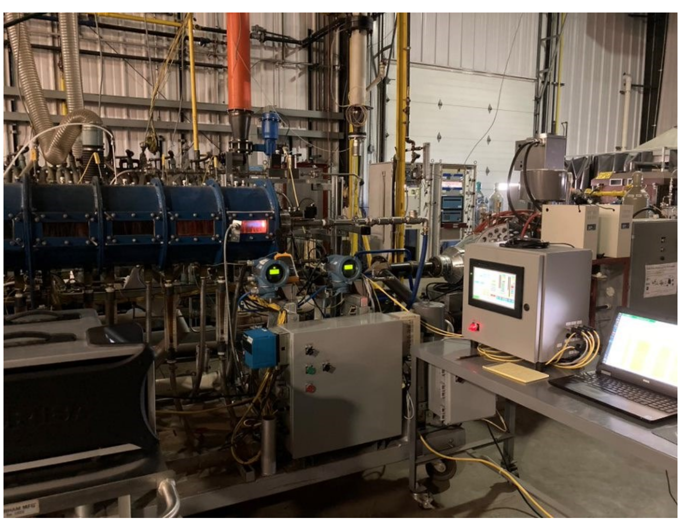
Conventional fixed port burners are constrained by being limited in the variation of fuel or oxidant flowing through the burner because of the need to stay within the required velocity limits to maintain stable combustion and performance. This project demonstrated that a prototype version of an innovative adjustable port burner technology could provide superior ability to operate on variable mixtures of Hydrogen Enriched Natural Gas (HENG) safely and reliably with minimal emissions (O_2 , CO_2 , CO, NO_x) compared to current conventional fixed port burners.

Benefits / Market Implications

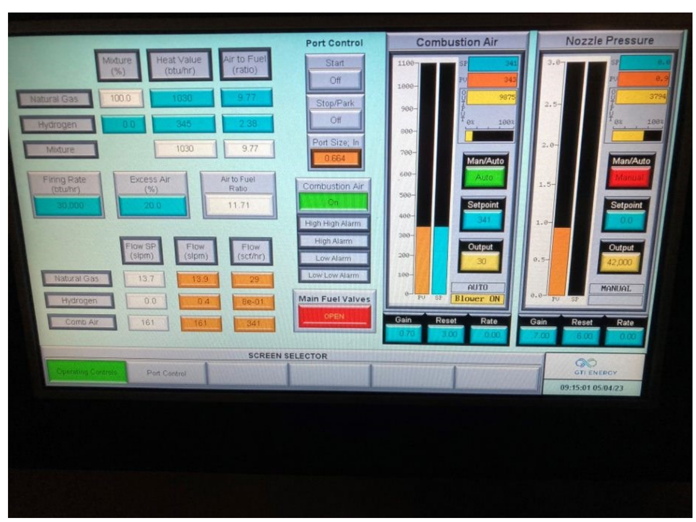
Operating fixed-port burners on HENG or other low carbon fuels can present some real challenges in real world use applications in terms of combustion stability, resiliency, efficiency, and process control. There is a need for new technical solutions and there are significant differences in operational requirements for the present designs of fixed-port burners to operate effectively with HENG natural gas mixtures or alternative low carbon fuels. The combustion characteristics of HENG will change significantly as more hydrogen is added to the supply fuel; for example, increased amounts of hydrogen can increase the flame propagation speed by about 5 times. An innovative new adjustable port technology can benefit consumers and ratepayers by: expanding competitive choices when operating on future low carbon fuel alternatives; preventing product obsolescence by being adaptable to changes in gas supply compositions including HENG mixtures; and allowing flexible operation on multiple fuels and lower carbon mixtures while retaining superior performance and operational reliability. This is expected to accelerate the reduction in greenhouse gas (GHG) emissions when low carbon fuel sources are used.

The primary target markets impacted will be commercial/industrial gas-fired equipment in capacity ranges of >0.5 MBH and <15 MBH such as water and firetube boilers, furnaces and kilns, and ovens. Secondary target markets include mCHP, DG and other end use products that can benefit from a fuel flexible high-performance burner.

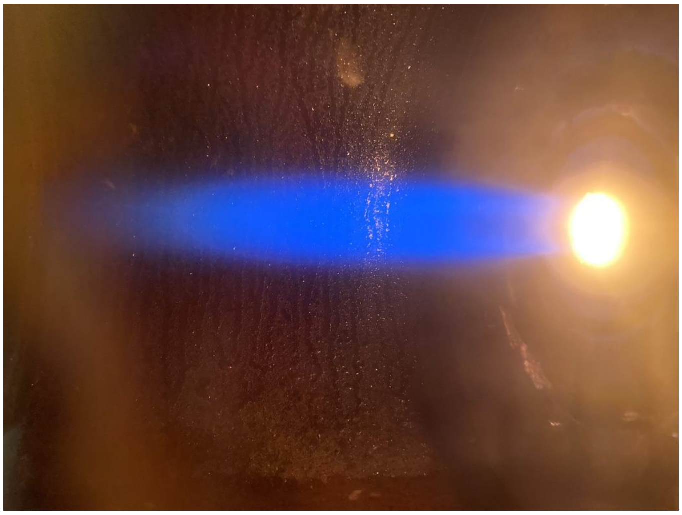
In the U.S., the American Boiler Manufacturers Association (ABMA) reported sales of 4,000-5,000 boilers per year since 1992 in the <10 MMBtu/hr market segment with an average unit size of 3.5 MMBtu/hr. Boilers in this segment of the boiler inventory are mostly found in the food, chemical and other industries and at education and health care facilities. A 2005 analysis by Energy and Environmental Analysis, Inc. (EEA) for the U.S. Department of Energy estimated that the commercial boiler inventory includes 120,000 units with an aggregate capacity of 1.1 million MMBtu/hr and consume approximately 1,630 TBtu/year, which is 28 percent of all energy inputs in the sector. Commercial boilers at U.S. office buildings, health care facilities and educational establishments account for more than half of commercial boiler units and capacity.



Laboratory Burner Testing



Burner Test controls


40% Hydrogen by volume at 90 kBtu/hr

Technical Concept & Approach

This project built upon earlier bench-scale testing of a conceptual prototype adjustable port burner by evaluating and demonstrating the burner performance fueled by HENG with increasing hydrogen content. The work focused on refining the operation of prototype adjustable port burner and demonstrating the active port concept with lower carbon fuel mixtures. The effort advanced the technology from Stage 3 – Research Implementation to Stage 4 – Technology Development.

The following tasks were performed in the project:

Task 1: Test Planning and Preparation

A test plan was developed to evaluate the performance of the prototype adjustable port burner which included a testing matrix and the parameter measurements consistent with typical laboratory burner evaluations. Testing in a single burner nozzle test station was planned.

This testing station facilitated direct testing of burners by recreating the heat transfer and flue gas flow conditions of a typical burner application while allowing for in-situ measurements that would not be possible if installed in a typical equipment configuration. The station featured a twelve-inch water-cooled firing chamber with quartz glass observation windows along one side for flame observation. Multiple ports were available for insertion of instrumentation and gas analysis probes. The single nozzle test station was modified as necessary to operate the burner on HENG with mixtures with up to 100% hydrogen.

Task 2: Burner Performance Testing

Based upon the test matrix developed in Task 1, the adjustable port burner technology was evaluated with a range of HENG (blending of hydrogen in natural gas from 0-100% by volume). The burner was tested for combustion emissions (O_2 , CO_2 , CO, NO_x) and flame appearance. Ignition testing was performed to ensure the burner ignited reliably, repeatably, and efficiently. Incorporation of modular design components that were easily replaceable and/or modifiable during the project was a primary consideration during this task.

Results

This testing confirmed that the adjustable port burner technology provides superior capability for a premixed burner to operate on Hydrogen Enriched Natural Gas (HENG) with higher hydrogen content more safely and reliably than conventionally-designed fixed port burners. The burner provided stable ignition and fuel combustion while operating with changing HENG composition (0 to 80% hydrogen blending), firing rate (30 to 90 kBtu/hr), excess air flow rate adjustments (20 to 35%), and exit port size adjustments made during burner operation. The burner was able to maintain low NO_x emission levels throughout the testing matrix. Automated burner operating controls were developed and they demonstrated how a burner with adjustable port technology can easily be incorporated using a standard industrial programmable logic controller (PLC) and Human Machine Interface (HMI). These controls were used throughout the testing to control the burner firing rate, fuel blend composition, excess air, and port size or exit port pressure control.

Status

A Final Report which describes the work performed, results, conclusions, and recommendations was issued in August 2023. Opportunities for next-step funding and efforts to advance the development of this innovative technology to a larger scale, including exploratory discussions with potential commercialization partners and seeking governmental or other research and demonstration grants, are being sought.

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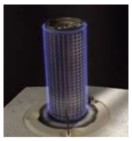
UTD Utilization Technology Development

Mitigating Methane Emissions From Large Commercial and Industrial End Use Equipment



Researchers quantified methane emissions from large commercial and industrial end use natural gas burners (focusing on startup and shutdown) and in partnership with burner manufacturers identified and tested some broadly applicable methods to mitigate these emissions, with a goal of reduce methane emissions by >50% during transient operations.

Project Description

The goal of this project was to identify and demonstrate broadly applicable methods to mitigate emissions from large commercial and industrial end natural gas burners, after first quantifying the methane emissions. Different widely-used burner types were evaluated, including high velocity, baffle and premixed burners with various ignition systems.

Earlier UTD efforts under UTD project 1.18.F tested methane emissions from three residential and small commercial burners which ranged from 180 KBtu/h to 1 MMBtu/h in capacity (each with a different burner design) and identified opportunities to mitigate those emissions. Testing showed that methane emissions during start-up were affected by the air-fuel ratio and overall burner designs, and that higher emissions were seen with higher excess O_2 in the mixture. Those results have been published.

UTD project 2.22.E extends those earlier efforts to larger commercial and industrial burners, by testing three types of burners rated from 1.0 to 3.2 MMBtu/h that cover a broad range of applications - from ovens and furnaces to boilers which are commercially available in capacities of 0.150 to 20 MMBtu/h.

Key Performance Indicators (KPI) for project success were to:

- Quantify methane emissions from three widely used large commercial and industrial burners representing a broad cross-section of applications. The burners will be selected in consultation with leading manufacturers.
- Quantify impacts of changing fuel-air mixing, ignitor positioning, lag time between air and fuel input and fuel ramp up.
- Develop methods for each of the burners to lower methane emissions during start-up and shutdown.
- Reduce methane emissions by >50% during transient operation.
- Engage burner manufacturers towards demonstrating transient methane emissions reduction in the field.

Benefits / Market Implications

Natural gas is considered a cleaner fuel alternative to coal, producing roughly 56% the amount of CO_2 per unit of energy as coal. Despite the environmental benefits of natural gas as an low carbon fuel source, the primary constituent of natural gas is methane (CH_4), a relatively short-lived GHG that has 28- 34 and 84-86 times the cumulative radiative forcing (ability to trap heat) of CO_2 on a mass basis over 100 years and 20 years, respectively. Recent studies indicate that CH_4 leakage into the atmosphere may negate some of the fuel's advantages, therefore, identifying significant sources of CH_4 emissions is imperative for effective development of methods to control emissions of GHGs.

Equipment tested – Large commercial/industrial furnace (left), commercial water heater (center) and modulating boiler (right)

Thus natural gas producers and distributors are under pressure to identify, quantify and reduce or eliminate the emission of methane, a greenhouse gas (GHG) with significantly greater warming potential than carbon dioxide (CO_2). While upstream origination and distribution have been a primary focus to date, post-meter emissions are beginning to be a focus area as well. Therefore this project provides measured data on methane emissions from large commercial and industrial burners, and identifies opportunities to mitigate these end use emissions.

Technical Concept & Approach

This project will develop and demonstrate methods to mitigate methane emissions from large commercial and industrial burners. The effort will advance the technology from Stage 3 – Research Implementation to Stage 4 – Technology Development.

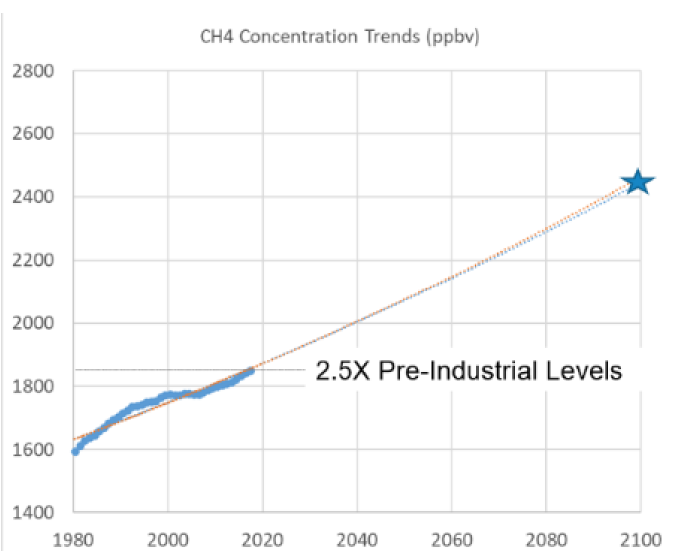
The project is broken down into the following tasks:

Task 1: Select commercially available burners

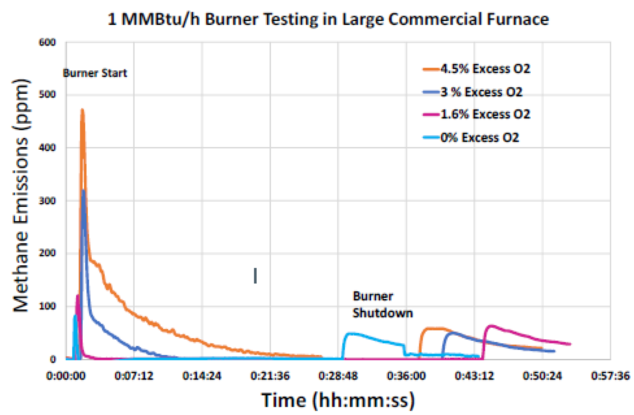
The team down-selected and acquired 3 different widely used large commercial-industrial burners to broadly cover fuel-air mixing types (high velocity, baffle and premixed burners) and ignition systems (spark and pilot).

Task 2: Setup test rig for burner testing

The team setup a test rig to operate with natural gas and installed the required flow controllers and instrumentation. The system allowed testing of the selected burners. The system was instrumented to measure air and gas flow rates, and combustion emissions. Testing was performed for a range of firing rates, air-fuel ratios, ignitor types, and lag and ramping times.



Increase in total methane emissions over time



Methane emissions in a large commercial furnace firing at 1 MMBtu/h at different air-fuel ratios

Task 3: Perform multiple burner testing

Baseline testing of the burners for methane emissions was performed to collect data and perform analysis based on the way these burners operate. This provides a clear understanding of the start-up, shutdown and steady state emissions and operational challenges related to methane emissions.

Task 4: Burner modification and testing to reduce or eliminate methane emissions

The team, in discussion with burner manufacturers, evaluated impacts of ignition, air-fuel mixing and injection timing and ramping changes to identify techniques for lowering the transient methane emissions, while maintaining burner performance. The testing provided experimental data for performance improvements that can reduce methane emissions.

Status and Results

Testing has concluded and the project is complete. A Final Report was submitted to UTD members in December 2023. Results from this project are scheduled to be presented in May 2024 at the International Gas Research Conference 2024, a major gas industry research conference.

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UTD Utilization Technology Development

Tecogen Hybrid Gas/Electric Chiller Laboratory Evaluation

Researchers will validate a promising emerging high-efficiency hybrid (natural gas/ electric) chiller technology. The new product will increase operational resiliency for end users, expand integration of gas and electricity, and provide facility owner/operators with increased demand side management of their gas and electricity consumption.

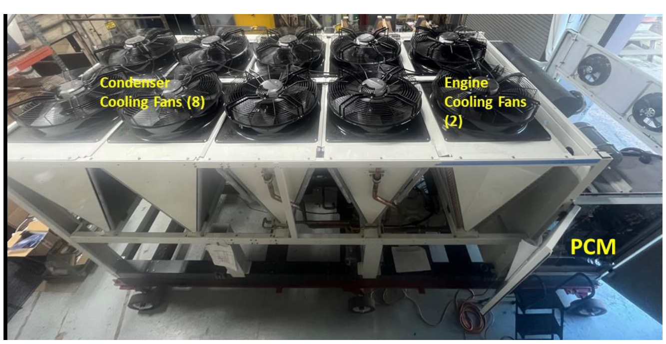
Project Description

The goal of this project is to validate an emerging high-efficiency hybrid (natural gas/electric) chiller technology being developed by Tecogen in order to support its market entry and successful commercialization. The new product line will provide 200-400 tons and represents a new option for end users to increase operational resiliency, provide more integration of gas with electricity, allow demand control of both electricity and gas consumption, align with microgrid developments, and build on Tecogen's proprietary power electronics / inverter / generator / engine system which is proven in their InVerde e+ combined heat and power (CHP) product.

The approach incorporates the proven integrated InVerde high voltage DC (600V) power electronics. Packaging will likely be a single-skid mounted unit that is significantly smaller than Tecogen's existing Tecochill RT product line. The packaging approach aligns with current market trends and supports resilience, sustainability, and ease of retrofit. The entire chiller is within the power scope and can power ancillary devices during a blackout. A utility electrical interconnection barrier is not required.

Key Performance Indicators of success for the research project will be to:

- Demonstrate capacity and measure efficiency from low load to 200 ton rating
- Demonstrate ability to power ancillary devices during blackout (pumps, etc.)
- Confirm heat recovery operation and capacity



Hybrid chiller prototype construction cell

- Support optimization of the control system to consider pre-programmed grid carbon intensity (gCO2/kWh), incorporate real-time utilization of heat recovery, and ability to dynamically shift percentage of one power input verses the other to provide the lowest GHG profile.

