the Energy to Lead

International Gas Union Research Conference 2014

Paper WO1-3

Development of Economical Gas-fired Ammonia-Water Absorption Heat Pumps for Water Heating and Space Heating Applications

Authors:
Paul Glanville, PE
Senior Engineer
Gas Technology Institute

Yongfang Zhong, Ph.D.
Principal Engineer
Gas Technology Institute

Michael Garrabrant, PE
President
Stone Mountain Technologies Inc.

Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

Introduction

In the U.S. 89% of residential natural gas is consumed by the gas-fired water heaters (GWH) and space heating (GSH) equipment combined, which are installed in approximately half of all U.S. residences. As such, continually improving the efficiency of warm-air furnaces, hot water and steam boilers, and water heaters is a critical goal of both government agencies and utility energy efficiency programs.

Widespread adoption of high-efficiency GSH equipment, with thermal efficiencies (TE) greater than 90%, began in the 1990s with the development of a range of economical condensing combustion technologies, including packaged premix combustion systems, pressurized low-temperature venting, and mass-produced secondary condensing heat exchangers. Now high-efficiency GSH equipment are prevalent, with over half of warm-air furnaces sold in the U.S. and Canada at a TE of 90% or greater and pending U.S. regulations to require high-efficiency GSH equipment in the 30 “Northern Climate” states.

More recently, residential GWHs have experienced a similar market and regulatory push towards high efficiencies, with Japanese and European-made tankless GWHs growing to 10% of the market with delivered efficiencies of 80% or greater compared to the typical 60% efficient storage GWHs. These shifts are significant, moving from unpowered, natural draft heating equipment with efficiencies of < 80% to powered, pressurized premix condensing combustion systems with efficiencies between 90% and 98%, however these technological advances offer no further room for improvement above a TE of 98%.

To move beyond the TE limits of standard condensing-efficiency residential space and water heating equipment, this paper describes parallel efforts to develop economic gas-fired ammonia-water absorption heat pumps deployed as a packaged storage water heater and hydronic space heater. In partnership with a major North American OEM, the project team has designed and demonstrated a packaged gas heat pump water heater (GHPWH) driven by 2.9 kW absorption heat pump (itself driven by a small 2 kW gas burner), that has demonstrated efficiencies twice that of standard water heaters with Coefficients of Performance (COPs) in excess of 1.5 and delivered efficiencies of 130%, while meeting strict California pollutant emission standards and seeking a competitive installed cost target of $1,800. With a thermal input of 16% of storage GWHs and 3% of tankless GWHs, the cost of GHPWH installation is minimized, requiring only small diameter gas and plastic vent piping, and standard electrical service. Following the GHPWH laboratory demonstration, the team is scaling up the gas heat pump (GHP) to 23 kW for hydronic space heating with a COP of 1.4 at 8°C, a 50% improvement over current high-efficiency space heating equipment at a competitive installed price.

Figure 1: Rendering of GAHP Prototype

These two developments of the GHP (Figure 1) and GHPWH (Figure 2), designed and built by Stone Mountain Technologies Inc. (SMTI), are summarized in Table 1.

Table 1: Characteristics of GHPWH and GHP Developments

Characteristic	**GHPWH**	**GHP**
Stage of Development	Pre-commercial Field Trials	Laboratory Prototype Demonstration
Heat Pump Output (kW)	2.9	23.4
Firing Rate (kW)	1.9	16.1
Efficiency	1.3 Energy Factor	COP > 1.4
Storage Size (L)	265	N/A
Emissions (projected)	10 ng NO_x/J	14 ng NO_x/J
Commercial Introduction (projected)	2016	2017
Installation	Indoors/semi-conditioned space (garage), sealed NH3 charge < 25% max allowed by ASHRAE Std 15	Outdoors
Venting	½" – 1" PVC	N/A
Gas Piping	½"	¾"
Estimated Consumer Cost	<$1,800	<$4,500

Figure 2: Rendering of Pre-Commercial GHPWH Prototype and Photo of Laboratory Prototype

