High Efficiency, Residential Gas-Fired Adsorption Heat Pump Water Heater Development

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Hot Water Forum
Water Heating, Distribution, and Use Efficiency
American Council for an Energy-Efficient Economy (ACEEE)
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Recent Heat Pump Work at ORNL

• Design and Development of Integrated Heat Pump (IHP) concepts reduced to practice

• Collaborative R&D with multinational companies and manufacturers

• Wide range of products brought to the marketplace

• Seeking partnership with industry on next generation of water heaters
Industry CRADA Collaborations are Delivering Additional Equipment Solutions to the Market
Ripple effects of General Electric-ORNL heat pump water heater CRADA

Began production in Louisville KY Feb 2012 (created ~1,000 jobs)

62% energy savings compared to a conventional electric storage water heater, pays for itself in < 3 yr
After CRADA with ORNL, ClimateMaster Launches Trilogy™ 40 Q-Mode™ (1st AHRI Rating > 40 EER)

- Heating, cooling, 100% of water heating (not just a desuperheater)
  - 55-65% energy savings vs. minimum efficiency (SEER 13) equipment
  - 30-35% savings vs. state-of-the-art two-stage GHP with desuperheater
The Trilogy 40 Q-Mode Ground Source IHP

- With rated efficiencies as high as 42.1 EER, the Trilogy™ 40 series is the first geothermal heat pump ever certified by the Air Conditioning, Heating, and Refrigeration Institute (AHRI) to exceed 40 EER at ground-loop (GLHP) conditions.

- The Trilogy™ 40 utilizes variable-speed technology to provide an extremely wide range of heating and cooling capacities.

- In addition, patent-pending Q-Mode™ technology produces year-round domestic hot water on demand, even when space conditioning is not required.
Pushing the Envelope at ORNL on Adsorption Technology

Old applications

100 kW chiller
ISAAC solar Icemaker
In Kenya

ORNL Pushing the envelope

Gas domestic hot water COP ~ 1.0
Challenge: increase COP to 1.5

Application of Adsorption technology for domestic/commercial hot water production
The Case for Sorption HPWHs

- Sorption HPWH uses fossil energy resource more efficiently
- Focus on AdHPWH for domestic WH

\[ \theta = \frac{\text{Energy to make HW}}{\text{Thermal Energy at Source}} \]

Elect. WH

- 1 kW_e
- 3 kW_t (at Source)

Gas. WH

- 0.92 kW_t
- \( \theta = 0.92 \)

Eff\~0.92

Surroundings

- 2 kW_t

Sorption HPWH

- 1.38 kW_t
- \( \theta = 1.38 \)

EEF\~0.92

- 1.5 kW_t (COP=1.5)
- 1 kW_t

- 0.5 kW_t

Gas. WH

- 0.92 kW_t
- \( \theta = 0.92 \)

Eff\~0.92

Surroundings

- 3 kW_t
- COP=3

- 1 kW_e
- 3 kW_t (at Source)

Elec. HPWH

- 2.76 kW_t
- \( \theta = 0.92 \)

Eff\~0.92

Surroundings

- 1 kW_e
- 2 kW_t

Residential Adsorption HPWH
Water Heaters Affected by New Standards, Effective April 2015

<table>
<thead>
<tr>
<th>Product Class</th>
<th>Energy factor as of January 20, 2004</th>
<th>New Energy Factor Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-fired Water</td>
<td>0.67 – (0.0019 x Rated Storage Volume in gallons).</td>
<td>For tanks with a Rated Storage Volume at or below 55 gallons: EF = 0.675 – (0.0015 x Rated Storage Volume in gallons). For tanks with a Rated Storage Volume above 55 gallons: EF = 0.8012 – (0.00078 x Rated Storage Volume in gallons).</td>
</tr>
<tr>
<td>Oil-fired Water Heater</td>
<td>0.59 – (0.0019 x Rated Storage Volume in gallons).</td>
<td>EF = 0.68 – (0.0019 x Rated Storage Volume in gallons).</td>
</tr>
<tr>
<td>Electric Water Heater</td>
<td>0.97 – (0.00132 x Rated Storage Volume in gallons).</td>
<td>For tanks with a Rated Storage Volume at or below 55 gallons: EF = 0.960 – (0.00003 x Rated Storage Volume in gallons). For tanks with a Rated Storage Volume above 55 gallons: EF = 2.057 – (0.00113 x Rated Storage Volume in gallons).</td>
</tr>
<tr>
<td>Tabletop Water Heater</td>
<td>0.93 – (0.00132 x Rated Storage Volume in gallons).</td>
<td>EF = 0.93 – (0.00132 x Rated Storage Volume in gallons).</td>
</tr>
<tr>
<td>Instantaneous Gas-fired Water Heater</td>
<td>0.62 – (0.0019 x Rated Storage Volume in gallons).</td>
<td>EF = 0.82 – (0.0019 x Rated Storage Volume in gallons).</td>
</tr>
<tr>
<td>Instantaneous Electric Water Heater</td>
<td>0.93 – (0.00132 x Rated Storage Volume in gallons).</td>
<td>EF = 0.93 – (0.00132 x Rated Storage Volume in gallons).</td>
</tr>
</tbody>
</table>

New, higher energy efficiency standards for residential hot water heaters came into effect April 2015, cutting the energy use of all sizes and types of water heaters significantly, and dramatically changing the home hot water landscape. The new regulations require electric water heaters to use 47% less energy, and gas water heaters to be 30% more efficient.

There are a variety of products that are already compliant with the 2015 standards.