Benefits / Market Implications

Rapidly-escalating electricity prices and a focus on grid resilience has caused some facility owners to investigate alternative cooling systems such as gas-fired absorption chillers, gas-fueled engine driven chillers, and hybrid systems. Hybrid chillers can be optimized to provide the most economical or lowest carbon intensity cooling, often depending on the time of day used (e.g. during on-peak or off-peak electric periods) or when loads are light.

The primary target markets to benefit from this technology will probably be large commercial, industrial and other applications that need 200-400 tons or more of cooling with a high degree of resiliency and energy source flexibility in gas-grid supply-constrained markets or electric-grid supply-constrained markets with high electrical energy and demand charges. This may include:

- Hospitals, nursing homes, and other life-safety-critical institutions
- Food processing facilities and high-value manufacturing operations for which reliable temperature control is needed to avoid spoilage/lost production during electrical outage
- Mid-size colleges and universities; high schools
- Large multi-family residences
- Governmental or other mission-critical facilities
- Corporate or other small/mid-sized data centers

Tecogen's planned new product offers a hybrid gas/electric chiller to serve the very large market of end-users that need 200-400+ tons with key advantages:

•This product is a compact, integrated unit with built-in controls to allow easy fuel-switching, resiliency, and time-of-day

Tecogen InVerde e+ CHP (source Tecogen)

controls, which can optimize operation for maximum GHG reductions, minimum costs, or other factors selected by end user.

•It incorporates heat recovery for high efficiency CHP when in the operational mode fueled by gas and it's two power sources offer extra resiliency, such as during grid outages.

•It meets the strictest ultra-low emissions standards, including being SCAQMD compliant.

•It allows consumers to avoid electric demand charges and peak "time-of-day" rates and it can provide power to some ancillary devices during a blackout or even operate without a utility electrical interconnection.

Technical Concept & Approach

The project will validate the performance of Tecogen's hybrid gas/electric chiller over an 9-month period.

The project is broken into the following tasks:

Task 1: Evaluation agreement

The specifications of the hybrid chiller to be tested, evaluation approach, ownership of data etc. will be developed in an evaluation agreement.

Task 2: Test planning

The project team will develop a detailed plan for evaluating the performance of the gas/electric hybrid chiller over a range of turndown ratios and operating scenarios. The plan will describe the conceptual retrofit scheme, evaluation test matrix, schedule, duration, measurements to be made and intended outcomes that are consistent with laboratory evaluation.

Task 3: Installation and testing

The team will prepare a site in a laboratory for the hybrid chiller, secure the unit and initiate testing per the test matrix developed in Task 2, and analyze the test results.

Results

Tecogen has worked to complete fabrication of the test unit. Per Tecogen, work was conducted in the following areas. A Power Control Module was installed into Tecogen's electronics laboratory and successfully tested with power first applied to the engine/generator side and then to the utility side. The load was limited to about 80 kW, about 2/3 of the full rating and utilized a load bank. Testing was able to complete the initial draft of software relating to the Power Control Module control, although fine tuning of the control parameters will be necessary when chiller testing is initiated. An outdoor test loop was prepared for chiller testing with the main efforts applied to the chilled water piping.

Status

Tecogen has worked to complete fabrication of the test unit. A detailed project agreement with Tecogen is being prepared.

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FOOD PREPARATION AND SERVICE

UTD Utilization Technology Development

Commercial Foodservice Equipment Demonstrations

Through restaurant and commercial-cooking field demonstrations, researchers are gathering valuable data and refining a performance comparison tool to quantify the operating savings and efficiency benefits for end users of gas-fired commercial food-service equipment in real-world situations.

Project Description

Researchers and gas-industry representatives are conducting demonstrations of gas-fired commercial foodservice (CFS) equipment to quantify the benefits of the equipment in real-world situations. Demonstrations are designed to address the reluctance of some CFS operators to replace existing equipment with newer high-efficiency models because of concerns about higher costs or uncertainty that the new equipment will be able to prepare the food as expected. Chain restaurants – which represent about 50% of the CFS industry – are recognizing the long-term cost benefits of newer equipment; however, this information is not generally available to the rest of the industry.

In UTD-supported CFS demonstrations, technicians test selected equipment in the laboratory and/or at commercial demonstration sites and document performance. Testing is being conducted with some of the industry's most recent market introductions, including a steam kettle, range, conveyor oven, convection oven, boiler-less steamer, low-oil-volume fryer, and griddle. Any other appliance of particular interest could be targeted for laboratory performance testing or field demonstrations.

Demonstration activities are focused in two areas: 1) long-term demonstrations in restaurants; and 2) single-day demonstrations at test kitchens and trade shows showing how well new high-efficiency equipment performs when compared to traditional equipment, including the development of software and associated data collection to visually demonstrate equipment performance results.

Griddle testing at Piedmont Tech Center.

Benefits / Market Implications

Verifying the performance of a CFS technology in the laboratory or the field will demonstrate the advantages of specific technologies and provide valuable performance information for end users, utilities (to aid the development and refinement of their energy efficiency incentive programs), manufacturers and others with the ability to quickly evaluate appliances (whether gas-fired or electric-driven), and understand the true efficiency and cooking performance of the appliance.

Technical Concept & Approach

The appliance performance and feedback from the test sites will be incorporated into reports detailing the benefits and performance of the systems. In addition, a system to provide comparative real-time energy consumption and product performance of various CFS equipment will be developed.

Opportunities for demonstrations are being identified at other utilities and end-user host sites as additional project funding is provided. The time and cost varies based on the appliance and scope of the tests.

Results

Whole-kitchen assessments (WKA) were conducted at:

- A 120-seat restaurant that serves a wide variety of dishes and is especially known for its extensive dessert menu of pies. **Findings:** Replacing the existing fryers, convection ovens, and griddle with energy-efficient models would save 2,597 therms ($1,346) per year of energy usage. Assuming an operational life of 12 years, the total savings is 31,164 therms and $16,152.
- A full-service caterer. **Findings:** Replacing the existing convection oven, combination oven, and griddle with energy-efficient models would save 668 therms ($349) per year of energy. Assuming an operational life of 12 years, the total savings is 8,016 therms and $4,188.
- Two counter restaurants with menus that focus on hot dogs, burgers, sausages, and French fries. **Findings:**

"UTD developed and provided software capability that allows our customers to make an informed decision on energy consumption before purchasing. It is user friendly and allows a clear demonstration of energy use with live data. Our new Technology & Design Center is all about innovation, flexibility, and versatility. The implementation of this program adds to the overall capability of the Center, delivering added value and helping our customers make the best purchasing decisions."

- Carl Peterson
Manager, Gas Regional Sales
Piedmont Natural Gas

Replacing the existing fryers and griddle with energy-efficient models would save 2,721 therms ($2,535 per year) of energy. Assuming an operational life of 12 years for both appliance types, the total savings is 32,652 therms and $30,420.

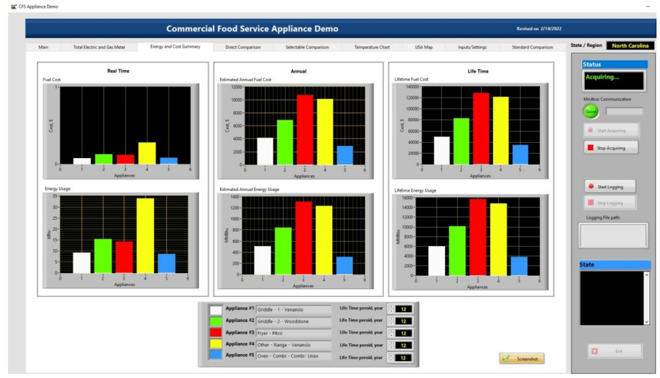
Overall, the WKAs showed the potential savings of 109,000 therms and $85,716 over a 12-year appliance lifespan if the standard equipment used in just these four locations were replaced with existing energy efficient options.

A fryer comparison demonstration was initiated at a casino. The demonstration compared three different models from different manufacturers. Three baseline fryers were monitored. After about a month of monitoring, the baseline fryers were replaced with ENERGY STAR equivalents from three different manufacturers.

In 2018, a cooking demonstration was conducted in Tulsa, OK, where the energy usage for four fryers were compared with each other and with standard gas and electric units. Annual energy cost savings for the highest-efficiency fryer tested was $540 per year when compared with a standard gas fryer and $785 per year when compared with an electric fryer. Data collected during the demonstration showed that a CFS facility could achieve significant operational savings by using energy-efficient natural gas-fired equipment compared with standard gas-fired and electric equipment. Based on these results, UTD members directed the project team to further design and develop a Foodservice Energy Monitoring System (FEMS) under subsequent phases of this project that could be used at trade shows, test kitchens, and similar venues.

In 2019, a new demonstration site was identified and evaluated for replacing an electric fryer with an energy-efficient gas unit. The entire menu is prepared in the kitchen equipped with an electric fryer, oven, and rangetop. Advancements were also made to the FEMS system.

In 2020, researchers also began working on a unique opportunity on a larger rack-oven monitoring project. Data from rack ovens in California and the Midwest was analyzed to determine potential energy savings of efficient models. Efficient gas ovens should have a much lower source-energy use and significant cost savings that can be proven through this project.



One tab of the FEMS Tool

Unfortunately progress under this UTD project was impacted during 2020-22 due to Covid-19 and its dramatic impact on the CFS industry, including at some field test sites planned for this project.

In 2021, the project team completed work with Duke Energy's Piedmont Natural Gas subsidiary to install and test a FEMS data collection and visualization system in Piedmont's new test kitchen. The system monitors, records, and displays data on the performance of various appliances being cooked on at the same time and how they compare to each other. Researchers also continued to monitor the baseline fryer in Detroit and a Royal range high-production fryer in Tulsa; analysis of the data found a 50% reduction in gas use with the new Royal range fryer.

In 2022-23, a high-efficiency fryer was delivered to a restaurant in Detroit in coordination with UTD project 1.14.C, but the opening of the restaurant has been delayed due to facility renovations as well as unavailability of some other equipment. In addition, the FEMS system was upgraded to be able to print a pdf report of the results of live testing; this report can be instantly printed for end users to take with them and help make informed equipment purchase decisions.

Status

Researchers are closing out two fryer demonstration field demos as well as the rack oven analysis. The timing of this will depend on the status of the ability to gain data from the high efficiency fryer installed in the Detroit restaurant.

The FEMS software is available for equipment distributors or other test kitchens that want to show live cooking performance of equipment and help end users assess and implement energy conservation and operating cost saving options.

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UTD
Utilization Technology Development

Demonstration of High-Production Fryers

Commercially-available high-production, high-efficiency fryers are being evaluated in a test kitchen and in operating restaurants to compare their performance to alternative gas and electric models in order to support decision making by end users.

Project Description

High-energy-density electric-powered fryer models are capable of delivering more heat in a given amount of frying space than gas-fired fryers on the market. However, today's advanced gas heat-exchanger designs can transfer more heat from a burner in a given frying space than electric models, allowing gas models to better serve end users who need high-production capacity.

To demonstrate current technology, in this project a research team is testing and evaluating two high-production fryers at test kitchens, followed by demonstrations at field sites.

Sites within the sponsors' territories are chosen to demonstrate the efficiency, cost, and production benefits of commercially available gas fryers.

Detroit baseline fryer.

Benefits / Market Implications

High-performance gas-fired fryers are often used in commercial kitchens. Generally, gas-fired models will save end users money and reduce emissions (on a source-energy basis) versus their electric counterparts. Producing high-production models that cook well and deliver even greater cost savings will further serve end users in the fryer market.

Technical Concept & Approach

Leading high-production gas fryers are being compared to standard electric and gas fryers. Sites are being sought to document the energy efficiency and performance advantages of high-production fryers and include baseline monitoring of previous fryers to demonstrate the potential cost and energy savings. Sites with both legacy electric and gas fryers are being sought to assess the benefits over older -generation models.

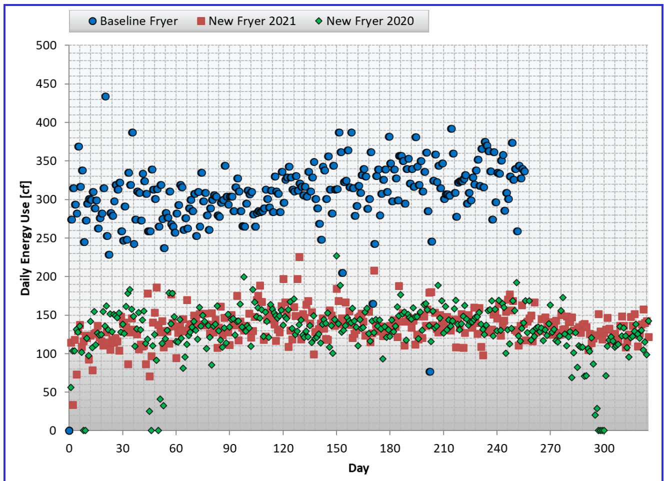
Site surveys will also obtain direct feedback from users on the performance advantages of the new system.

Results

In 2018, the research team conducted a field demonstration of a high-production fryer in Oklahoma, with a one-day test demonstration comparing four different fryers. The fryer was installed at a field test site and data and results are being collected.

A high-production fryer was demonstrated in collaboration with UTD CFS demonstration project 1.14.B. This high-end gas fryer was compared in a test kitchen one-day evaluation with a low-cost ENERGY STAR gas fryer, a baseline gas fryer, and an additional standard gas fryer the site had on hand (as well as a comparison to an estimated electric fryer). Energy use was monitored in real time with gas and electric meters, while also measuring recovery time with thermocouples in the oil. Results showed that the unit saved 56% energy use while also recovering quicker and cooking the food faster than the baseline gas model. The unit also saved 32% over a low-cost ENERGY STAR gas model.

The project team purchased one of these same fryers for installation at a barbeque restaurant in Tulsa that had already been baselined. In 2019, the new fryer was delivered and installed in Tulsa.



Results from the Tulsa demonstration show that large energy and cost savings can be achieved with the new high-production fryer.

Tulsa test fryer.

A second site was found in Detroit and baseline monitoring completed. At the test sites, detailed energy usage, cost analysis, and usage profile reports are being produced to demonstrate the benefits of high-production gas fryers. The high-production gas fryers are being compared to standard electric and gas fryers.

Researchers also monitored the baseline electric fryer in Detroit. The project team specified and ordered a high-production, high-efficiency fryer to finish out this testing. The new fryer is planned to be delivered and installed in the fall of 2023.

In 2020-2022, researchers monitored the high-production fryer in Tulsa. The fryer monitoring had issues with a temperature sensor and control that was leading to the oil being too hot, and this led to the installation of a new controller. Finding this issue as part of the demonstration will lead to permanent changes for the model design and make this high-production fryer operate more efficiently in the future.

The research team completed analysis of the site in Tulsa, finding around a 50% reduction of gas use with their new high-production fryer.

Status

The first fryer demonstration has been completed and large cost and energy savings have been shown. The second fryer demonstration at a restaurant in Detroit was delayed for a long time due to the impacts of Covid-19, and remains on hold. The project team specified and ordered a high production and efficiency fryer to finish out this testing and the fryer was delivered during the last quarter, but the restaurant is waiting on other equipment to arrive as well as to complete some facility renovation work before the new high production and efficiency fryer is put into service and performance data on it can be obtained.

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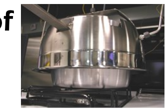
Residential Cooking Pollutants and Indoor Air Quality

Researchers are conducting an analytical and laboratory investigation on the impact of residential cooking on indoor air quality (IAQ). Rigorous scientific methods are being used to determine emissions. Novel new burner designs are also being investigated.



Project Description

A research team is conducting an analytical and laboratory investigation on issues and concerns for indoor air quality (IAQ) with residential cooking based on information from a review of existing literature and data from this project.

The project uses rigorous scientific techniques to experimentally determine the impact of residential cooking on IAQ and to identify opportunities to advance technologies.

Phase 1 of the project studied capture hoods and showed that the capture effectiveness of residential hoods was less than 50% for cooking on the front burners and would be ineffective at capturing cooking and combustion emissions. The current phase of the project is being conducted to determine what types and the volumes of emissions that are present in residential cooking, including NO_x, particulates, heat, and moisture. Phase 1 also conducted a review of the relevant scientific literature, and the characterization of some studies in some popular press articles. This review also analyzed the methodology of measuring emissions and conclusions drawn based on that data.

Information from Phase 1 was used to guide Phase 2 laboratory tests, including determining which emissions should be measured and what technology improvements may be needed to improve IAQ.

Shakedown of cook-testing equipment.

The objective of Phase 3 is to develop and test new burner designs for residential ranges. These will include drop-in designs for existing ranges and power burners for new models. The goal is to design a drop-in solution for residential range burners with at least a 50% improvement in efficiency and 60% improvement in NO_x emissions compared to existing burners. Reviews of new technical publications pertinent to this topic will also be performed.

Benefits / Market Implications

With increased concerns about tight homes and Net Zero Energy homes data is needed to fully understand the impact that residential cooking has on indoor air quality and what changes may be needed to residential cooking ranges, burners, and capture hoods to meet consumer's needs.

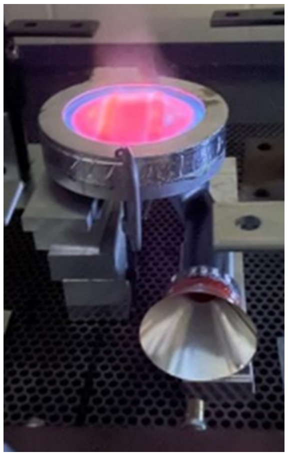
Technical Concept & Approach

Researchers are using an existing residential cooking setup to perform an analytical and laboratory investigation into the pollutants contributed by gas and electric residential cooking for a standard residential range that includes rangetop and oven cooking. These emission types were identified in the literature as the ones most negatively associated with cooking with natural gas. Established testing protocols and procedures for cook testing emissions capture are used to quantify the emissions. A comparison will be completed for gas and propane vs. electric ovens and an evaluation completed to establish emission capture impact on IAQ and implications for rangehood design.