Both technologies are based on the vapor absorption cycle, using the ammonia-water pair, which an absorbent (water) is used as a carrier for the refrigerant (ammonia). While the refrigerant is still compressed by an electromechanical pump, unlike more typical vapor compression cycles, it is compressed as a liquid in solution with the absorbent. Lifting the pressure of a liquid versus a vapor requires significantly less energy. For example, comparing a 1.3 $COP_{heating}$ ammonia-water heat pump to an 8.2 HSPF vapor compression heat pump, the absorption cycle solution pump requires less than 1.0% of the total energy input to the electric compressor [1] . A thermal energy input is simply required to drive the refrigerant vapor from its absorbed state in the generator (or "desorber"). As adequate refrigerant/absorbent pairs require high affinities and stability over a wide range of temperatures and pressures, they have significant heats of absorption. When operating in heating mode, this heat is recovered in addition to that rejected at the condenser. As refrigeration was discovered prior to widespread electrification and the development of internal combustion engines, absorption cycles were developed and commercialized prior to vapor compression cycles, which now comprise of over 90% of all air-conditioning systems in residential, commercial, and industrial applications [2]. For example, ice production in the late 19th century in the U.S. was primarily driven by ammonia-water vapor absorption cycles prior to widespread use of vapor compression [3].

Gas Heat Pump Water Heater Development

With improving building envelopes reducing space heating loads and the growth of condensing efficiency warm air furnaces, estimated at over 50% of the U.S. furnace market, water heating represents a growing portion of the residential gas load on the west coast at 35% and growing, nearly 50% in California [4,5]. Despite this, of the approximately half of all residential water heaters sold in the U.S. and Canada that are natural gas-fired, the majority are minimum efficiency gas-fired storage water heaters with an average Energy Factor (EF) of 0.60. Higher efficiency gas-fired options exist on the market for retrofit, however they are incremental in nature or suffer from discrepancies between rated versus realized energy savings, as follows:

- Non-condensing storage EnergyStar® water heaters yield nominal savings, with EFs of 0.67-0.70, however electrical service is required with this added installation and operating cost potentially erasing net savings [6].
- Small condensing storage water heaters require a venting upgrade and power service, which while they are rated as greater than 90% thermal efficiency, uncertified laboratory testing shows performance would result in an EF of less than 0.80 [6].
- Converting to tankless water heater, with an EF typically between 0.82 and 0.95, requires a venting upgrade, power service, and an up-sizing in the gas service from ½” to ¾” is required. This higher delivered efficiency is in dispute, however, as due to the impact of cyclic/startup losses from distributed hot water usage, differing from that with which they are rated, several groups “de-rate” the efficiency by up to 9% [7].

Looking beyond these options, a team lead by SMTI with support from the Gas Technology Institute (GTI), A.O. Smith, and the Georgia Institute of Technology successfully designed and demonstrated a GHPWH with a projected EF of 1.3, twice that of standard gas-fired storage water heaters in a US Dept. of Energy Sponsored Program. The packaged GHPWH heats the approximately 265 L of stored water with a nominal 2.9 kW output ammonia-water absorption heat pump, driven by a small 1.9 kW low-emission gas burner, exceeds the thermal efficiency limitation of standard gas-fired products with Coefficients of Performance (COP) in excess of 1.5.

The GHPWH represents a similar leap forward in water heating efficiency to the recent generation of residential electric heat pump water heaters (EHPWH), that have demonstrated delivered efficiencies at least twice that of standard electric resistance water heaters [8]. Like the packaged EHPWHs, the GHPWH is comprised of three major components: a) storage tank, b) sealed system (set of heat exchangers containing the refrigerant) and c) supporting components such as the evaporator fan, combustion system and controls. Within the sealed system, the total ammonia charge is about 25% of the limit required for indoor use by ASHRAE Standard 15. The safe use of ammonia as a refrigerant for indoor equipment has been well demonstrated since the first widespread use of absorption refrigerators in the early 20th century to current times where the quieter absorption mini-refrigerators are preferred by large hotels.