Ref: CONTRACTOR: The online resource for mechanical contracting
Two distinct projects funded by BTO, U.S. Department of Energy

- Commercial Gas-Fired Absorption Heat Pump Water Heater
  - Working pair is ammonia-water
  - Prototype system is essentially complete
  - Demonstrated that target goals with prototype in 2015.
  - Testing of next generation beta unit ongoing

- Residential Gas-Fired Adsorption Heat Pump Water Heater (AdHPWH)
  - Working pair is ammonia-activated carbon (AC)
  - AdHPWH system, modeled and tested but results fell short of performance target to achieve a minimum energy factor of a standard non-condensing gas fired water heater and have a competitive cost premium for market introduction
US Market/Environmental Impact

- In 2010, residential water heating accounted for 2.9 Quads (8.40 TWh) of primary energy use (2011 Building Energy Data Book, Table 2.1.5).

- When fully deployed, the AdWH may provide up to 0.45 Quad (130 TWh) of primary energy savings, equivalent to 24 million tons of CO₂ emission reductions annually (2011 Building Energy Data Book, Table 1.4.8), eliminating the need for HFC refrigerants with significantly higher ODP and GWP.

- Market for AdHPWH is about 15% of residential water heating market
Participation in IEA Annex 43/Research Program

- The U.S through the Oak Ridge National Laboratory became a participant in Annex 43 – Fuel Driven Sorption Heat Pumps in March 2014

- The program of research is the development, demonstration, and promotion of gas-fired heat pumping technology for the commercial and residential markets with COP >1 with working materials having 0 GWP and 0 ODP

- Research is conducted under the directive of the U.S Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Buildings Technology Program (BTO)
Water Heater Shipment Projections

All Water Heater Industry Shipments: U.S

Electric Storage and Gas Storage units dominate sales
Objectives:

- Residential Gas-fired Adsorption Heat Pump Water Heater
  
  - To develop an adsorption heat pump water heater (AdHPWH) at an installed cost low enough to enable widespread residential market adoption
  
  - 1 to 3 kW capacity
  
  - Provide hot water at 50°-60°C
  
  - Ambient temperature range -10°C to 37°C
  
  - EF>1.0 as determined by the standard rating procedure for storage water heaters.

- Industry collaborators to be determined. Currently, In-house R&D at ORNL
R&D Status

- Established technical feasibility of AbHPWHs with EF>1.0 using working materials that have 0 GWP and 0 ODP

- Identified possible working pairs (activated carbon-ammonia)

- Established process constraints and acceptable cost for the manufacturer

- Developed a model for parametric analysis

- Quantified system size based on cycle times, adsorption capacity, and capacity

- Prototype testing
Activated Carbon Samples

Adsorption data fitted to Dubinin Equation:

\[ x = x_0 \exp \left( k \left[ \frac{T}{T_{sat}} - 1 \right]^n \right) \]

<table>
<thead>
<tr>
<th>Sample</th>
<th>( x_0 )</th>
<th>( k )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2GK</td>
<td>0.5204</td>
<td>-5.6321</td>
<td>0.8010</td>
</tr>
<tr>
<td>2GS</td>
<td>0.3360</td>
<td>-4.9070</td>
<td>1.156</td>
</tr>
<tr>
<td>VM-5CC--0408</td>
<td>0.2672</td>
<td>-5.8932</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Adsorption Isotherms Developed from the Dubinin Parameters

Selected Activated Carbon: G2K because of higher loading: $x_0 = 0.52$
System Components
Prototype Subsystem
“Dead Mass” Strongly Limits COP

\[ \text{COP}_{\text{WH}} = \frac{1}{\text{Carnot COP}} \]

Parameter: \( T_{\text{OAT, in}} \) in 10°C intervals

Dead Mass adsorb = Dead Mass desorb = 0.25
What COP can we expect?

Effect of $\varepsilon_{\text{evap}}$ on COP
$T_{\text{OAT,in}}$ as parameter in 10°C steps

Dead Mass (abs/des) = 0.25

$T_{\text{OAT,in}} = 30^\circ\text{C}$

$T_{\text{OAT,in}} = -20^\circ\text{C}$
Adsorption is fast but “dead mass” too high

Although adsorption rate is fast, with adsorber bed heating from 22°C to 88°C in 155 s (2.6 mins), the overall cyclic performance fell below target limits. The total energy consumed was more than was produced, mainly due to the dead mass of the system, which was 36 times greater than that assumed by the simulation.
Recommendations

• 85% of the adsorber mass is in the flanges. Need to redesign the adsorber to reduce “dead mass” within acceptable limits
• Use ceramic paper in the adsorber to reduce thermal losses to the adsorber shell. This allows a greater fraction of the heat of adsorption to heat the water through internal insulation.
• Re-configure components to bring them into closer proximity to further reduce mass of metal and to facilitate transport of ammonia over shorter distances, and to lower pressure drops.
• Improvise a TXV. Vendor-supplied TVX’s do not appear to be suitable for bench-top applications
• Look for better adsorbents that have a larger spread of the isosteres, thereby reducing the system pressure considerably.
U.S Consumer Sentiment

- Consumers are interested but remain skeptical about efficient models
- ENERGY STAR ranking is a significant selling point
- Cost-conscious consumers want efficiency rebates and incentives
- About 26% of consumers are skeptical about claims of utility bill savings
- Consumers willing to pay a modest premium for energy efficiency
- Consumer skepticism is reinforced by inexperienced installers
- Consumers are increasingly relying on on-line information to research products
- The single greatest factor in decision-making is the cost of purchase and installation

Source: NEEA Report # 12-234, January 16, 2012
Thank You!
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