Research is being conducted to determine how improvements in emissions and efficiency can be achieved by modifying the existing residential burner design or using a new burner concept. The impact in IAQ issues will be calculated based on the improvements in emissions and efficiency, including percent reductions in NO_x and other combustion products.

The technical approach includes:

- A complete review of existing literature and data on cooking with natural gas and IAQ
- Data and analysis from the laboratory investigation on burner and hood performance, and

- Details on how burner design and performance impact IAQ.

Testing were conducted with propane as well as natural gas under co-funding provided to UTD by the Propane Education and Research Council (PERC).

Results

A review of existing articles and presentations on the effects of cooking with natural gas on residential IAQ found many examples of conclusions or statements based on inconclusive or inadequate data. These results create more questions than answers for what conclusions can be determined for the effects of residential cooking on IAQ for both gas and electric as the primary energy source.

This project's researchers found that many of the publications had questionable conclusions on NO_x and asthma – specifically making conclusions about the relationship between cooking with natural gas and asthma that appeared to be more coincidence than causality. The articles tended to use implied results from several studies to make a single conclusion against natural gas when none of the articles make a definitive claim on the causes of asthma and all stated that more research is needed. One report did not include NO_x emissions data from the oven or data on how NO_x disperses from the oven into the living environment. Basically, no attempt was made to correlate the NO_x emissions from the oven to total value of measured NO_x in the home. Another almost universal conclusion from the reviewed articles was that proper ventilation for both gas and electric cooking greatly improved indoor air quality.

Cook testing is providing consistent results such that the data can be used to compare natural gas, propane, and electricity. Results showed cooking emissions were more a function of the cooking vessel and food product cooked than energy source. In some tests, electric ranges had higher food emissions than electric, apparently due to difference in the consistency of the heat provided for cooking.

The project team designed a prototype burner concept that had NOx emissions of less than 10 ppm compared to 80-100 ppm for a standard range burner. The prototype also had improved efficiency.

Status

The team is completing ventilation testing for Phase 4. In Phase 5 and 6, more cook testing will be completed including comparing gas to induction in terms of cooking emissions, cooking performance and combustion emissions including source emissions. Results will be presented at the 2024 ASHRAE Winter Conference.

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UTD Utilization Technology Development

High-Efficiency Smart Convection Oven

Efforts are under way to develop a prototype high-efficiency smart convection oven that increases energy efficiency by 5% to10% and integrates superior smart operating controls to maximize food preparation quality and consistency.

Project Description

Commercial convection ovens use a high-temperature cooking process, which means that the flue products need to leave the system at no less than the oven setpoint temperature of 350ºF-500ºF. Convection ovens by design also constantly flow heat out of the oven as they operate (with the fan flowing air across the oven and then out the flue), which results in high standby energy use.

There are currently 36 gas ENERGY STAR convection ovens available, but they deliver only 44%-55% cooking efficiency.

In this project, researchers are incorporating a heat exchanger to recover heat from the flue and feed it back into the combustion air. The objective is to develop a prototype high-efficiency smart convection oven that increases efficiency by at least 5%, and also integrates superior smart operating controls to maximize food preparation quality and consistency.

This project will also demonstrate the design through a field demo of prototype units at one or two field test sites selected in partnership with UTD project funders.

Earlier, researchers investigated a high-efficiency oven design, showing that this design in bench-scale tests was able to achieve a 3% improvement to cooking efficiency and a 10% improvement to preheat energy use despite not being fully optimized. Based on these results and areas for improvement that were found in that initial design, the project team anticipates that a 5%-10% cooking efficiency should be achievable once the design has been optimized. In addition, a targeted 10%-20% reduction in NO_x and CO emissions are expected.

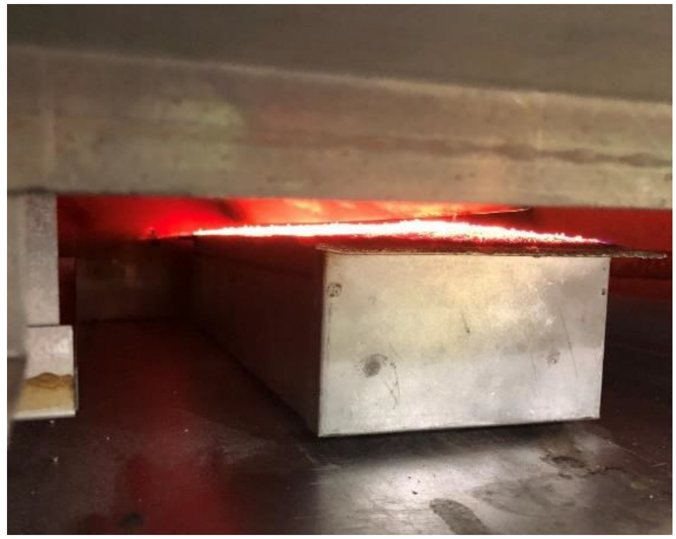
Benefits / Market Implications

The population of convection ovens in the U.S. is estimated to be around 650,000-700,000, according to a 2015 U.S. Department of Energy study. About 32% of commercial foodservice operations have at least one standard convection oven.

Convection ovens currently use 800 therms annually according to the ENERGY STAR calculator tool. A 2013 California Energy Commission analysis found that replacing existing convection ovens with even 44% minimum ENERGY STAR level ovens resulted in an average energy use reduction of 40% across three field test sites.

The proposed design is targeted to be 10% more efficient than current ENERGY STAR designs. When compared to

Laboratory analysis of a commercial oven

Left: Burner firing in the combustion chamber. Right: Premix burner installed on the bottom of an oven.

installed ovens, it could save more than 50% of the energy use (i.e., over 400 therms per year). A 50% savings translates to $300 in savings annually for the customer (assuming $0.75 per therm) compared to baseline existing ovens. It would be expected to pay back in one to two years, since the cost premium may only be around $300-$400.

The project team is also incorporating experimental smart system controls for end users to enhance the quality and consistency of food preparation. Smart system controls may also provide a useful data stream to a manufacturer to provide enhanced warranties, superior customer service, and identify future product marketing and development priorities.

Technical Concept & Approach

This project focuses on developing and demonstrating a prototype next-generation, high-efficiency, smart convection oven in coordination with a leading manufacturer. An innovative heat-recovery heat exchanger and burner design will be incorporated into an existing oven, with the goal of reaching 5%-10% improvement to the cooking efficiency and standby energy use of the oven. In addition, the project team will determine if sensors can be incorporated to make the oven smarter.

Results

In 2020, baseline testing of a current ENERGY STAR oven was completed. A computational fluid dynamics model was made to model several different heat-exchanger designs that could be applied to this oven design. Several heat-exchanger designs and variations were created and researchers began modeling their performance.

Technicians fabricated a prototype heat-exchanger design and installed it on the convection oven for testing in the laboratory along with a blower and controls. The initial testing showed that the standby energy use was reduced by 15%. A few additional design modifications were decided on in coordination with a leading manufacturer and modeling designs were completed. A final heat-exchanger design was selected based on all of the modeling results.

A potato cook test was completed using the prototype oven. Results showed a 4%-5% increase in efficiency over the baseline. A heat-exchanger modification was made to further boost efficiency and installed in the oven. All of this testing was done with the existing oven burner setup. Researchers specified and ordered a new prototype burner to be used with a premix system.

The team completed ASTM testing of the premix burner system. The results of premix without modulation didn't show improvement over the standard burner system with heat recovery, but it's possible it could be further improved by modulation.

Status

A final report has been submitted for Phase 1, showing the cook efficiency improved by 12% and the standby energy use by 15% with the heat recovery system. The team is seeking a manufacturing partner to take the technology to market.

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UTD Utilization Technology Development

Gas-Fired Warewasher

Efforts are under way to develop prototype gas-fired door- and conveyor-type ware-washers in the laboratory. When commercialized, consumers could achieve significant energy and cost savings by using a new option of gas-fired warewashers.

Project Description

Most commercial dishwashers (also called warewashers) are electric driven, and many electric warewashers use chemicals (i.e., "chemical warewashers") rather than high temperatures to disinfect, which further increases their environmental impact. This project is developing reliable gas-fired warewashers so that consumers can have more energy choices and reduce their environmental impact and operating costs.

Four types of commercial dishwashers are available to wash and sanitize plates, eating and cooking utensils, and other items: flight type; rack conveyor; stationary door; and undercounter. Flight-type and conveyor warewashers are used for high-volume applications.

This research project is developing prototypes of both door-type and conveyor-type gas-fired warewashers. These are two very popular warewasher types, representing a combined 43% segment of the warewasher market.

Benefits / Market Implications

Warewashing equipment is a significant part of the commercial foodservice business, with global equipment capital costs estimated to be approximately $4 billion per year. There are more than 100,000 conveyor-type warewashers in the U.S. alone. A reliable gas warewasher would provide large operating savings for commercial foodservice facility owners and operators while also reducing source-energy and chemical use.

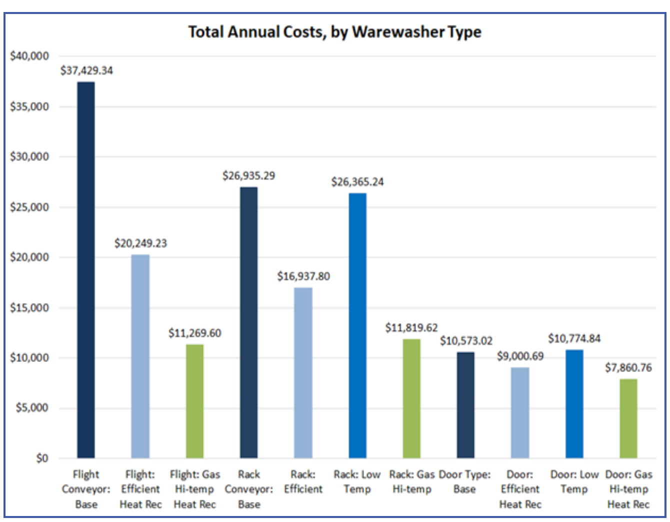
Initial estimates indicate a site will only use one-third of the source energy with a gas warewasher compared to alternative technologies. Even a representative low-usage restaurant, with only 1,100 therms of annual usage, would reduce the carbon footprint of the restaurant from 49,610 pounds of CO_2 per year with electric units to 16,088 pounds of CO_2 per year. In addition, it would cost the restaurant three times more (using national average gas and electric prices) to run that warewasher on electricity instead of gas. The restaurant would save more than $1,900 a year on operating costs with switching to a gas warewasher.

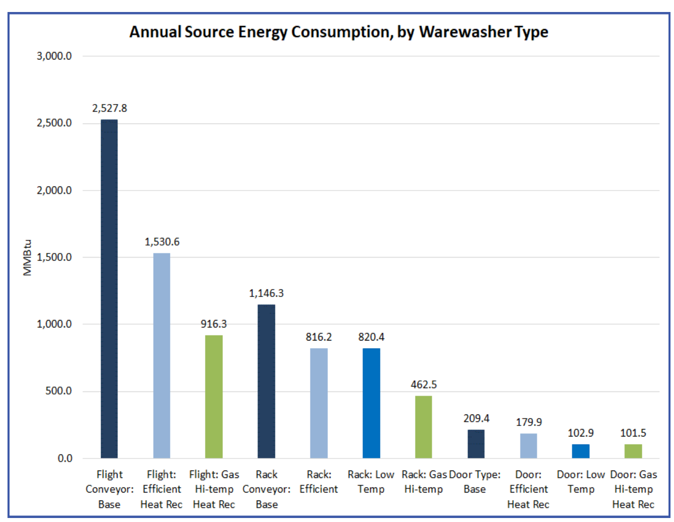
Data from earlier UTD project 1.18.B showed that a gas-fired conveyor warewasher would save a restaurant $15,115 per year over a standard electric warewasher and $5,118 per year over a more efficient electric warewasher with heat recovery.

Technical Concept & Approach

In this project, researchers and a manufacturing partner are modifying current electric-driven warewashers as they develop prototype gas-fired warewashers.

Different heat exchanger designs are being modeled to



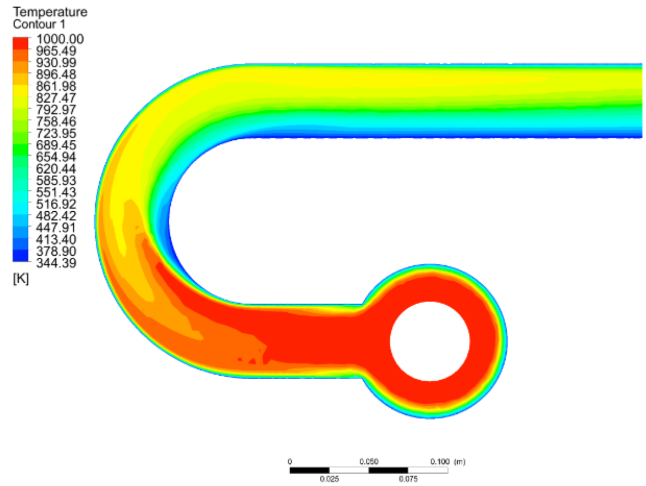


determine the best-performing designs that fit into the needed footprint of an existing electric warewasher. Prototype heat exchanger(s) will then be fabricated and put into prototype warewashers along with a burner and blower. The design will be tested and refined to continue to improve performance and address any issues that occur with initial testing.

Functional prototypes will be tested for combustion efficiency, safety, and emission standards. The results from testing will also assess improvements over electric units.

One prototype will be tested by a manufacturer partner in its facilities and one in a laboratory to prove the performance of the machine. The results will be used to finalize the design or any potential issues that may need to be resolved.

A field demonstration will be conducted at test sites. Test sites will be baseline-monitored for six months, followed by at least six months of monitoring the prototype gas-fired warewashers.



Example CFD model.

Results

Door Gas-Fired Warewasher

In 2020 and 2021, the project team continued to work closely with a manufacturing partner. Researchers modeled 13 variations of different heat-exchanger designs and tested the combustion system in the laboratory with the prototype warewasher tank and heat exchanger.

The project team developed some basic heat-exchanger designs that would fit into a given warewasher tank space. The main constraints were the small dimensions of the tank as well as avoiding contact with and allowing for access to the strainer.

Researchers investigated a variety of burner types to fit in the heat exchanger and provide the needed surface area for heat exchange. Two burners were provided, both of which performed well on emissions.

Technicians assembled the burner, blower, and gas valve assembly, along with a new control for the combustion system. Initial testing of the combustion system in the prototype heat exchanger was completed.

Conveyor Gas-Fired Warewasher

Modeling was conducted to determine the heat-exchanger designs that could have the best performance in a conveyor warewasher. The team was able to test the real-world performance of this at an installation in the Chicago area to get actual performance data of the heat exchanger and burner. After some modifications, the test results did align with the expectations of the model.

Status

Next steps in this project will involve demonstrating in coordination with the manufacturing partner the effectiveness, cost savings, and energy savings of gas-fired conveyor warewashers for end users at field test sites.

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Field Evaluation of Indoor Air Quality in Residential Kitchens

Efforts are under way to determine the effect of cooking emissions on residential indoor air quality in a scientific manner in real-world situations through field evaluations. This project presents the opportunity to collect field data to differentiate emissions from cooking processes versus emissions from appliances.

Project Description

Some publications reporting on residential indoor air quality (IAQ) have suggested that emissions from cooking can negatively affect a home's air quality. Specific emphasis is sometimes put on combustion emissions instead of emissions produced from the food, whether cooked using electric or gas. This project will help address the need for scientific data to quantify the effects on IAQ from natural gas cooking, and collect real-world scientific data.

A field evaluation study of overall building performance on two geometrically twin multifamily buildings is being conducted in Chicago. The uniqueness of the location is that it represents one of the only buildings in North America that not only meets rigorous energy-design standards, but includes natural gas for cooking purposes.

This UTD project is using the unique ready-made field test project site to help quantify the effects on IAQ from natural gas cooking and collect scientific data.

Benefits / Market Implications

This project presents the opportunity to collect field data to differentiate emissions from the cooking processes versus emissions from the appliance (gas and electric) in order to aid consumer understanding.

Technical Concept & Approach

To determine the emissions attributed to cooking food versus emissions attributed to residential ranges, emissions testing is being conducted with gas ranges in 12 units (six direct-vent outdoor hoods in an ENERGY STAR building; six recirculating hoods in another building).

Researchers will evaluate trends in concentrations of various emissions, temperature, and humidity in the kitchen space during cooking with the gas range. Technicians will cook two of the same meals in at least eight of the 12 apartments in addition to the laboratory. Emissions among apartments will be analyzed.

In the second configuration, a select number of gas ranges will be replaced with electric-induction ranges. Emissions testing will be conducted in the same manner as with gas ranges.

Energy consumption data on the heat pump space conditioning systems that are already installed will also be collected.

Specific tasks include:

- **Site and Instrumentation Preparation**

  The project team prepared an information guide for tenants, site agreements, pre- and post-tenant surveys, a survey of existing instrumentation, and specifications for sensors.

- **Installation and Commissioning**

  All IAQ instrumentation was installed. Cooking event log/surrogate will also be installed prior to commissioning.

Frying Bacon and Eggs on a Gas Range Top in the ENERGY STAR Residential Unit with a Direct Vent Range Hood

IAQ sensor installed in kitchen with an energy-recovery ventilator.