GHPWH Performance

The operating principle of a GHPWH is very similar to the EHPWH; the electrically-driven compressor is replaced by a “thermal compressor” comprised of two heat exchangers (desorber-absorber) and a very small solution pump. Energy from the ambient air is still transferred to the heat pump via an evaporator coil, slightly cooling the ambient air stream. The COP of the cycle ranges from 1.8 when the water in the tank is warm, to 1.4 when the water is hot. After accounting for combustion and stand-by losses and the small amount of electrical power needed for the pump and evaporator fan, the resulting EF is 1.3. The GHPWH uses a single-effect absorption cycle, which requires fewer heat exchangers (thus less complex and costly). During the development of the prototypes, the opportunity for a higher-efficiency Generator-Absorber Exchange (GAX) cycle was explored using experimental breadboard testing but the incremental efficiency gains were not justified by the increased estimated system cost [9,10]. The performance of three generations of GHPWH laboratory prototypes are shown in Figure 3, indicating performance typical of single-effect cycles.

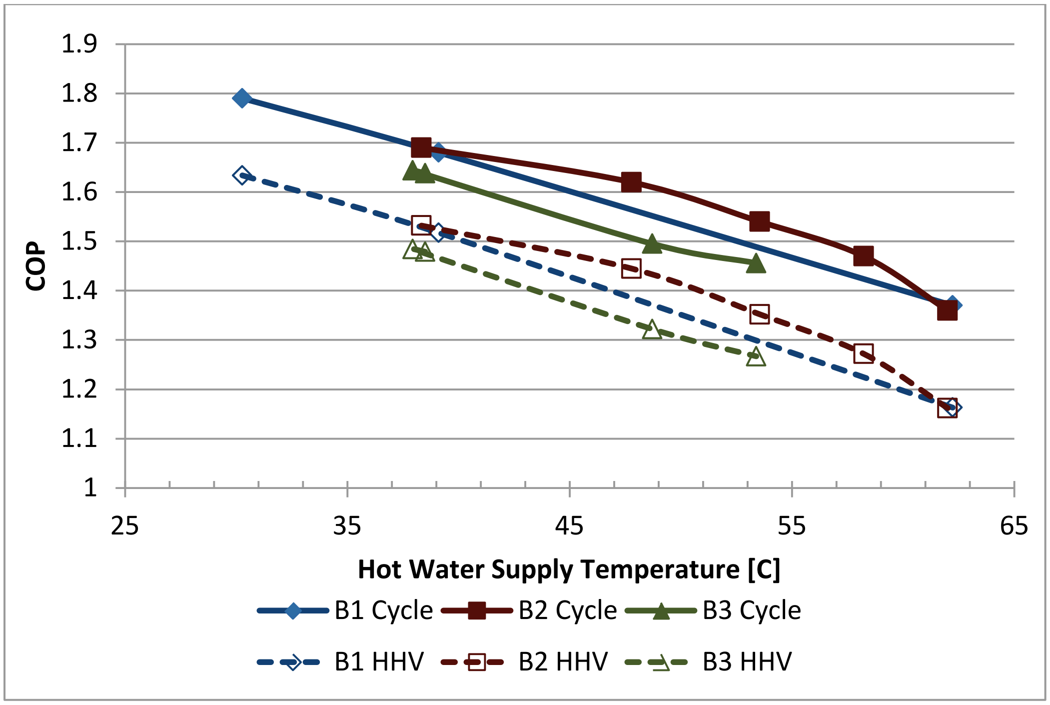

Figure 3: Laboratory GHPWH Prototype Steady-State Performance and 20°C Ambient Conditions (Multiple Generations of Prototype)

Following the initial laboratory demonstration, GHPWH units were commissioned for field evaluations, starting with an installation at a residence in Tennessee. The GHPWH was installed in a garage with an occupancy varying from 2 to 4 full-time occupants, due to children returning from university. Performance of the unit is shown in Figure 4, which the unit operated successfully with ambient temperatures below 2°C and inlet water temperatures as low as 4°C. Extrapolating the daily energy input and output to those of the U.S. rating method of test for large demand homes (318 L/day), this corresponds to a delivered energy of 1.30. Subsequent field demonstrations are underway throughout the U.S., with a focus on the West Coast where gas water heating is most prevalent.

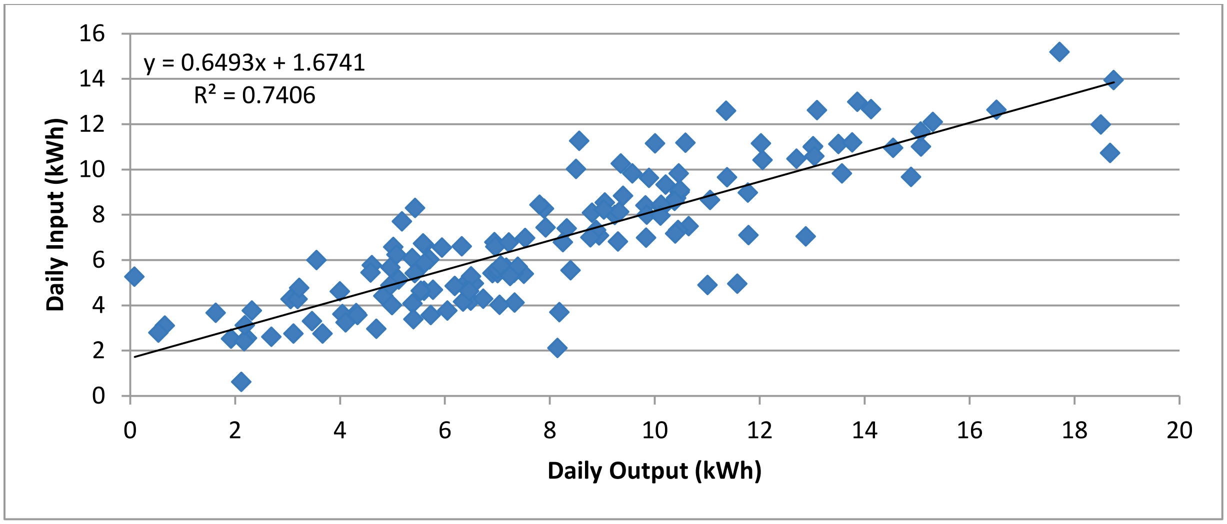

Figure 4: Performance of GHPWH in Field from 3/14 to 8/14

Economics of the GHPWH

Considering the operating cost of the GHPWH versus that of typical gas storage water heaters, gas tankless water heaters, and EHPWHs, using the current U.S. method of test extrapolated annually, a comparison is shown in Figure 5 which highlights the reduced operating cost for GHPWHs. Electricity and natural gas consumption for each model are from laboratory studies [6, 8, 9] and utility prices are statewide averages for California and New York, which are \$0.175/kWh & \$0.893/therm and \$0.193/kWh & \$1.339/therm respectively.

The GHPWH offers retrofit installation advantages over other high-efficiency gas products: compatibility with existing smaller diameter gas piping, small diameter ¾" PVC venting, and it requires standard 120 VAC service. These in turn provide for a reduced installation cost to balance the higher equipment cost versus other high-efficiency gas equipment. Using estimated equipment costs and installation costs [6] and extrapolating these operating costs over a 10 year life, the total cost of ownership of these water heating technologies is shown in Figure 6. At its current projected equipment cost, the GHPWH has the closest cost of ownership to the lowest efficiency option, and for regions with higher cost natural gas (New York) it has the lowest absolute cost of ownership. With a target installed cost comparable with alternative high-efficiency gas-fired options (EF 0.8 – 0.95), the GHPWH will provide a faster economic payback compared to gas tankless or condensing storage models.