- **Field Test**

  The project team is providing on-site monitoring and troubleshooting. Complementary support from a testing laboratory will be provided to ensure consistent cooking in housing units by providing same-ingredient meals.

- **Data Analysis and Reporting**

  Preliminary analyses will include general trends and correlations. Results will compare cooking emissions from gas and electric residential ranges.

Project participants include a researcher from a leading university.

Results

The IAQ sensor packages and range cooking-location sensors gathered gas and particulate measurements from six kitchens in ENERGY STAR units and six Phius-occupied units. (Phius is non-profit organization committed to decarbonization.) The gas and particulate data are being analyzed during cook events and non-cooking periods. Researchers are comparing ventilation strategies based on gas and particulate measurements between the direct-vent range hood in the ENERGY STAR units and the recirculating hood and heat-recovery ventilator in the other units.

A variety of food products – including bacon, eggs, pasta, and chicken nuggets – were cooked in an apartment to evaluate the hood performance and IAQ effects. The apartment was constructed to Phius energy standards. The cooking processes included pan frying, boiling, and baking. Foods were cooked on both the gas range and induction hob. A recirculating range hood and an energy-recovery ventilation system was operating in the apartment used for the IAQ cooking evaluation.

The team has completed analysis of:

- 1-second gas and particulate measurement data during the natural gas and induction cooking events and non-cooking periods in the ENERGY STAR and PHIUS buildings
- IAQ sensor data for NO2, CO2, CO, RH, TVOC, PM2.5 and Formaldehyde during ambient and background conditions
- IAQ sensor data during cooking tests conducted in apartments and comparing ambient, background conditions.
- Time weighted averages
- Ventilation strategies between the direct vent range hood in the Energy Star units and the recirculating hood and heat recovery ventilator in the PHIUS units

For Phase 2, the team sourced and purchased typical residential range hoods, both direct vent and recirculating, reviewed current residential hood performance standards and performance test methods, and characterized typical hood airflow measurements. The team is in the process of measuring performance characteristics of the baseline hood such as airflow rates and capture and containment effectiveness.

Status

The Final Report for Phase 1 was submitted to UTD members in December 2023. The project team will continue measuring performance characteristics of the baseline hood such as airflow rates and capture and containment effectiveness, and work with the Association of Home Appliance Manufacturers (AHAM) to choose the best-in-class hood for Phase 2.

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UTD
Utilization Technology Development

Technical Support to Address Gas Foodservice Technologies

This project provides technical support and assistance to commercial foodservice industry groups and manufacturers to make advancements so that end users can increase energy efficiency, decarbonize, reduce emissions, and enhance cooking performance.

Project Description

The majority of appliances used in the projected $900 billion North American commercial foodservice (CFS) industry use natural gas as the main fuel source. Compared to other commercial products, CFS has traditionally had fewer regulations in terms of efficiency, emissions, and other operational requirements. However, with the push for more efficient technology, improved emissions (especially in California) and decarbonization, newer regulations are being developed and implemented. Concerns with new regulations and misinformation about the performance of gas-fired units compared with electric units resulted in many CFS locations deciding to purchase electric equipment. In some cases, the advantages of the electric equipment justify its use, but in most cases gas fired would still have the advantage in terms of cooking performance and energy costs.

Energy-efficient options for most categories of cooking equipment are currently available; however, the industry has been reluctant to adopt new technologies. CFS owners and operators have traditionally been hesitant to replace functioning equipment or buy new efficient equipment because of first costs and concerns that the new equipment will not cook to the same quality as the current equipment. The main issue is that end users do not have information readily available detailing the long-term savings vs. the initial costs of more energy-efficient equipment and have not had a chance to observe and compare the cooking performance. Post COVID recovery of the industry has also resulted in the sales of cheaper less efficient equipment to increase because of the initial cost savings.

Cooking demonstration at Louisiana Restaurant Expo of energy-efficient CFS Applications.

For previous projects similar in scope to this one, the project team attended meetings or served on committees that addressed over 40 issues associated with CFS equipment, including NOx emissions in California, gas vs. electric cost for a CFS fryer for two chain accounts, data protocols for CFS, and meetings with various trade organizations and industry groups.

More than a dozen cooking demonstrations were conducted at conferences and other industry events. At the events, information on the energy and cost savings of efficient gas equipment was conveyed to consumers using the CFS tools and calculators developed with funding from the UTD.

This project provides technical support and assistance to CFS groups and manufacturers to make advancements related to energy efficiency, environmental impact, decarbonization, cooking performance, and COVID recovery.

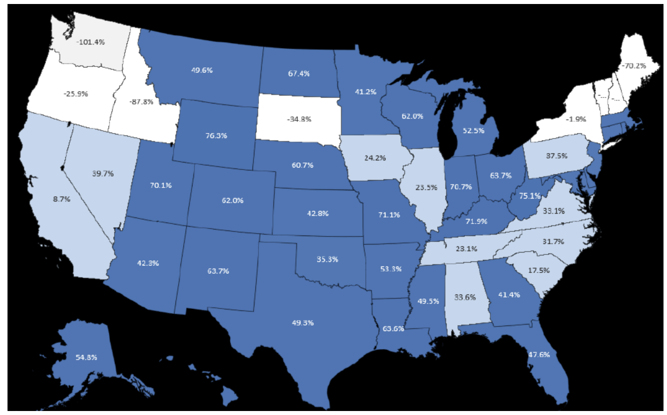
Project representatives represent gas ratepayer interests by assisting in consensus-development efforts within technical advisory committees, including ASTM F26 for commercial foodservice, the North American Association of Food Equipment Manufacturers (NAFEM) Technical Advisory Committee, ASHRAE CFS Ventilation, and the Blue Flame Alliance Technical Advisory Committee. Technical information that helps CFS manufacturers meet California's low-NOx requirements will be provided.

The project team will also work with CFS manufacturers and end users to provide data and education on the benefits of developing and adopting efficient, low-emission gas appliances.

Benefits / Market Implications

CFS is a large market with sales of about $900 billion in North America before COVID. Post COVID projections show the industry is expected to recover and grow at a rate greater than 5% for next several years. This growth is significantly ahead of most other commercial industries. The National Restaurant Association also projects total employment grow to over 16.9 million by 2029.

Of the approximate nine million commercial cooking appliances installed and operating in North America, roughly 70% are powered by natural gas (in categories where there are gas and electric options), with an estimated five billion therms of natural gas consumed annually. This large customer base needs accurate information about equipment performance, impacts, rules, regulations, and other topics related to energy selection.



Percent Difference in Annual CO2e Emissions (efficient gas compared to electric; example output from http://cfscalc.gastechnology.org/)

Technical Concept & Approach

The following tasks are being performed:

- **Technical Assistance to CFS Industry**

  In this task, a project team provides scientific and technical information to support technical committees as they consider changes to existing or new standards and methods of test relevant to CFS equipment design and use. Focus areas include decarbonization and NOx emissions.

- **CFS Consumer Education and Outreach**

  Researchers demonstrate the value of efficient, clean-burning gas-fired cooking equipment and promote advanced CFS equipment by providing data using the CFS tools and calculators developed in previous UTD projects and also by developing new calculators.

- **Technical Assistance to CFS Manufacturers**

  The project team assists manufacturers with addressing technical issues related to gas burner design and operation. This includes complying with pending NOx and efficiency standards, specifically distributing information on testing procedures and required testing equipment.

Results

In 2023, the project team provided technical support and/or expertise to organizations including NAFEM, Blue Flame Alliance, and a major gas utility. The team also met with a residential range manufacturer to discuss technology issues with current designs for burners in residential ranges.

A project representative led the Fuels Group in NAFEM's Technical Liaison Committee. The group presents and discusses energy usage and supply issues with CFS manufacturers and other energy-related organizations.

The project team has provided information to the gas industry about the use of hydrogen in CFS and how CFS industry is changing post pandemic. One of the biggest changes in the industry has been increased consolidation of CFS equipment manufacturers due to acquisitions of competing OEMs. The project team conducted several webinars on indoor air-quality issues with residential cooking.

An existing tools and calculators website is being modified to have a new user interface including highlighting decarbonization calculations (http://cfscalc.gastechnology.org/).

In 2023 the team helped inform technical issues by continuing to serve as the chair of the Fuels committee for NAFEM, supplying information and data for developing energy efficiency measures for range tops in California, and providing information and expertise on potential NOx emissions rules at the state level.

The team worked with various manufacturers on concerns ranging from resolving issues with a stove burning a mix of gas and hydrogen, providing information on past projects and discuss involvement in upcoming projects, evaluating and providing recommendations on issues with a gas fryer.

Status

The project team released a Final Report for Phase 2 to UTD members in July 2023. Phase 3 is currently in progress, with activities such as providing technical support to NAFEM's Technical Liaison Committee and the ASTM F26 committee.

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UTD Utilization Technology Development

CFS Burner Technology Carbon Reduction Including Hydrogen Blending

Efforts are under way to determine the potential decarbonization of typical CFS appliances using improved burner technologies, enhanced control systems, and blending natural gas with hydrogen on existing CFS appliances in a laboratory setting.

Project Description

Because commercial foodservice (CFS) has lagged in terms of technological advancement, it presents several challenges when considering using fuels blended with hydrogen.

While controls, construction materials, and insulation have improved in the CFS industry, most burner designs have varied little over the past decades and are atmospheric stamped metal or cast iron with drilled ports. Previous efforts by manufacturers to improve the cooking characteristics of these burners typically focused on modifying the existing designs by changing the configuration of the burner ports or the air-to-fuel ratio and not by investing in advanced combustion technology. This lack of advanced technology makes CFS appliance less tolerant to changes in the fuel content. There is also concern that changing fuel content will change the cooking performance of the appliance. This includes inconsistent crust color on breads, over or under cooking of fried foods, and inconsistent cook times on other products. Most food in quick-service restaurants is cooked using timers and are not being watched by employees.

Efficiency gains and improved emissions have been limited in CFS due to issues with the willingness of owners and operators to pay a premium for units with advanced combustion systems. The result is that most gas-fired CFS appliances use relatively simple, old, and inexpensive technology. These older technologies are less likely to operate correctly if the content of energy source is changed. A previous study showed that several appliances (including some high-efficiency appliances) were incapable of safe operation when the heat content of the natural was increased due to the addition of liquefied natural gas (LNG). Hydrogen represents another issue because the increase in flame speed is likely to cause flashback on many of the older CFS burner technologies. Also, changes in flame appearance will cause concern among restaurant operators, even if the flame is still safe.

Fryer pilot light using 100% natural gas.

Because of these issues, the objective of this project is to determine the potential decarbonization of typical CFS appliances using natural gas blended with hydrogen and using improved burner technologies and enhanced control systems. Specific topics being addressed include energy-reduction technologies and controls, including burner modulation.

Benefits / Market Implications

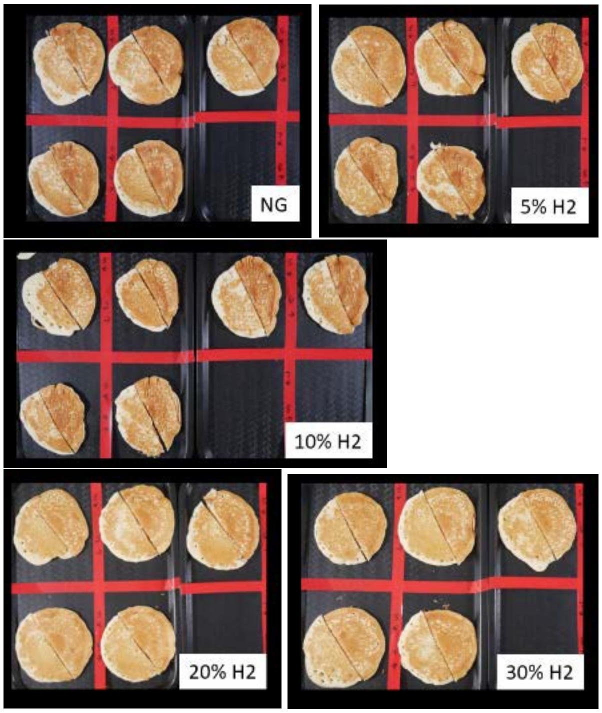
CFS is a large market with sales of about $900 billion before COVID. Post COVID projections show the industry is expected to recover and grow at a rate greater than 5% for next several years. This growth is significantly ahead of most other commercial industries. The National Restaurant Association also projects total employment growth to over 16.9 million by 2029.

Of the approximately nine million commercial cooking appliances installed and operating in North America, roughly 70% are powered by gas (in categories where there are gas and electric options), with an estimated five billion therms of natural gas consumed annually. Increasing the amount of hydrogen blended into natural gas will retain end-users options for gaseous fuels and customer choice while increasing decarbonization.

This project will help the industry determine the potential for improved burner technologies, control systems, and blending with hydrogen in CFS appliances.

Technical Concept & Approach

A research team will test an existing stock of CFS burners using a range of natural gas mixtures blended with hydrogen (0%-30%). The burners will be tested for combustion emissions and flame appearance. A determination will be made on the compatibility of each burner to the different blends of up to 30% hydrogen, as was done in previous interchangeability studies. Specifically, researchers are looking to see if the cooking performance changes such that it would not be acceptable to end users. Safety issues (e.g., such as carbon monoxide emissions and flashback) will also be investigated.



Pancake Comparison

The goal is to determine the level of decarbonization that can be achieved for a standard-efficiency CFS appliance by using advanced burner technology and improved burner controls. A standard appliance will be baseline tested for efficiency and combustion emissions and then updated with new technology and retested for comparison to the baseline.

The deliverable for this project will be a report with data and calculations for the decarbonization of CFS appliances using hydrogen blending and advance burner and control systems. The results will show if hydrogen blending of up to 30% will have a negative impact on performance and safety.

Key performance indicators to measure the success of this project will include:

- Efficiency and emissions data for a variety of stock CFS appliance burners when operating on 0%-30% hydrogen blended with natural gas, including changes in cooking efficiency and emissions
- Initial recommendations for relevant limits on hydrogen for a spectrum of stock CFS appliances based on measured changes in cooking performance, emissions, and safety based on existing standards
- An assessment of the potential of some possible near-term modifications (e.g., controls) to increase allowable hydrogen content, and
- The development of energy-savings and decarbonization calculations for current N.A. appliance populations.

This project builds upon earlier research to assess the interchangeability of domestic natural gas with imported LNG.

Phase 2 and 3 of this project focuses on determining if using blends of hydrogen have an affect on the cooking performance including the quality and quantity of food prepared. Common CFS appliances are being tested and images of the food prepared compared to determine if changes occur.

Results

Of the 13 CFS burners that were tested, flash back and flame appearance do not appear to be an issue for blends of natural gas and hydrogen of up to 30% for the burner types tested. Flashback did not occur during testing for any of the test conditions except for the stock pot burner. This incident was the function of how the burner was shut off and not of the addition of hydrogen to the fuel mix. The appearance of the flame did not significantly change with the addition of up to 30% hydrogen to the fuel mix and would unlikely be noticed by operators.

Burner emissions of CO and NOx were shown to be more affected by changes in firing rate than the percentage of hydrogen in the fuel. Typically, the values were within the same ranges for each percent of hydrogen. The only exceptions were CO for the fryer and NOx for the Infrared burner where both slightly, but consistently decreased with an increase in the percentage in hydrogen.

In order to test combustion and cooking performance, the team developed a method to conduct performance tests by cooking pancakes on a range top. The tests are designed to compare the appearance of the food that was cooked using the different blends of natural gas and hydrogen. The team also tested French fries in a standard commercial fryer and will be testing a charboiler and griddle. The images show the results for the range (pancakes) and fryer (fries and hash brown) tests. The pancakes were noticeably lighter in color as the percent of blended hydrogen increased, raising concerns that operators would notice the change in gas content. The fries and hash brown were not noticeably different. A color mapping method to compare the doneness of the cooked products is also being developed.

Status

The Final Report for Phase 1 has been released to UTD members. The team is currently comparing results for the range and fryer and preparing for testing of the charbroiler and griddle.

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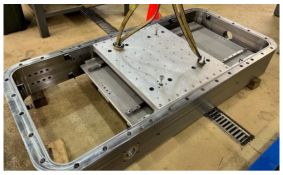
CLEAN TRANSPORTATION

Cost-Effective CNG/GH2 Pre-Cooling Technologies



A research team is developing an innovative, cost-effective system to pre-cool compressed natural gas (CNG) or hydrogen prior to it being dispensed into a vehicle. Pre-cooling will enable full fills and extend operating range, improve user experience, and effectively reduce the volume, weight, and cost of on-board storage tanks.

Project Description

Compressing gas into a compressed natural gas (CNG) or gaseous hydrogen (GH2) fuel storage tank causes a significant temperature increase, resulting in the pressure limit being reached prior to transferring the total mass that defines a full fill. Pre-cooling the gas before it enters the vehicle is essential to achieve consistent full fills under most fueling and ambient conditions.

Research has been ongoing to improve full fills by developing improved dispenser algorithms, investigating vehicle-to-dispenser communication, and analyzing pre-cooling systems. These activities have concluded that some form of pre-cooling is necessary to guarantee a full fill.

The most obvious method for pre-cooling is to use a vapor-compression chiller to cool the gas being delivered to the vehicle. This method is being used for some virtual pipeline filling stations but is too expensive for most CNG vehicle filling stations. Alternatively, existing CNG compressors could be used to drive a Joule-Thomson cooling loop that is used to store cooling capacity between vehicle fills, and then use that cooling capacity to pre-cool the CNG going into the vehicles during a fill. This strategy can reduce capital cost since it uses existing CNG station equipment, but will add run time, complexity, and maintenance cost to the CNG compressor; operating costs will also increase.