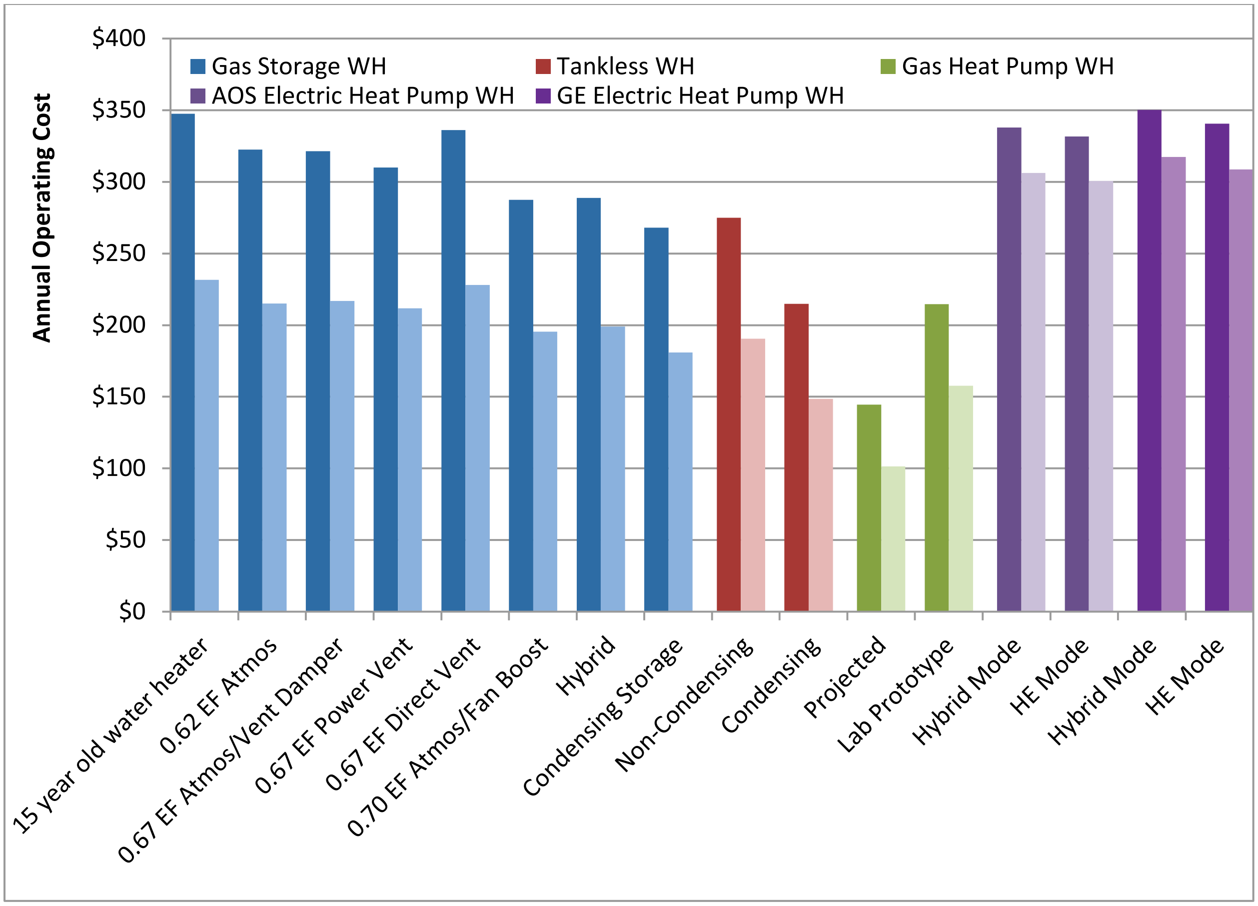

Figure 5: Operating Cost Estimate of Different Residential Water Heaters in California (Light Shade) and New York (Dark Shade)