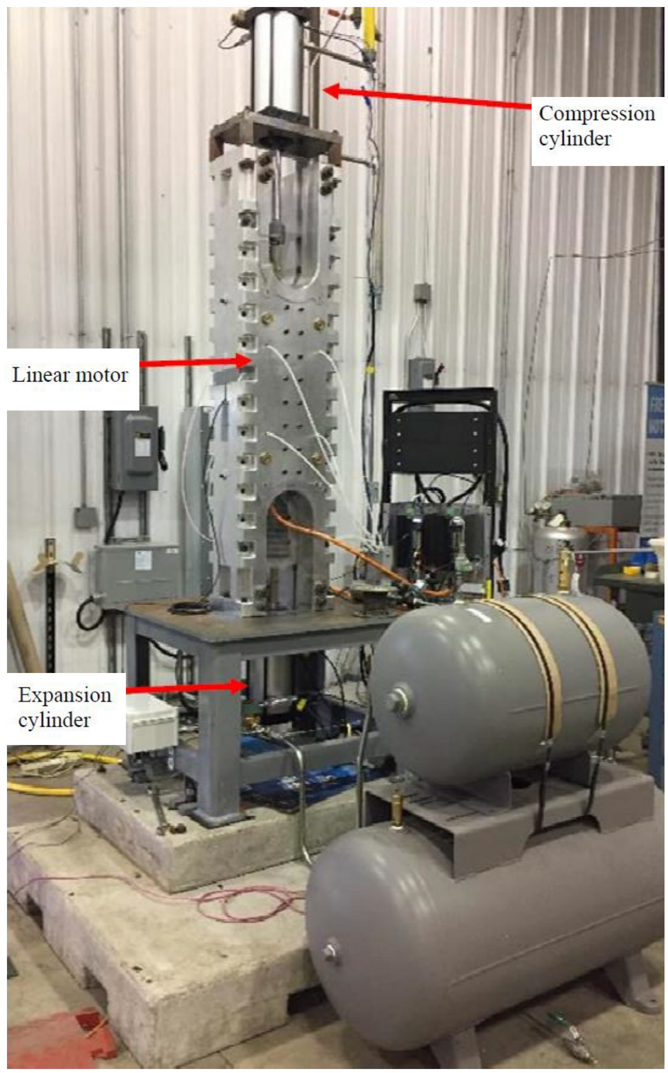
It is also possible to use a turbo-expander or similar device to pull energy out of the gas as it flows into the vehicle. An expander causes the gas to get colder than it would with Joule-Thomson cooling, allowing more gas to enter the vehicle before the pressure limit is reached. Expanders show the most promise since they do not require additional input energy to achieve the desired pre-cooling, but conventional radial expanders would need to be custom-designed for the high pressures required for CNG or compressed GH2 storage and would likely be difficult to operate over the necessarily-wide range of pressure ratios.

The objective for this project is to design, build, and demonstrate in a laboratory a prototype of a novel linear piston expander to pre-cool CNG or compressed hydrogen, in order to achieve full fills of gaseous fueled vehicles and thus increase effective storage capacity by 20%-25%.

This UTD project is providing co-funding to a significant prime contract funding award from the U.S. Department of Energy.

Benefits / Market Implications

The issue of under-filling directly impacts the volume of storage required on a vehicle. By providing consistent full fills, a vehicle requires a smaller fuel system, reducing the cost and weight of the vehicle's CNG or hydrogen cylinders. This improves the vehicle's range, economics, and the user experience.



Early prototype linear expander in laboratory test.

The use of pre-cooling would improve the quality of the fueling procedure since the gas temperature would be controlled by the station and would have less variability than occurs in existing fueling stations. This technology can provide significant potential benefits to economically fill zero-tailpipe-emission, gaseous-hydrogen-fueled vehicles, for which market interest is rapidly growing.

Technical Concept & Approach

The project team will perform a preliminary design analysis of a novel expander for pre-cooling CNG. The design will include detailed models, simulation, and schematics of the selected technology that estimate the expected cooling performance and how much it impacts CNG full fills, as well as the estimated capital and operating cost of the technology in a simulated station. Based on the optimized design, a complete working prototype will then be fabricated and tested under simulated operating conditions.

Results

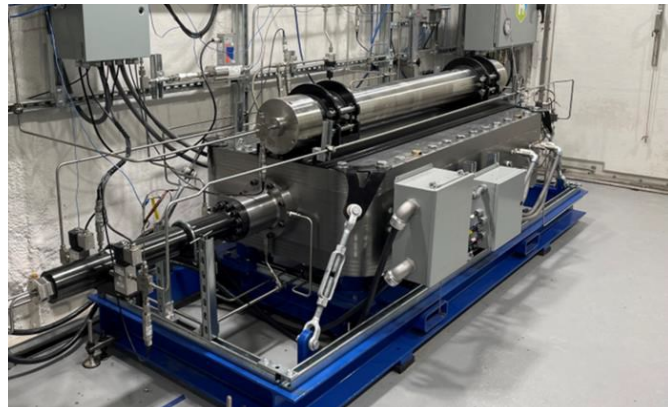
The project team developed a design for the free piston expander that will remove energy from the CNG and hydrogen and reject that energy as heat. In the future that energy could be converted to power that can be used to reduce the cost of operating the fueling station.

A simulation of the free piston expander was completed to better estimate the performance of the system. The simulation optimized stroke, frequency, and other relevant design parameters. The initial goal was to simulate an "ideal" expansion cycle at nearly 100% efficiency, and then start adding system losses into the simulation to accurately represent the real-world expander performance. The simulation determined how the expander attributes such as stroke length and piston diameter impact the efficiency.

The simulation also allowed the team to finalize the expander geometry and components. The project team developed custom valves that can be actuated by the expander piston. However, commercial valves were later identified and used to test the expander operation. The custom valves are still being actively considered, but the commercial valves reduced some of the risk associated with the prototype development.

The project team completed the design, fabrication, and assembly of the prototype expander. The expander was initially tested with nitrogen up to about 12,000 psi to test the controls and operation of the design. During operation, several operational issues were identified and corrected. This included inconsistent signals from the encoder which required the expander to be partially disassembled to correct.

Following the successful completion of the nitrogen testing, the team switched to 12,000 psi hydrogen testing before switching again to CNG testing. In preparation for the switch to hydrogen, helium was used to verify that the seals were working properly and that no hydrogen would enter the motor housing. This was done by pressurizing the fluid ends using helium and then taking gas samples from the motor housing and looking for the presence of helium using a gas chromatograph.



Fabricated expander currently being tested in laboratory.

Following the validation that the seals were working as intended, the expander was tested with hydrogen at pressures up to 12,000 psi. The team consistently achieved thermal efficiencies around 70% and believes this could be improved to 80-85% with some relatively simple modifications to the design. The expander is also producing power at about 50-60% efficiency which can be used to offset some of the power consumed by CNG or hydrogen compressors at fueling stations.

The team is now in the process of testing the expander with natural gas. Efficiencies are lower than with hydrogen, at around 40%. However, this is not completely unexpected since the design was optimized for both hydrogen and CNG fueling, which led to some compromises for either fluid service. The team believes that the CNG performance can also be significantly improved by optimizing seals, valves, and the piston geometry. However, this will not be tested under the current scope. Overall, the results look very promising, and the project team believes that the expander development was a success in that it is the first of a kind design that is operating at these pressures and efficiencies, while also adjusting in real time to variable expansion ratios as a vehicle cylinder is filled from stationary ground storage.

Status

The project team is finalizing testing with natural gas, and then will release the final report. Next steps to advance and commercialize this technology are being explored, such as seeking additional funding to install a prototype linear expander at a working CNG or compressed H2 fueling station.

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UTD Utilization Technology Development

CNG Dispenser – Tank Communication

Researchers are designing, building, and demonstrating a prototype compressed natural gas (CNG) station that includes a smart CNG dispenser and a smart natural gas vehicle (NGV). Pre-commercial prototype hardware and protocols are being designed to enable the vehicle and station to communicate about the vehicle's fuel system to deliver safer, fuller fills for end users.

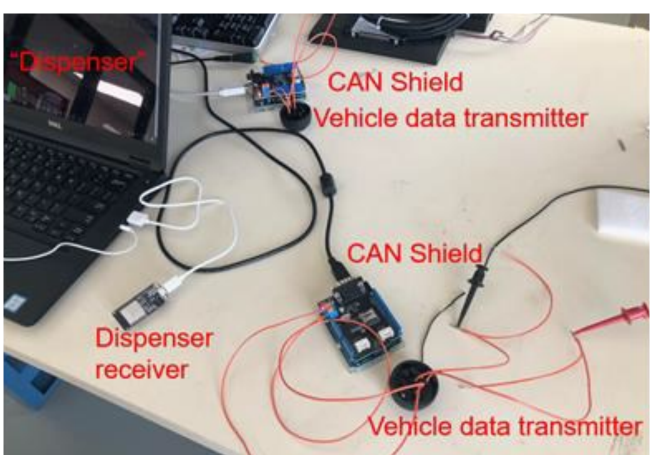
Project Description

Research is under way to improve natural-gas-vehicle (NGV) full fills using a multi-tiered approach. This includes the development of an improved dispenser algorithm, establishing vehicle-to-dispenser communications, and an investigation into various pre-cooling technologies. Improvements in all three areas are necessary to deliver a full fill.

Pre-cooling has been receiving more attention lately as fleets become aware of under-filling drawbacks. While it is simple (although expensive) to add a pre-cooling loop into the fueling process, over-filling of storage systems can occur if the algorithm does not account for the below-ambient gas temperature and pre-cooling alone will not ensure that the vehicle is filled accurately or safely. Earlier UTD-funded research developed an advanced full-fill algorithm that was shown to accurately fill vehicles to nearly 100% full across a range of test conditions; however, that algorithm requires information about the vehicle's real-time pressure and temperature and pre-cooling is necessary to achieve full fills on warm days. A means for communicating the vehicle's real-time pressure and temperature is needed.

Development of a smart compressed natural gas (CNG) dispenser and vehicle would enable vehicle sensors to transmit temperature and pressure to the CNG dispenser. This system could also be programmed with the age and volume of the vehicle's CNG cylinders, improving accuracy and safety of the fill and effectively reducing operating costs.

In summary the objective of this project is to design, build, and demonstrate a prototype CNG station that includes a smart CNG dispenser and a smart NGV. A project team will develop pre-commercial prototype hardware and protocols to enable a vehicle and station to communicate information about the vehicle's fuel system. This information will allow safer, fuller fills while also enabling fleets to more accurately track their vehicle's fuel consumption. Low-cost, off-the-shelf data transmission hardware will be used to guarantee that NGVs safely and consistently receive the maximum amount of gas possible during every filling event. By maximizing the volume of gas received, the volume of the NGV fuel system can be minimized, thus saving cost and weight of the vehicle.



Smart dispenser components being bench tested.

This UTD project is co-funding a $2.6 million smart CNG station research project award from the U.S. Department of Energy's National Renewable Energy Laboratory. UTD's project partners also include CSA Group, a leading CNG tank and fuel system provider, and a major concrete supply company as the end-user host site.

Benefits / Market Implications

Improving full fills using communications can lower the cost of an NGV by up to 10%. The lower cost per vehicle reduces the risk of adoption for fleets considering CNG and reduces costs for end users.

Active communication will also improve the safety of a CNG fill. Testing of existing algorithms demonstrated that it is unlikely, but possible, to over-fill a vehicle. Using communications, researchers developed a filling algorithm that should never result in an over-filled vehicle.

The primary target market impacted will be NGVs with a focus on heavy-duty trucks. Secondary applications may include for example virtual pipeline gas transport, locomotives, and some marine ferries. While the core technology being developed in this project will be demonstrated for CNG applications, it is expected to be transferrable and also benefit achieving full fills of vehicles fueled with gaseous hydrogen (GH_2).

Smart dispenser components being tested with storage.

Technical Concept & Approach

Tasks for this project are to develop and validate wireless connection protocol, develop CSA standard with stakeholder input, and build and test smart dispenser and vehicle. Project efforts are being coordinated with the work under way in UTD project 2.20.G.

Results

The project team finalized the design of a pre-commercial smart vehicle data-acquisition and wireless communication system to install on CNG vehicles. Researchers completed bench-scale development of a smart dispenser module that can communicate with the smart vehicle to improve full fills.

One data logger connected to the vehicle fuel system recorded the vehicle's pressure and temperature, adding the measured data to the CAN Bus data and then broadcasting everything to the cloud over a cellular connection while also broadcasting over WiFi for local devices. The cloud storage allowed the team to monitor the vehicle's fuel consumption and fill quality during real driving cycles. The local WiFi allowed the vehicle to communicate data with local devices such as the smart dispenser being developed.

The dispenser and smart module shared information from the smart module to control the dispenser's fill logic when a smart vehicle was identified. The team also developed a connection protocol that will ensure the correct CNG vehicle is always identified. If the system is unable to identify the vehicle, then the system will revert to a standard CNG fill.

Project researchers also supported efforts by CSA Group NGV 4.3 Committee to incorporate language related to pre-cooling and communications to enable improved fills into the tests for certifying dispensers.

In 2021, with the development of the data-collection system and the start of a smart CNG module, the demonstration of a smart vehicle and dispenser was initiated. Once the smart dispenser module was complete, research began to integrate the module with a dispenser. Efforts were made to determine the capabilities and limitations of controllers and if they are suitable for the short-term and long-term needs of the application.

In 2022, the project team completed the bench scale development of a smart dispenser module that can communicate with the smart vehicle to improve full fills. The team installed the bench scale system in a test cell for testing during CNG fills.

In 2023, data loggers were fully installed on the concrete mixer trucks. Data was received and the team developed automated data processing software to organize and analyze the large volumes of data being received. The smart dispenser module has been installed in a laboratory test cell and is connecting to the CNG cylinders and transmitting that data to a LabVIEW dispenser.

The team developed a modified version of the smart dispenser module that will interface with multiple dispensers at a single station from a central processing point. This device can also manage time fill stations and process vehicle data as vehicles enter the station. No new hardware is required inside the dispenser, just a modbus connection.

The smart controller was tested using simulated data from multiple CNG fills. The controller was able to positively identify the connected vehicle for each dispenser. These simulated fills are a good indicator that the controller will work when connected to the actual CNG dispenser. The team tested communication with a commercial CNG dispenser. The team is able to monitor the dispenser variables using Modbus communication.

The commercial CNG dispenser was installed into a laboratory environmental chamber and the team conducted test fills to validate that smart hardware can communicate with the CNG dispenser. This has been verified and the team can see real time dispenser data.

Status

The team is editing and refining control code that enables the vehicle and dispenser to be matched. Final testing of smart components is underway and the project is expected to conclude in 2024.

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Utilization Technology Development

Next-Generation NGV Driver Information System

This research project is developing and demonstrating a next-generation NGV driver information system to provide an accurate miles-to-empty estimate for the vehicle. By increasing confidence in the fuel gauge, excess fuel storage capacity can be reduced and the cost of the fuel system can be lowered by as much as 20%.

Project Description

Maximizing the fuel used in onboard storage is a well-identified impediment to greater adoption of natural gas vehicles (NGV), and similar challenges will apply to vehicles fueled by compressed hydrogen. The U.S. Department of Energy's (DOE) Clean Cities program performed a nation-wide survey of NGV drivers, and unreliable fuel gauges were a consistently mentioned deterrent to adoption due to causing range anxiety, frequent and unnecessary fueling stops, reduced driver productivity, and disrupted workflow for the fleet operator.

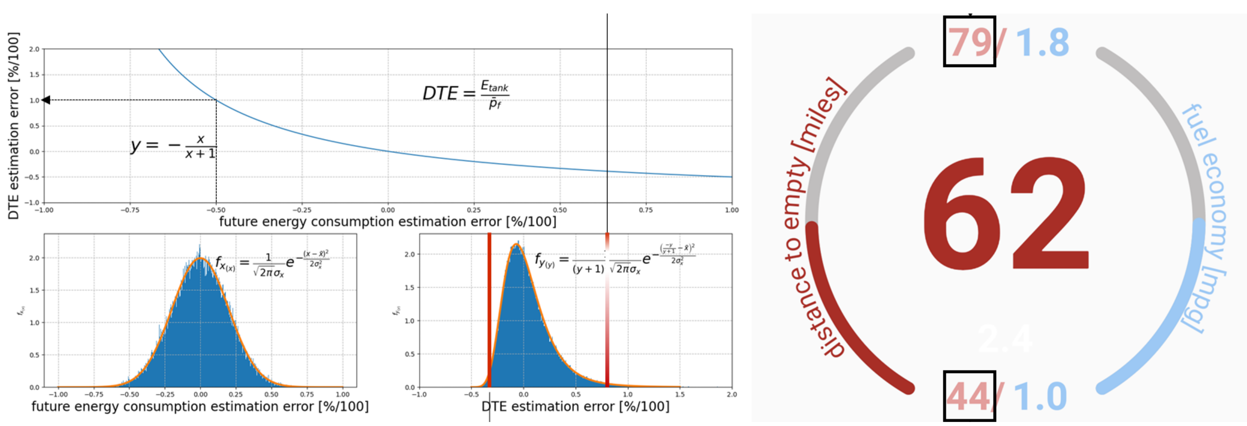
The goal of this project is to provide the NGV driver with an accurate estimate of the distance the vehicle can travel with the fuel left on board, which is a crucial piece of the driver's information system. While often simplified to a pressure measurement, large variations in gaseous fuel pressure can occur due to large swings in temperature. During fueling, the gas in the tank heats up to as high as 185°F, which can provide a premature "full" indication. As the gas cools down, the pressure drops sharply, giving the appearance that a full tank leaving the fueling station has drained very quickly. The gas in the tank also expands and cools as fuel is consumed (to temperatures as low as 80°F below ambient temperature), which further reduces tank pressure and leads the driver to mistakenly believe that the tank is almost empty. In summary this project will demonstrate how additional information such as the fuel consumption rate of the vehicle in various driving situations (traffic, weather, terrain, etc.), knowledge of the route to be followed, and storage tank performance can be used to provide an accurate miles-to-empty estimate for the driver in real-world applications.