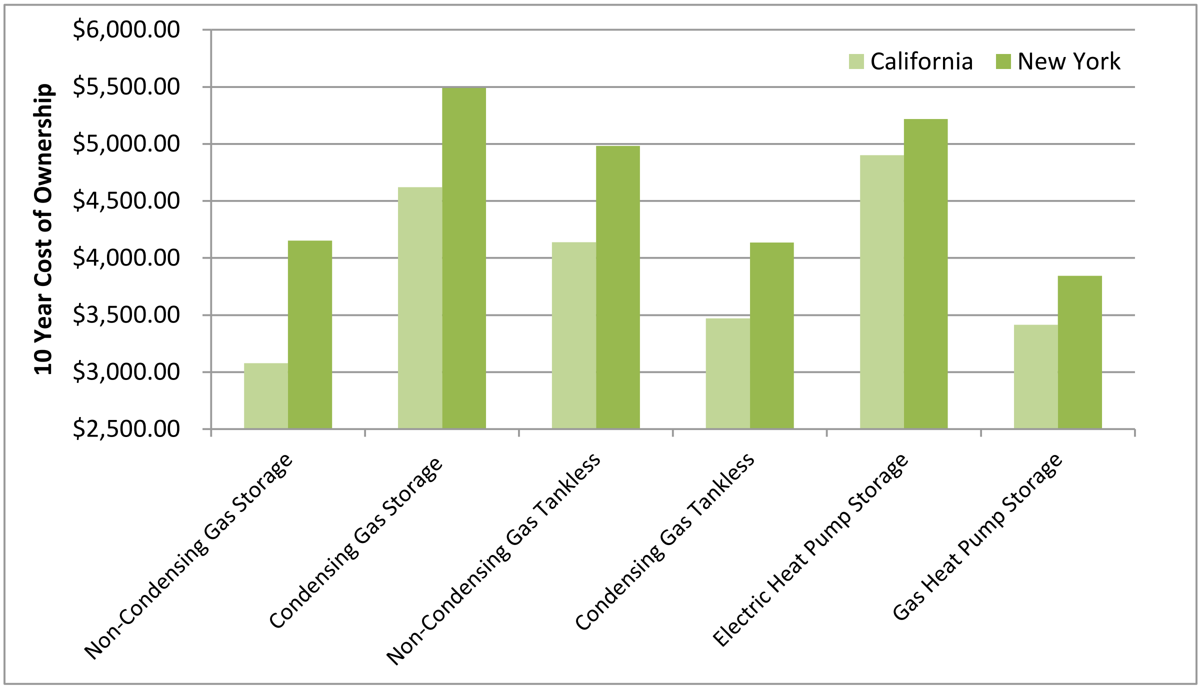

Figure 6: Total Cost of Ownership Estimates for Various Residential Water Heating Equipment

Gas Heat Pump for Space Heating Development

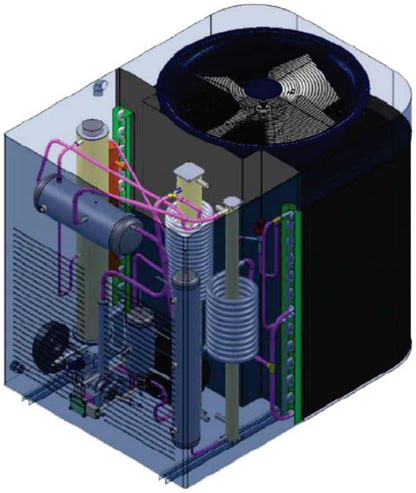

Figure 7: Rendering of Packaged GHP

In parallel to the GHPWH development, SMTI is leading a similar team to design and validate the performance of an economical residential gas-fired heat pump for building space heating in cold climates, with a target COP of at least 1.4 at 47°F (8°C) and 1.2 at -13°F (-25°F), reducing the cost of heating by up to 50% compared to conventional gas furnace and boiler technologies. Like the GHPWH concept, this GHP is based on a simple single-effect ammonia-water absorption cycle, with mass-producible heat exchanger technologies. As shown in Table 1, the GHP system has an output of 23.4 kW, approximately an 8-fold scale up of the GHPWH design. The GHP will be retrofit capable with hot water boilers or warm air furnaces, provided that the GHP is linked to the forced air heating system with a hydronic coil for the latter.

Following initial system modeling and design, breadboard testing of components suggest that these COP targets are feasible, with the tailoring of certain components (e.g. the solution pump) to the size and duty of the GHP as compared to the GHPWH. The design of the packaged system is near finalization (Figure 7), with prototype testing planned for late 2014 in a psychrometric chamber.