UTD is partnering with the DOE on this effort by providing co-funding to a major research contract with prime funding provided by the DOE. Other project team members include Argonne National Laboratory (ANL) and a leading concrete delivery supplier.

Benefits / Market Implications

Heavy-duty NGVs (Class 8-10 trucks) and vehicles fueled by compressed hydrogen will benefit the most from an advanced driver information system due to the larger savings in fuel-system size and cost. Medium- and light-duty NGVs can also benefit. Market entry, however, will focus on the large existing fleet of heavy-duty fleet NGVs.

The benefits of an improved NGV driver information system will depend upon the driver's risk tolerance and driving behavior, but discussions with vehicle drivers indicate that they typically return for fueling when their vehicle tanks are 20%-40% full. Decreasing this remaining fuel reading to below 10% would result in significant savings in fuel-system costs, driver productivity, and fueling efficiency.NGV fuel systems are typically oversized due to concerns about achieving a full fill and range-anxiety issues. By increasing confidence in the fuel gauge reading, the vehicle fuel capacity can be reduced, lowering the cost of the fuel system by as much as 20%. The productivity of the driver can increase as the truck would make fewer trips to refuel, and fewer refueling trips will lower emissions and save energy.



The information system output will include a upper and lower bound of expected range based on historical truck operation. This display concept was adapted from common displays for electric and hybrid vehicles which also have a high variation of expected range based on driving behavior.

Technical Concept & Approach

- **Data Collection and Application Development**

  Instrument a fleet of vehicles to collect compressed natural gas temperature and pressure data during filling events and regular operation. Combine this data with data from controlled laboratory testing to enable development and validation of a thermodynamic model to estimate the usable fuel status of a vehicle's fuel system at any given time. Equip the fleet vehicles with data-acquisition systems that transmit data via a cellular modem. Conduct laboratory testing that includes controlled-rate tank de-fueling to measure temperature and pressure behavior. Use this temperature/pressure behavior to determine the relationship between measured parameters and the amount of usable fuel remaining in the fuel system.

  Develop a more accurate miles-to-empty prediction method and integrate it into previously developed fleet-management software, which already contains information about routes and duty cycles. From this estimate, the dispatch center can determine if a refueling stop will be necessary, determine if changes to vehicle routes could improve fleet performance, and evaluate driver performance for maximum efficiency.

- **Application Validation and Deployment**

  Validate models using laboratory data to ensure proper operation of all data collection and transfer systems. Use data from fleet vehicles to validate the thermodynamic model in the field.

- **Performance Monitoring, Improvement, and Knowledge Transfer**

  Compare NGV fuel gauge predictions to driver reports and operating data gathered from the data-acquisition systems on the vehicles. Solicit driver feedback to evaluate the perception of system accuracy and identify changes in driver behavior. Approach potential commercialization partners.

Results

In 2020, an analytical model was built to calculate the gas remaining in the fuel tank based on tank pressure and temperature – with accuracy >95% for a wide range of gas compositions between -60°F and 140°F.

In 2021, data-acquisition systems were installed on all 12 trucks participating in this program, including sensors to measure internal tank temperature and pressure. The collected data was used to validate and improve the calculation of remaining fuel on board the vehicle. The upload speed and time intervals of the data loggers were adjusted to ensure the loggers can successfully upload all information in the allotted time. These modifications were applied to all new logger units. Calculation of the remaining fuel on board the vehicle was finalized.

In 2022, a data visualization tool was completed and beta-tested. This tool uses cellular phones with customized cases installed by ANL that allow display of only desired information and prevent their use as phones. Researchers found that the driver information display needs to include an upper and lower bound for range in addition to the central estimated value, due to the variability observed in the vehicle duty cycle. Because the test vehicles are concrete trucks the duty cycle varies with large amounts of time spent idling, the energy used to turn the drum, and driving differences between urban and rural environments.

Fuel gauge displays were installed on eight concrete delivery trucks. The fuel gauges use data from the sensors installed on the vehicle as well as engine data (distance traveled and fuel mass flow rate). Distance-to-empty is predicted using readings from these sensors combined with operating history data. This distance-to-empty calculation has been validated to be accurate within the upper and lower bounds displayed. The prediction does not require any knowledge of the fuel system size or gas composition; this information is calculated on a per-vehicle basis each day the vehicle is operated.

A custom end plug incorporating an in-cylinder temperature sensor was designed. This will enable the temperature data to be uploaded through the CAN system without requiring an expensive data acquisition unit. This information will then be picked up by the fleet dispatch software and calculations completed in a cloud server to display the relevant information.

Meetings were held with the concrete delivery company, their drivers, and representatives of their dispatch system supplier to discuss how the new fuel gauge and data will be integrated with their truck monitoring software, how this could be utilized to improve truck efficiency and driver habits, and to incorporate their feedback.

Status

Next steps for the team will be to: collect additional data on functionality and reliability of the fuel gauge systems; work with the concrete delivery company and its supplier to incorporate the distance-to-empty calculation into its dispatch system; finalize end plug design for commercial applications; and prepare a technical paper for submittal to an industry journal and further explore commercialization options.

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Smart CNG Station Field Demonstration

A novel CNG fueling system is being developed to increase the utilization of the onboard CNG storage capacity by 10%-25%. The smart fueling system will use improved sensors and algorithms to provide consistent full fills, resulting in up to 25% lower capital cost for fuel storage. The technology could likewise benefit compressed H2 fueling stations.

Project Description

A "smart" compressed natural gas (CNG) fueling system is being developed that will increase the utilization of onboard CNG storage capacity by 10%-25% compared to current practices and provide substantial savings to end users. The smart CNG fueling system will use improved sensors and algorithms to provide consistent full fills, resulting in up to 25% lower capital cost for fuel storage on natural gas vehicles (NGVs). While currently focused on CNG applications, if successful the innovations in this project could also greatly benefit compressed hydrogen fueling stations.

CNG vehicles are often under-filled because the gas heats up and expands during the filling process; 20%-25% under-filling is frequently cited by fleets and industry experts. This is further supported by the fact that commercial fuel systems are nominally designed 30% larger than the "usable" fuel capacity quoted by the manufacturer. On many heavy-duty CNG vehicles, adding 30% extra storage can easily be the difference between needing three versus four storage cylinders to achieve the vehicle's required driving range. By eliminating the fourth cylinder, the weight and cost of the fuel-storage system can be significantly reduced.

Researchers will install sensors and communications equipment on the vehicle and station and feed the information to an improved CNG filling algorithm. The project team will demonstrate the system at one fueling location to analyze the real-world improved filling performance, and any increase in the vehicle or dispenser costs. Fuel-system and operational savings will be calculated to determine the true net benefits, and the results will be used to support a commercialization strategy.

In this project, UTD is partnering with the U.S. Department of Energy (DOE) and leading manufacturers and end users. UTD is providing co-funding to a significant prime contract from the DOE.

Benefits / Market Implications

The initial target markets for this technology are heavy-duty trucks, with the focus on reducing the frequency of fills to improve the productivity of CNG-fueled trucks. Higher productivity can lead to greater economy for end users.

Developing and commercializing a smart CNG fueling system would reduce the capital cost differential between CNG and diesel trucks. This expands customer's competitive choices for fuels, including potential applications for hydrogen fueling. It is estimated that the smart CNG fueling system could reduce the capital cost for fuel storage by about 25%.

(LEFT) One of the HEM DAS with a built-in streamer. (CENTER) The router connected to the HEM DAS. (RIGHT) The micro-controller that connects the dispenser to the vehicle.

"Oklahoma Natural Gas is pleased to partner with the U.S. DOE and others through UTD to demonstrate this innovative smart station. We're excited about its potential to increase onboard CNG storage capacity by up to 25% while reducing station and fleet operating costs. With 127 CNG stations in our Oklahoma service area, this significant technology advancement can potentially provide substantial savings for our CNG customers and help reduce greenhouse gas emissions in our state."

- Dave Miller
National Accounts and CNG
ONE Gas

Technical Concept & Approach

This project addresses the major technical issues by working closely with commercial partners and using real-world testing. Tasks include developing and deploying an advanced dispenser algorithm and wireless vehicle-to-station communication devices that will transmit real-time fueling information between the vehicle and the dispenser for the first time.

The project team will assemble and deploy data-acquisition systems on multiple demonstration sites and vehicles to collect necessary filling data. Station components for vehicles and dispensers will be developed. These smart components will be designed to securely transmit real-time data (e.g., temperatures and pressures) between the vehicle and station, enabling a safer, more accurate full fill using an advanced fueling algorithm. Components will be designed to applicable wireless data-transmission standards.

Researchers will initially test and validate the performance of the components and algorithm in a controlled laboratory setting. Testing will include validation that the dispenser wirelessly connects to the correct vehicle and then accurately transmits the required data when filling a variety of CNG cylinder types, volumes, and configurations. Upon successful validation of the smart component performance, the systems will be integrated into test dispensers and vehicles, and then operated for a year at a demonstration site.

The research team will monitor data collected from a variety of CNG stations and vehicles during smart-filling events. This data will be analyzed and compared to the baseline to quantify the improved performance and accuracy of the prototype system. The project team will also begin initial commercialization steps for the technology.

Results

Researchers deployed 18 HEM data-acquisition systems (HEM DAS) onboard a local fleet of concrete mixers. This allows the project team to collect fueling and fuel-consumption data onboard each vehicle in order to better understand how baseline dispensers operate and how much they truly underfill vehicles. The system is transmitting data about the fuel system to the cloud where investigators download and evaluate fills and driver filling practices.

The fully installed ANGI dispenser

The team has also installed a commercial dispenser in an environmental test chamber to test smart fills across a wide range of operating conditions. Two vehicle cylinders were also installed along with HEM DAS to test the vehicle communication with the station. As the vehicles are filled, they are broadcasting the vehicle information to the station's Wi-Fi network. A smart controller is monitoring the vehicle via the Wi-Fi network and comparing that information to data received from the dispenser via a Modbus connection. The smart controller then determines which vehicle is connected to which dispenser so that it can override the dispenser and assure the vehicle receives a full fill. This system is fully operational and the project team is working out some of the bugs in the smart controller algorithm to ensure more accurate and consistent operation.

Status

The team is actively testing the smart controller and algorithm using a commercial CNG dispenser and two target cylinders connected to HEM DAS.

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Utilization Technology Development

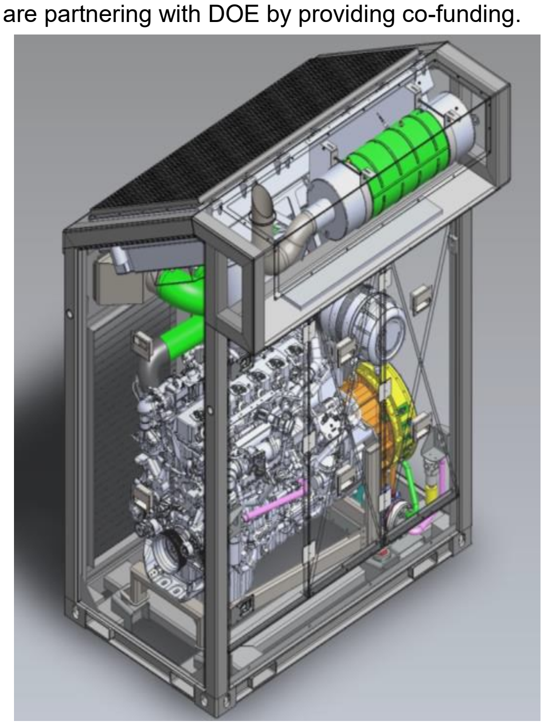
CNG/RNG Locomotive Field Demonstration

Researchers are designing, building, and testing a pre-production compressed natural gas/electric hybrid line-haul locomotive to demonstrate the commercially available Cummins X15N near-zero-emission engine in rail service in order to substantially reduce GHG and particulate emissions while also reducing operating costs.

Project Description

For this project, a natural-gas-powered locomotive will be designed, built, and tested at the Federal Railroad Administration's (FRA) Transportation Technology Center (TTC) testing facility. The locomotive will operate on a 50-mile test loop in real-world conditions. Operation at TTC will allow researchers to perform controlled testing and gather critical data for emissions, fuel consumption, specified performance metrics, dynamic and other safety characteristics, and reliability during revenue service simulations. This locomotive demonstration will provide needed solutions and support the Class I, II, and III railroads as they seek ways to reduce the adverse environmental impacts of aging high-emission, diesel-fueled locomotives.

A key technical component of this demonstration – the Cummins X15N engine – is an evolution of ISX12N engine developed with earlier support from UTD. This project is funded primarily by the U.S. Department of Energy (DOE) and will demonstrate the first use of the on-road Cummins engine in off-road markets, which may open additional markets for other end users (e.g., marine and agriculture). UTD and others are partnering with DOE by providing co-funding.



Refined engine pod design

DOE's objective to increase commercialization of alternative fuels in the railroad industry has been limited by the pace of engine technology development from traditional locomotive manufacturers. This project will expand the use of natural gas to serve a new class of off-road customers with large potential by demonstrating two significant challenges that can be met: 1) achieving near-zero emission operation, and 2) multi-engine, line-haul service feasibility.

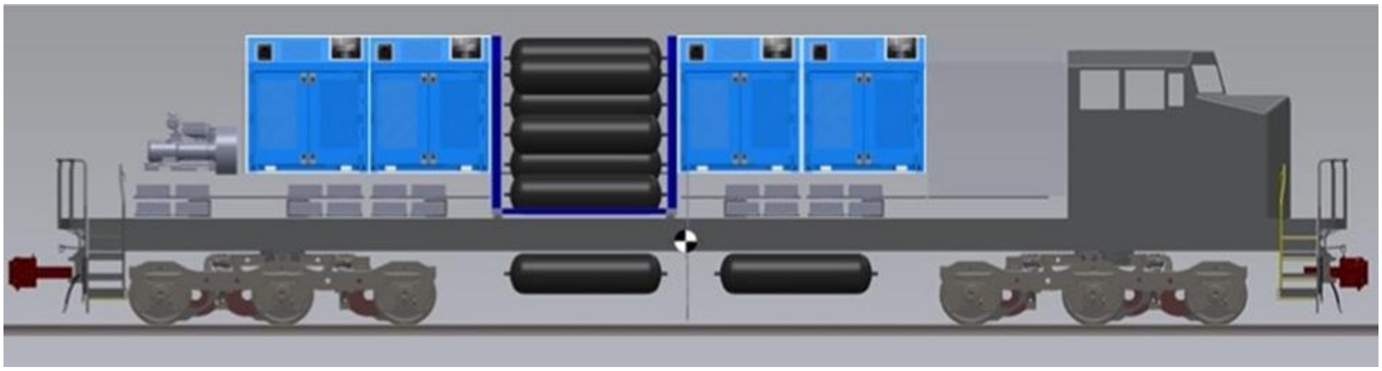
The locomotive will use U.S. Environmental Protection Agency certified rail engines and will reduce criteria emissions by more than 95% vs. current Tier 4 standards, reduce fuel costs, and reduce greenhouse gas (GHG) emissions by more than 40%. Reducing criteria pollutant emissions is of critical importance because railyards tend to be in environmental justice areas where underserved populations are exposed to some of the lowest air quality.

The intent of this project is to document that multiple CNG (compressed natural gas) engines in hybrid locomotives can increase overall system energy efficiency and reduce fuel consumption by 20% to 40% by including the utilization of regenerative braking. This project also intends to show that Class I, II, and III railroads can dramatically lower GHG emissions compared to diesel by using compressed renewable natural gas (RNG). There will also be significant importance to validating success in the most challenging applications (i.e., line-haul) to remove concerns for the rail sector to adopt RNG or CNG as a viable fuel.

Benefits / Market Implications

This technology program will demonstrate how a suite of commercially-available products can be integrated to create a viable CNG hybrid system to power locomotives with near-zero emissions. This solution will be safe and reliable, while at the same time, reducing fuel costs, having a nominal maintenance impact, and creating a roadmap for accelerated deployment with predictable costs and production schedules. Anticipated benefits include:

- 20% lower fuel consumption than diesel, with negative GHG emissions when consuming carbon-negative RNG
- Capital costs of the CNG hybrid (when commercialized) will be comparable (or lower) to conventional Tier 4 diesel loco-



Overall layout of engine pods, batteries and storage modules

motives

- Demonstrate that a 4,300 HP line-haul locomotive can be re-powered as a natural gas hybrid locomotive at near-zero emissions – to exceed Tier 4 emission standards and meet proposed Tier 5 standards, and
- Advance the potential for gas-driven engines to serve a key role in addressing emission challenges and environmental justice concerns in dense urban areas affected by railyards or commuter operations.

Validating the performance and maintainability of the Cummins engine in highly-challenging line-haul locomotive service will support commercialization in all rail sectors (e.g., passenger rail and switching locomotives) and provide a springboard to expand applications in off-road transportation, construction, and other markets.

Technical Concept & Approach

Specific tasks for this project include:

- **Specification, Engineering, and Design**

  Create detailed system specifications for the locomotive that will drive quantitative metrics to be used during systems validation and operational testing.

- **Procurement and Production**

  Use feedback from manufacturing to update the designs and identify process improvements.

- **System Testing and Validation**

  Conduct functional testing, including dynamics and static vehicle testing as well as full operation on a 50-mile test loop at FRA's TTC facility in Pueblo, CO.

Results

An innovative design for the locomotive was developed which will employ individual modules (engine pods, fuel storage, batteries) locked onto platforms and to each another, which will allow quick and easy assembly and serviceability. A variety of modules are being designed, including eight natural gas engine pods (45 inches wide x 80 inches deep x 80 inches high), each with a water-cooled 380 kW generator, associated water-cooled power electronics, and radiator-based cooling system. Each engine pod will be tightly connected to adjacent pods and to the top of each battery pack bay.

Baseline power will be provided by eight 510 Hp Cummins X15N natural gas engines to provide 4,000 hp (minimum). The project initially planned to use Cummins ISX12N engine but switched to the X15N after its successful initial demonstrations in trucks during 2022-23, with expected wide-scale adoption in 2024. To get the goal of 4,400 hp, 400 hp of batteries will be used to be added in a hybrid configuration. The configuration of the engine modules on the locomotive is optimized to increase air flow to the radiator of each module while providing upper space for the catalyst and the radiators.

The team also switched the locomotive platform to an EMD SD90M-2, allowing more space on the locomotive deck to arrange the engine/RNG modules and move the batteries below deck. The two above-deck RNG storage modules (with a total of 1,700 DGEs) are the middle of the locomotive to help balance of the locomotive (front to back) to help tractive effort be applied evenly on both trucks, as well as yielding compact plumbing to the storage modules. Work also continued on the design of power electronics, primarily built around BAE's Modular Power Control Systems (MPCS).

Status

The project team is continuing to work on locomotive design and procurement of long-term components (CNG tanks, batteries, engines, alternators, and power electronics).

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Distributed RNG or Biogas Production and Cleanup

Researchers are analyzing and improving the productivity of renewable natural gas production and cleanup technologies suitable for distributed small-scale operations by investigating a variety of anerobic digestion and gasification technologies, assessing unique feedstock opportunities, and helping optimize technology performance.

Project Description

While large-scale anerobic digestion is feasible at many locations across the country, this project focuses on small-scale anerobic digestion to enable an even wider range of applications and locations, allowing for the growth of renewable natural gas (RNG) production that is needed to meet decarbonization goals.

There is an increasing variety of anerobic digestion technologies to consider. Each method has unique technical and economic barriers to overcome. Conventional anerobic digesters are physically large, specially-designed for each facility, and constructed on site with correspondingly high costs. Anerobic digesters can be used to treat wastewater and have potential to be used at small- and medium-sized facilities such as breweries, distilleries, cideries, dairies, cheesemakers, seafood processors, and campuses could benefit from anerobic digesters. However, their operations are normally too small to afford the capital expense of a traditional digester.

Significant effort is needed to: analyze applications; optimize novel, emerging technology packages and other potential high-value co-products; and find ways of increasing reliability and productivity without increasing the need for labor and management.

This project seeks to determine technical and market requirements to build and operate novel, integrated technology packages to convert various organic wastes into high-value RNG. In particular, there is a need to assess to what extent these systems can be commercially viable at much smaller scales than previously possible via enabling strategies such as: novel modular technology packages; optimized co-production, co-product development, marketing and sales of co-products given the geographic location; and alternative and innovative business models to capitalize the equipment.

Prefabricated units drive down capital costs and allow for quick delivery.
Credit for image above: Chomp

In summary, researchers are investigating anerobic digestion and gasification technologies that are suitable for small-scale onsite service, potential feedstocks, feedstock preparation and pre-treatment options, reactor designs, biogas and producer gas cleanup, economic modeling and performance analyses, and methods of digester monitoring and control to increase the throughput of small-scale digesters.

This project serves the end users, society, and the environment by advancing RNG in distributed energy applications. This technology can lower greenhouse gas (GHG) emissions, increase energy resiliency, and decrease solid waste disposal costs paid by the onsite user.

Benefits / Market Implications

Example target markets are smaller municipal waste management facilities, food processing plants, small farms and dairies, and campuses with foodservice for large populations. Potential secondary target markets are horticultural operations, restaurants, grocery companies, and microbreweries.

A 2019 assessment of RNG by the American Gas Foundation illustrates RNG potential as a GHG emission-reduction strategy. According to this study, "…there is a portfolio of potential feedstocks and technologies that are or will be commercialized in the near-term future that will help realize the potential of the RNG market." Most RNG continues to be produced using anaerobic digestion paired with conditioning and upgrading systems. The post-2025 outlook for RNG will increasingly rely on thermal gasification of sustainably harvested biomass, including agricultural residues, forestry and forest product residues, and energy crops."

This project focuses on broadening the quantity of organic waste accessible for RNG production and is intended to advance technology that can be deployed for smaller dairies, farms, water-resource-recovery facilities, and food processing plants.

Technical Concept & Approach

This project is analyzing small-scale RNG production technologies with feedstock inputs ranging from hundreds to thousands of pounds of waste feedstock per day. Two technologies are being considered: anerobic digestion and gasification. Gas cleanup technologies such as membranes, solvents, or more novel solutions are being studied for small-scale as well as medium-scale applications such as farms with herds of 100 to 1,000 head of cows.

Technical barriers will be identified for each application and potential solutions will be identified and analyzed. Efforts will be made to identify, develop, or implement better sensing and control technology that is affordable to small-scale installations in order to increase uptime and therefore annual productivity without upsizing major equipment.

For the most promising applications and technologies, a detailed technical-economic analysis will be conducted to examine costs, benefits, risks, uncertainties, and timeframes of the studied technologies.

Results

The team conducted a literature review and collaborated with a small scale digester vendor to identify known and hypothesized limiting factors of long-term small scale anaerobic digester productivity, and assess sensing, control, and analytical strategies to increase digester productivity.

A detailed experimental plan was created with the goal of studying typical digester behavior, especially focusing on typical small scale digesters being used to process food waste. The nature of upsets and performance challenges was logged and multiple monitoring approaches for small-scale digesters were simultaneously used for optimal monitoring and control. This project has collected substantial operating logs from an operating, 480-gallon, continuously-mixed digester designed for onsite organic waste treatment service.

Data collection for this effort includes the FOS/TAC score via the Nordmann method, biogas quality (% CH_4), biogas quantity (flowrate), digestate pH, and digestate alkalinity. Data was collected for a baseline, first, and second level of digester feed rate in an experimental test series. The first increase in feed rate (100 lb/day to 140 lb/day) was completed in early Q2 2023, and definitively verified that successful long-term performance was viable at this level of digester duty.

The second increase in feed rate was to 180 lb/day. A rise in FOS/TAC score was then noted (from about 0.14 to 0.59), which alerted the digester operators of a developing over-fed, also known as over-acidified state. Operators were then able to cease feeding of the digester. The FOS/TAC score then returned to normal levels within a couple of days, upon which in a commercial installation, normal feeding could once again be resumed. Both the normal operating state as well as the over-fed state were simultaneously evaluated using all of the digester monitoring parameters that were being trialed to evaluate their effectiveness.

"Impact Bioenergy has built and deployed over 17 small-scale, onsite, modular anaerobic digester solutions since 2013. We are excited about how our distributed and modular systems empower their owners to divert organic waste from landfill, reduce the waste-transportation footprint, generate energy, and generate organic plant food that supports food production onsite or in the community or campus hosting the digester. We appreciate UTD's support and partnership."

- Jan Allen
President
Impact Bioenergy [now called Chomp]

Status

Some of the other monitoring techniques that were tried in the experimental program did produce some indication of the overfed state, and ongoing efforts are underway to find more technologies and methodologies for real time monitoring of anaerobic digesters with minimal labor requirements. This project has now documented about eleven products for monitoring digester status that are commercialized or in commercial development, but in most cases they are currently either too expensive for small-scale digestion installations, too labor intensive to be conducted frequently enough for ongoing monitoring, or have not been proven to provide reliable monitoring and timely detection. This project plans to continue to evaluate these products and where appropriate, support their commercial development progress and application strategies.

Specific to envisioning a pathway to broader implementation of these digesters, the team will be identifying pathways to improve automation and remote access to these technologies, by utilizing experience and in-house knowledge on these topics. Increasing automation and allowing remote monitoring of the systems will help decrease overhead associated with manual intervention of these systems, and thus reduce costs for distributed RNG or biogas production.

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UTD
Utilization Technology Development

Improved Hydrogen Fueling for Heavy-Duty Vehicles

In partnership with the National Renewable Energy Laboratory and others, a research team is creating a publicly available draft protocol for high-pressure, high-flow hydrogen fueling of heavy-duty vehicles.

Project Description

Deployment of heavy-duty fuel-cell vehicles is currently limited by the availability of hydrogen fueling technologies that can affordably and reliably dispense hydrogen. High-flow fueling (approximately five times faster than current light-duty hydrogen-vehicle fueling) is necessary because heavy-duty trucks need to store 50 to 100 gasoline gallon equivalent (GGE) of hydrogen onboard, which is at least 10 times what is typically stored on current light-duty hydrogen vehicles.

While the fill rate required will vary depending upon a truck's class and vocation, the U.S. Department of Energy's (DOE) fueling rate target for Class 8 long-haul trucks is 10 kilograms (kg) per minute (one kg of hydrogen is approximately one GGE) to enable full fills within timeframes comparable to those for today's diesel trucks (e.g., approximately five to six minutes). This target is based on a desire for hydrogen fuel-cell trucks to achieve a 750-mile driving range between refueling, which will require onboard storage of approximately 60 kg of hydrogen.

One accepted fueling procedure is a protocol that was developed with support of current National Renewable Energy Laboratory (NREL) researchers that allows for more flexible and lower cost fueling stations while maintaining safety and reliability. Currently, a prescriptive protocol for high-flow hydrogen fueling does not exist. This project – in partnership with NREL and in coordination with Southern California Gas (SoCalGas), a major public transit agency, and others – involves the development of a standardized prescriptive fueling protocol which is applicable to a wide range of vehicles and storage system designs and can be used for public-access fueling stations.

Researchers will conduct the modeling and testing required to validate the fueling protocol and facilitate its potential adoption in future international consensus standards, within the limits of the project resources.

Benefits / Market Implications

In order to achieve deep decarbonization goals in the transportation sector, a wide variety of alternative pathways are needed. It is clear that just one solution will not satisfy the diverse needs and duty cycles required, especially for heavy-duty vehicles. This sector is particularly important because it is a critical growing industry for goods movement, and it is challenging to electrify because of the energy-density requirements. U.S. DOE data shows that heavy-duty trucks produce approximately 25% of the greenhouse gas emissions in the transportation sector while comprising only 5% of the total

Example of heavy-duty hydrogen vehicle. Image credit: Nikola Corp.

Hydrogen fueling dispenser. Image credit: California Energy Commission

vehicles. This shows the environmental impact that is caused by each truck as well as the potential emissions reductions that could be caused by switching to zero-emission technologies.

This project will facilitate the installation of public high-flow hydrogen stations for heavy-duty vehicles to expand the range and operation area of these vehicles. This is especially important as California and other states adopt aggressive zero-emission vehicle targets for heavy duty vehicles (e.g., California's Advanced Clean Truck Regulation and the 15-state initiative signed in 2020 to advance the market for electric medium- and heavy-duty vehicles).

Technical Concept & Approach

Specific activities of the UTD project team include:

- Organizing and coordinating discussions with relevant stakeholders on process and interfacing specifications.
- Supporting the data analysis of modeling and experimental results, and
- Performing validation testing, if time and budget allows, including fueling and defueling vehicle pressure vessels.

Key project goals are:

- Creation of a simulation model to validate fueling procedure across a wide variety of scenarios
- Testing to correlate modeling to real-world results to validate modeling results and safety
- Creation of a draft fueling scientific protocol for high-flow fueling of heavy-duty vehicles, which can be endorsed or modified by consensus standards-setting organizations for use at public access fueling stations, and
- Develop a validation calculator to allow station or dispenser manufacturers to validate equipment performance.

Results

The UTD project team participated with NREL in several technical meetings, and a definition of protocol specifications (e.g., expected fuel-system size and target final fill conditions) was created.

NREL conducted modeling tasks in order to validate the temperature/pressure behavior of ground storage tanks during fueling events. They developed a matrix of simulations to find end-of-fill conditions for a range of cases and conducted high-flow fueling component testing. They have obtained data allowing them to finalize their fueling protocol for high flow applications. These results will be used to guide a safe fueling protocol. They are also developing a validation tool, which the project team will assist with in coordination with NREL.

The project team has focused on conducting testing on an extremely valuable pathway for heavy-duty fueling, which is developing a time-fill protocol. Heavy-duty vehicles have seen huge benefits from time-fill fueling in CNG applications, and the same potential exists in hydrogen fueling. Significant challenges exist in this area to ensure the tanks remain within their temperature limits, while achieving full fills and maintaining flow rates above the minimum check valve chatter flow rates advised in the high-flow fueling protocol. Developing this protocol will also lead to a preliminary time-fill fueling station design that can be utilized for station deployments in the future.

Status

The team has begun construction of the time-fill test unit. The Hazard and Operability review is complete. Operation of the test unit is expected to begin in early Q1 2024. The team will also assist NREL in validating the fueling protocol developed for high-flow fueling.

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Technical Support for Clean Transportation Testing, Performance, and Safety

This project provides technical support and input related to natural gas vehicle standards development and refinement, including revisions to temperature compensation guidelines and compressed natural gas dispensers.

Project Description

Over the past several decades, the natural gas industry has supported the development of minimum safety standards that guide natural gas vehicle (NGV) industry stakeholders. As a result, the NGV industry developed and improved a suite of compressed natural gas (CNG) and NGV components and systems while satisfying standards that allow for continuous improvement in technologies while ensuring the safety of vehicles, fueling infrastructure, and end users.

Ongoing innovations and changes necessitate that careful attention be placed on codes and standards. Knowledgeable technical input into the consensus-building process is critical to ensuring proper coverage to protect users and the general public. This includes clarifying coverage between new vs. existing standards and, where appropriate, expanding coverage to new applications and technologies. Outdated standards should not create an obstacle to product advancements that can benefit end users. As manufacturers of vehicle and station components expand their businesses to broader markets, harmonization of standards across North America, South America, and Europe is also gaining importance.

This project provides technical support and input related to NGV standards development and refinement, for consideration and/or ultimate consensus action by the technical committees of:

- CSA standards such as NGV 4.3 (Temperature Compensation Guidelines), NGV 4.1 (CNG Dispensers), NGV 4.8 (NGV compressors), and NGV 6.1 (CNG Fuel Storage)
- Gas quality standards from the CSA Group, ASTM International, American National Standards Institute (ANSI), and others, and
- National Fire Protection Association 52 revisions.

This project also provides technical data and information to the NGV America (NGVA) Technology and Development Committee to support accident investigations and help establish safety, technical, and environmental priorities.

Benefits / Market Implications

Enhancing the performance and safety of NGVs, the fueling infrastructure, and maintenance facilities helps end users and facility owner/operators reduce costs and incidents while gaining the environmental benefits of CNG.

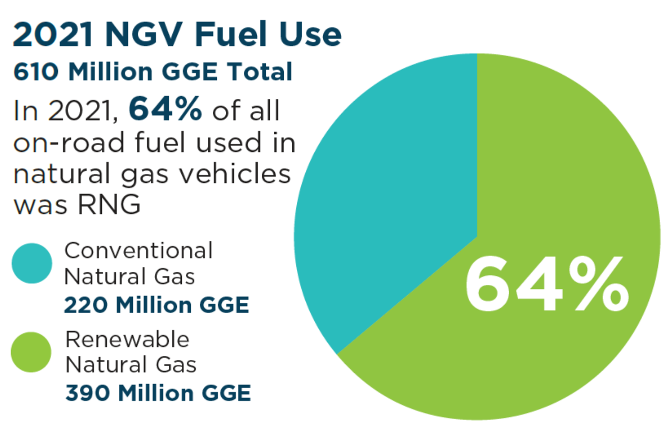
This project provides technical support to enhance consensus-developed standards and introduce new or updated minimum safety requirements affecting compression equipment, dispensers, vehicle components, and natural gas storage products in the North American marketplace.

By striving for single, globally-acceptable technical standards and conformance tests, new or improved products to benefit end users can be introduced at a broader scale and with lower cost and shorter time to market.

By participating on technical advisory groups, experts share best practices learned over decades of experience and influence the standards developers and product manufacturers.

The primary markets to benefit are:

- Overall NGV industry, including end-users and end-user fleets, vehicle and engine manufacturers, CNG station providers, and
- Additional stakeholders such as utilities and first responders.



The development of renewable natural gas (RNG) production is directly tied to the transportation sector and credits for RNG use in vehicles.
Source: NGVA Data on RNG Use in NGVs

Technical Concept & Approach

Project representatives participate as voting members in the Technical Advisory Group's standards groups and chair the NGVA Technical and Development Committee. Updates are provided through various tasks, including:

- **Technology Committee Support for Standards Development, Updates, Monitoring and Review**

  Project representatives participate in regular technical discussions and committee meetings scheduled by standards-setting organizations, testing organizations, and vendors to monitor and support by open meeting consensus the updates and progress of key standards and code documents.

- **NGVA Technical Development Committee Support**

  The project team's participation provides extensive NGV and fueling experiences.

Results

In 2022-23, the project team continued to participate in the development of CSA NGV 4.3 (Temperature compensation guideline for compressed natural gas vehicle fueling) which led to its finalization by CSA and its publication; this included serving as Vice Chair of the applicable CSA Working Group. NGV 4.3 underwent a major overhaul to include testing for new dispensers as well as updates to better reflect accurate temperature compensation. Researchers supported the base technical case for updates being evaluated by the entire Working Group. The process required defining specific operating conditions and test scenarios.

The project team also provided technical support to ANSI and CSA committees for the technical development of temperature compensation requirements in NGV 4.1, 4.8 and 6.1.

The project team also provided technical support to advance CSA NGV 5.1 (Residential Fueling Appliances) and CSA NGV 5.2 (Vehicle Refueling Appliances), which were finalized and published by CSA.