Conclusion

In parallel development programs, the progress in designing and demonstrating economical gas-fired absorption heat pumps, deployed in the North American residential market as a storage water heater and as a heat pump, is described. Concerning the GHPWH development, the laboratory-validated performance and estimated installed cost demonstrate that with a 1.3 Energy Factor, it will be competitive in the U.S. market with a total cost of ownership lower than all other high-efficiency options. This owes in large part to the estimated low retrofit cost of the GHPWH, with a small input capacity, requiring no upsizing of gas piping and minimal accommodation of small diameter plastic venting. This performance is shown to be robust over a range of operating conditions, including usage patterns, ambient temperatures, and water mains temperatures, by both laboratory testing and field evaluation of the GHPWH in a U.S. residence. Concerning the more recent cold climate GHP development, building on the successes of the GHPWH demonstration, a similar approach is used, focusing on the simple single-effect absorption cycle and scaling up mass-producible heat exchanger designs where feasible. Laboratory breadboard testing confirms the ability of the GHP to reduce the cost of heating by up to 50% compared to conventional gas furnace and boiler technologies, with packaged prototype GHP testing planned for late 2014.

References

1. Herold, K., Radermacher, R., and Klein, S. "Absorption Chillers and Heat Pumps". CRC Press, Taylor & Francis Group, 1996.
2. Westphalen, W. and Koszalinkski, S. "Energy Consumption Characteristics of Commercial Building HVAC Systems, Volume 1: Chillers, Refrigerant Compressors, and Heating Systems", Arthur D. Little Report For Office of Building Technology State and Community Programs, Department of Energy (4/01).
3. Elbel, S. and Hrnjak, P. "Ejector Refrigeration: An Overview of Historical and Present Developments with an Emphasis on Air Conditioning Applications", Proceedings of the International Refrigeration and Air Conditioning Conference, July, 2008, Purdue University, West Lafayette, IN.
4. Department of Energy, Energy Information Administration. Residential Energy Consumption Survey, 2009 ed. http://www.eia.doe.gov/emeu/recs/contents.html
5. Seto, B. et al. *California Energy Commission Energy Efficient Natural Gas Use in Buildings Roadmap*. Presented in Sacramento, CA 10/18/13. Link: http://www.energy.ca.gov/research/notices/2013-10-14-18_workshop/presentations/4_Residential_Sacramento_CA.pdf
6. Kosar, D., Glanville, P., and Vadnal, H (2012). "Facilitating the Market Transformation to Higher Efficiency Gas-Fired Water Heating". Prepared for the California Energy Commission, CEC-500-2013-060. http://www.etcc-ca.com/sites/default/files/reports/ET11PGE1111%20Residential%20Water%20Heating%20Program.pdf
7. RESNET. Results of Electronic Ballot of RESNET Board of Directors on Adopting Proposed Standard Amendment on Adjusting Instantaneous Water Heater Efficiency. April 4, 2012. http://resnet.us/board/Results_of_Electronic_Ballot_of_RESNET_Board_on_Adopting_Inst_Water_Amendment.pdf
8. Glanville, P., Kosar, D., and Suchorabski, D. "Parametric Laboratory Evaluation of Residential Heat Pump Water Heaters", Trans. of ASHRAE v. 118 pt. 1, Chicago, IL. (2012). Link: *http://aceee.org/files/pdf/conferences/hwf/2011/1B%20-%20Paul%20Glanville.pdf*
9. Garrabrant, M. *Development and Validation of a Gas-Fired Residential Heat Pump Water Heater - Final Report*. 2013, prepared for the U.S. Department of Energy, Contract DE-EE0006116. Link: http://www.osti.gov/scitech/biblio/1060285
10. Garrabrant, M., Stout, R., Glanville, P., Keinath, C., and Garimella, S. (2013) "Development of Ammonia-Water Absorption Heat Pump Water Heater for Residential and Commercial Applications", Proceedings of the 7th Int'l Conference on Energy Sustainability, Minneapolis, MN.