The project team also provided technical support for the NGVA Technology and Development (TD) Committee, including serving as TD Committee Co-Chair. Activities of NGVA's TD Committee included the assessing technical issues critical to end users and public safety, such as:

- Discussed and investigated, on a quarterly basis, the root causes of safety accidents and then communicated findings.
- Updated the Guide to Safe Vehicle Conversions with the latest requirements listed in FMVSS 304, NFPA 52, and EPA/CARB compliance regulations.

"CSA recognizes the input and insight that our committee members provide on NGV technical subcommittees. Through participation in the standards-development process, UTD contributes to the deployment of safe and reliable components, equipment, and practices for the industry."

- Julie Cairns
Sr. Project Manager, Alternative Energy
CSA Group

"NGVAmerica's Technology & Development Committee largely relies on the voluntary efforts of member companies and their representatives to address important issues in the NGV industry related to technology, innovation, safety, and sustainability. UTD's support to provide representation on the Committee and each of the subcommittee working groups has been instrumental in the many achievements to date for the advancement of natural gas as the most proven, cost-effective, and ready-now solution for decarbonizing transportation."

- Paul Sandsted
Director of Technology and Sustainability
NGVAmerica

- Held a Technology Webinar in September 2022 on the use of Modal Acoustic Emission (MAE) technology and its applications for vehicular and tube trailer CNG cylinder inspection.
- Created Recommended Practices for Unattended CNG Time-fill Refueling Stations document which can be found at: https://ngvamerica.org/wp-content/uploads/2021/09/ANGI-FDS-White-Paper-8.31.21.pdf
- The CNG Fuel System Inspection working group produced a CNG Cylinder Pressure Indication Safety Bulletin -https://ngvamerica.org/wp-content/uploads/2023/02/NGVA_safetybulletin_CNGcylinderpressureindication_28FEB2023.pdf

Status

This project continues to provide technical support in relevant CNG and NGV codes and standards technical committees as well as supporting key technical initiatives of the NGVA Technology and Development Committee.

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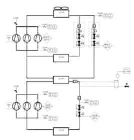
UTD
Utilization Technology Development

Cost-Effective Pre-Cooling for High-Flow Hydrogen Vehicle Fueling



Researchers will design, fabricate, and validate design of a cost-effective, high-efficiency chilling system to pre-cool hydrogen for high-flow fueling of heavy-duty trucks at 10,000 psi. This pre-cooling system will reduce the life-cycle cost of hydrogen fueling and reduce greenhouse gas emissions from heavy-duty vehicles.

Project Description

The goal of this project is to design, fabricate and validate a sub-scale version of a cost-effective, high-efficiency chilling system which uses commercially-available components and natural refrigerants to pre-cool hydrogen for high-flow fueling of heavy-duty vehicles at 10,000 psi (70 MPa).

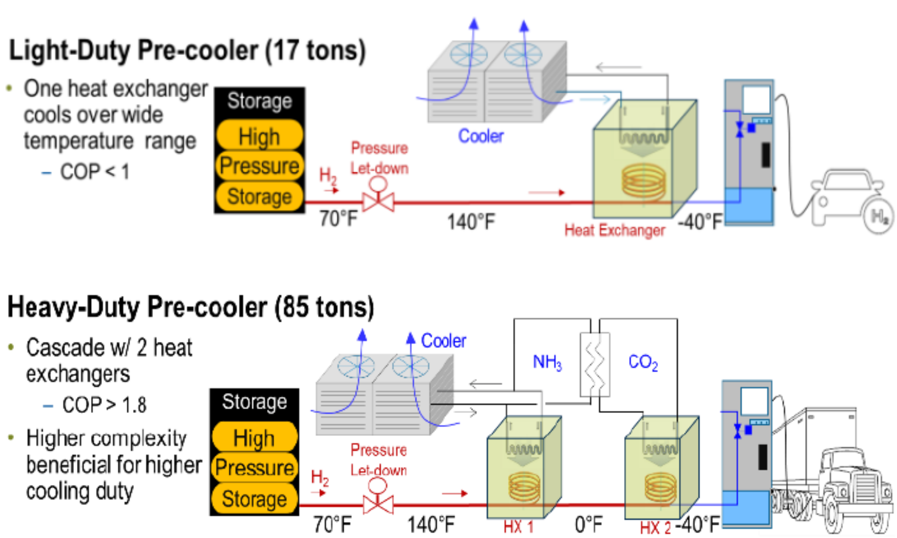
High pressure is required to provide reasonable vehicle range. However, the high pressure gas must be pre-cooled because the gas heats up significantly when compressed and the gas must remain below the maximum allowable temperature of the vehicle's hydrogen storage system. Equipment capable of cost-effectively delivering pre-cooled hydrogen at high flows for heavy-duty trucks is not commercially available. Applying commercially-available pre-coolers which are currently used for fueling light-duty hydrogen fuel cell vehicles would require five light duty chiller units at approximately $250,000 each for a heavy-duty hydrogen fueling station. For context, fueling stations for light-duty vehicles currently deliver hydrogen at approximately 2 kg/min, while typical targets for fueling stations for heavy-duty hydrogen vehicles are to deliver 10 kg/min.

Light-duty hydrogen pre-cooling units typically utilize a single refrigerant in a loop with a two-stage compressor and economizer to chill a large aluminum block to approximately -45°C. The hydrogen gas is then chilled from temperatures that can exceed 60°C down to -40°C in a single step. This design is suitable for intermittent light-duty fills because added complexity is cost-prohibitive at this small scale.

This project will utilize a cascade refrigeration cycle design that is more complex but provides large efficiency and energy savings - - more than a 100% improvement in total coefficient of performance (COP). The economic trade-offs of this option will be weighed against simpler single-refrigerant designs.

The US Department of Energy (DOE) is providing prime funding for this project, which focuses on developing near-term solutions utilizing commercial products while solving a considerable problem for end users. This low risk, high reward approach is expected to lead to rapid commercialization of a critical technology in this growing market segment. UTD is partnering with DOE by providing co-funding, along with the Southern California Gas Company (SoCalGas). Other project team partners include Argonne National Laboratory (ANL).

At the end of the project, the technology will be ready to transfer to a chiller manufacturer for detailed design of a full-scale system for subsequent installation and testing in a heavy-duty hydrogen fueling station. Key performance targets are for the pre-cooler design to fill a 60kg fuel system in 6 minutes (equivalent to diesel fueling speeds) at the temperature required by the applicable fueling protocol (currently under development), cost less than $500,000, and have a maximum power requirement under 200 kW. The team will build and validate a 2-3 kg/min lab-scale unit and develop a promising commercialization plan and economic analysis, with support from an industrial partner.



Benefits / Market Implications

The primary target market impacted will be heavy-duty trucks that require high pressure (70 MPa) hydrogen fueling. The development of this heavy-duty pre-cooling unit will reduce the life-cycle cost of hydrogen fueling, while accelerating a transition toward use of natural refrigerants – such as CO2 and NH3. This will reduce barriers to adopt heavy-duty hydrogen vehicles by lowering the cost of fueling stations.

Transitioning to hydrogen fuel cell heavy-duty vehicles would significantly reduce greenhouse gas emissions. Heavy-duty vehicles make up a small fraction of the vehicle fleet in the United States and travel only 10% of the total annual vehicle miles driven, but they contribute 23% of transportation emissions of greenhouse gases according to the Environmental Protection Agency.

Technical Concept & Approach

This project will develop an optimized pre-cooler design which will significantly benefit from refrigeration cycles that utilize several evaporator stages such as cascade refrigeration or more complex single-refrigerant circuits. The end product will be a fully-designed, optimized, and performance-verified chiller system capable of efficiently and cost-effectively fueling 70 MPa hydrogen vehicles at an average of 10 kg/min. The following tasks will be performed:

Task 1: Preliminary Chiller Design

Develop a preliminary design of a full-scale chiller system capable of fueling a heavy-duty vehicle within acceptable conditions, which include filling a 60kg storage system in less than 6 minutes with the flow profile and temperature defined by a heavy duty hydrogen fueling protocol currently being developed (e.g. see UTD project 2.21.H).

Task 2: Detailed Design and Build, and Economic Analysis

Complete the detailed design and build of a test unit, and perform laboratory testing. Also perform an economic analysis of the full-scale unit assuming production volumes of 100 units per year and assess if the targeted capital and operating costs of the system appear likely to be achieved.

Task 3: Lab Testing Set-up and Final Design

Perform lab testing of the test unit built in Task 2. The performance data and know-how gained from this testing can be incorporated into the design of a full-scale system suitable for commercialization by a manufacturing partner (to be identified) who would be interested in supporting subsequent demonstration at a high-flow hydrogen fueling station. Task 3 will also include commercialization planning to ensure the design is available for purchase by future stations.

Results

Modeling the worst-case scenario of a heavy-duty hydrogen vehicle fuel system showed that a pre-cooling temperature of -30°C is required to ensure a full fill at high ambient temperature. This matches recent progress reports from the team developing the fueling protocol. For the preliminary chiller design, the team only considered refrigerants which have a zero Ozone Depletion Potential and low Global Warming Potential (less than 10), which left only three refrigerant options: CO2, ammonia, and propane. A total of nine refrigerant systems have been selected for further consideration, all of which are various combinations of these three refrigerants.

A heat exchanger to cool the high-pressure hydrogen to -30C was sourced from two vendors. This heat exchanger is designed to withstand 15,000 psig of hydrogen on one side and a heat transfer fluid on the other side. Modeling of heat exchanger location revealed a delay of 100 seconds before the delivered hydrogen temperature fell below 25°C, which would cause an extended time delay for the fueling process. Therefore, locating the final stage of pre-cooling at the dispenser will likely be needed in most station configurations to ensure fueling efficiency.

The project team completed the preliminary design of the full-scale pre-cooling unit. One of the main decision points was whether to use propane or CO2 for the low stage of the chiller. The advantage of propane is the low operating pressure, making components cheaper and easier to procure. The downside is the high flammability that presents an additional hazard to the site. The team ultimately chose to move forward with CO2, even though the higher operating pressure of CO2 makes parts more expensive.

Modeling of the Coefficient of Performance and maximum power requirement was completed. The modeled maximum power for the NH3/CO2 system was found to be 110kW. This is before any over-design margin is allowed and some ancillary components (like cooling fans) are specified. The team expects this requirement to increase to a peak power requirement of 120-130kW for this system capable of filling a 70kg fueling system in six minutes at an ambient temperature of 20C.

For early-stage testing to inform the final design of the system, the team is conducting testing of the lower stage of the cascade chilling system. This CO2 stage will provide the final cooling before fuel delivery and will carry the requirement of achieving the final pre-cooling temperature. The cooling demand for this system is very transient and must respond quickly to changes in fueling flow rate. For this reason, the team decided it was important to test this stage alone prior to completing the design of the full test unit.

Status

The test unit design has been completed and undergone a full HAZOP review. Major components have been received. The team is currently constructing the low-stage test unit, and commissioning is expected in Q1 2024.

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Heavy-duty Hydrogen Vehicle Development and Deployment

Researchers will design, build, and demonstrate a hydrogen-fueled, zero-emissions regional-haul Class 8 vehicle to accelerate adoption of this type of vehicle in the market in order to reduce GHG emissions, enhance air quality, and delivering superior operating range for end users.

Project Description

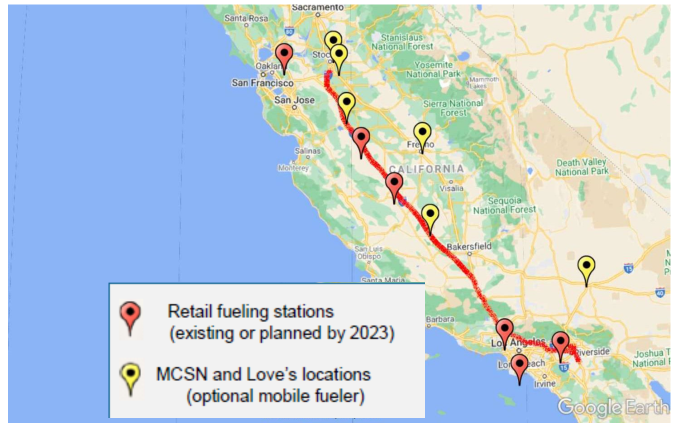
The goal of this project is to design, build, and demonstrate a hydrogen-fueled, zero-emission regional-haul Class 8 vehicle. With major funding support from the California Energy Commission (CEC) and Southern California Gas Company (SoCalGas), the tactical objectives are to integrate an advanced hydrogen fuel cell, hydrogen storage, battery, motive, and control systems to collectively provide a zero-emission solution for the challenging duty cycle associated with drayage and regional-haul operations. UTD is partnering with CEC by providing co-funding to the CEC-prime-funded project, which will lower greenhouse gas emissions and criteria area pollutants for consumers and the environment. Key performance indicators of the project success include:

- Develop and demonstrate a Class 8 fuel cell truck that can achieve one-to-one replacement of diesel truck
- Improve performance, durability, and maintainability of a regional-haul fuel cell truck
- Demonstrate reduced total cost of ownership (TCO) and other benefits in order to encourage adoption

Benefits / Market Implications

The project seeks to demonstrate a zero-emission alternative for the current market of diesel trucks used for regional haul and powered by 15-liter engines rated at 455 hp / 1650 lb-ft

Hydrogen tanks installed on the truck

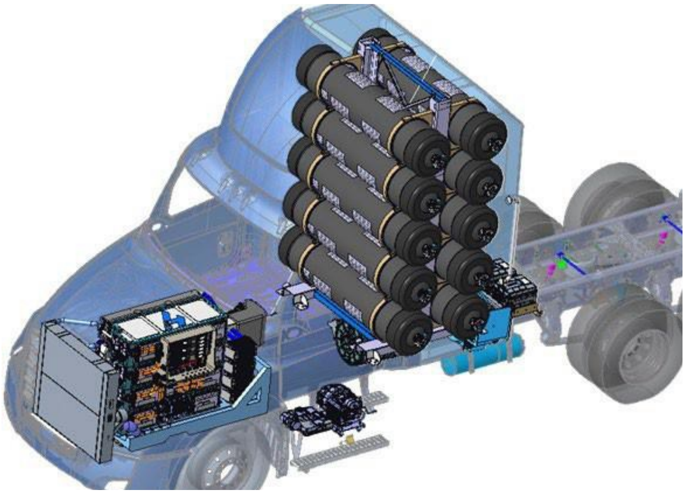


and equipped with 300 gallons of fuel tanks.

A typical loaded trailer being moved along the 400-mile demonstration route can weigh 23,500 to 57,000 lbs. The vehicle typically returns with an empty trailer weighing 13,500 lbs. The 300-gallon onboard fuel storage offers a 1,500+ mile range, theoretically supporting two roundtrips, which is not likely a critical need for a typical fleet. Currently, no zero-emission technology offers this amount of onboard energy storage and projected operating range.

The demonstration vehicle will overcome these barriers by storing 66.8kg of 700-bar hydrogen onboard, utilizing a 400-kW fuel cell, taking a strategic route with intra-route fueling in California's Central Valley, and employing a carefully-designed powertrain with components sized specifically for this duty cycle. US Department of Energy (DOE) national data suggests that 93% of the Class 8 trucks and 80% of their vehicle miles traveled (VMTs) can be served by vehicles with a 500-mile range. The 450-mile range vehicle will be able to perform both drayage and regional transport duties and the team has selected this application as not only a showcase of hydrogen fuel cell technology, but also because it can offer range that effectively covers most of intra-state California freight movement. The technology will also provide a substantial reduction in noise due to quieter powertrains and no need to use engine retarders on downgrades.

Over the last decade, the cost of fuel cell technology has been lowered by approximately 85%. It is expected that this trend will support the market to attain DOE's cost target of $80 per kW through technological improvement and volume production. Hydrogen fuel cost remains a concern among



Truck Packaging

Proposed envelope for fuel cell and low temperature thermal management equipment

fleet operators. By demonstrating the viability of hydrogen fuel cell trucks as a feasible zero-emission solution for long-distance operation, it will encourage the adoption of hydrogen-powered trucks and help create substantial demand for hydrogen as a transportation fuel.

According to a Total Cost of Operation (TCO) study by the National Renewable Energy Laboratory (NREL), fuel cell trucks could be cost-competitive with diesel trucks if the vehicle purchase price is $258,000 and hydrogen fuel prices are $4/kg. The project team believes that the successful execution of this project and the path-to-market strategies will align the TCO at scale with NREL's targets by 2025.

Technical Concept & Approach

The project team will design, build, and demonstrate a hydrogen-fueled, zero-emissions regional-haul Class 8 vehicle. The vehicle design, development, and verification work will take 24 months of the project. The vehicle demonstration will take 12 months. The following tasks will be performed:

Task 1: Vehicle Design, Build and Verification

Fuel Cell

The technical team will design and build the vehicle based on an existing Freightliner Cascadia platform. The task will include the definition of functional requirements, study of design trade-offs, and computational and numerical engineering. Following the build, the team will commission and verify the vehicle prior to delivery to the fleet operator.

Task 2: Demonstration, Data Collection and Analysis

Measurement and verification (M&V) activities will be performed and will leverage prior experience in data acquisition from advanced vehicle testing and data analysis.

Results

The project team has collected baseline data from a diesel truck. A Hydrogen Safety Plan and Safety Analysis Report has been developed, and the team had a project review with the CEC. Work has started to disassemble and convert the donor vehicle. Cooling and fuel cell subassemblies are being assembled. Hydrogen tanks have been received and installed. A fuel cell and component test and validation test bench have been developed. Thermal management systems, electrical and mechanical subsystems layout, control software design, safety design, and completed packaging design for all major components are being refined.

Status

The team is continuing work on design and assembly, safety plans, and establishing contracts with suppliers. The team will then develop a telematics and data collection system and a fueling plan.

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