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Development of a Novel Sorption-Type Heat Pump Water Heater for North American Homes

Paul Glanville[a*], Navin Kumar[a], Abbas Ahsan[a], Alex Fridlyand[a], Magnus Ekblad[b], Ingemar Hallin[b], Corey Blackman[d], Noe Contreras[c]

[a]GTI Energy, 1700 S Mt Prospect Rd, Des Plaines, IL 60018 USA
[b]HeatAmp Sweden AB, Sankt Eriksgatan 65, 113 32, Stockholm, Sweden
[c]Northwest Energy Efficiency Alliance (NEEA), 700 NE Multnomah Street, Suite 1300, Portland, OR 97232 USA
[d]SaltX Technology AB, Västertorpsvägen 135, 129 44, Stockholm,. Sweden

Abstract

Critical to decarbonizing gas-fired water heating, typically up to 26 GJ of natural gas consumed per home per year, is advancing heat pump water heaters (HPWHs). This paper provides an overview of the development and experimental demonstration of this novel sorption-type HPWH, using a nested buffer tank/heat exchanger approach driven by an integrated compact steam boiler. Led by a European technology developer with technology support from multiple U.S.-based partners, this fuel-fired HPWH concept is intended for North American homes, with a hybrid design of both up to 2 kW peak output from the sorption modules and up to 12 kW peak auxiliary output from the steam boiler. With an efficiency target of ≥1.25 UEF and a target first hour rating of 284 L of hot water, this paper focuses on several aspects of this product development and testing, including a) the development and testing of a compact steam boiler loop to drive the desorption process, designed for 14 ng NOx/J output and compatible with up to a 30% hydrogen/natural gas blended fuel, b) immersed sorption modules within the buffer storage tank for water heating with a $COP_{gas} > 1.40$ using limited moving parts, and c) heat exchange and preliminary system controls, per empirically-calibrated simulation, to meet UEF targets and high usage hot water patterns typical for 4-5 occupant homes. Following this review of testing results, the authors provide an outlook for fuel-fired HPWHs in a rapidly decarbonizing North American market.

Keywords: heat pump water heater; sorption-type heat pump; vapor adsorption cycle; ultra-low NO_x

1. Introduction

Of the more than four million fuel-fired storage-type residential water heaters sold in the U.S. each year, which outnumber sales of tankless water heaters by about six-to-one, only about 5% of these products have efficiencies greater than the minimum allowable efficiency of a uniform energy factor (UEF) of 0.62 to 0.64 (depending on storage tank volume[1]). This is despite concerted efforts on the behalf of manufacturers, technology developers, and researchers to introduce higher-efficiency equipment, which includes condensing-level efficiency storage water heaters, hybrid tank/tankless type solutions, and integrated heat pump water heaters (HPWHs). It is the last category that holds the greatest promise to decarbonize the approximately 26 GJ of natural gas consumed per home per year, through increases in efficiency as a critical emerging solution

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[*] Corresponding author. Tel.: +1 847 768 0782; fax: +1 847 768 0501.
E-mail address: pglanville@gti.energy.

[1] The Uniform Energy Factor (UEF) is a common efficiency metric in the U.S. and Canada, which is a daily efficiency metric (site energy basis) based on serving a specific simulated hot water usage pattern. This is defined in the U.S. Code of Federal Regulations, Appendix E to Subpart B of Part 430 – *Uniform Test Method for Measuring the Energy Consumption of Water Heaters*

to address a market that is challenged by cost-effective energy efficiency with 0.88 UEF storage-type solutions and 0.97 tankless-type solutions available today [1].

While residential electrically-driven HPWHs are mature and available in the U.S. for 10+ years [2], providing multiple options UEF > 2.50 (0.95 on primary energy basis for U.S. average), there are emerging air-source sorption-type HPWHs under development as well that are suitable for direct-fired applications with natural gas, propane, biomethane, and/or hydrogen-based fuels. Sorption-based HPWHs are available for commercial-sized water heating applications but are only now emerging for residential applications. Commercial-sized fuel-fired HPWHs are often able to serve much larger commercial hot water loads than integrated electrically-driven HPWHs (common to have > 3X rated capacity [3]) and have undergone multiple demonstrations in recent years over multiple building types, including hospitality, multifamily buildings, senior care facilities, schools, and restaurants/cafeteria applications [3]. For these commercial-sized products or prototype HPWHs, employing direct-fired vapor absorption cycles (single-effect and GAX-type), units with maximum outputs from 23 kW to 41 kW were operated in conjunction with existing site boilers and/or commercial water heaters as a retrofit for periods of 12 months or more in California, British Columbia, Illinois, Ontario, and Oregon. Results showed a reduction in site fossil gas consumption by 18% to 53% [4-7], with one study using hybrid air/water-source approach to provide supplemental A/C in addition to hot water for two full-service restaurant sites, yielding an additional 14% reduction in electricity demand for A/C in addition to hot water fuel savings, for a net 48% reduction in overall greenhouse gas (GHG) emissions [4].

These residential sorption-type HPWH developments are important, as the regulatory environment in the U.S. is shifting rapidly to accelerate further gains in end-use energy efficiencies. This includes proposed changes to the EnergyStar® specification to have a minimum allowable UEF $\geq$ 0.86 (original proposal was UEF $\geq$ 1.0) for gas-fired storage-type water heaters [8] and regional specifications like the Northwest Energy Efficiency Alliance (NEEA) advanced specification creating three performance tiers of minimum allowable UEF from 1.0 to 1.3 [9]. These shifts in performance metrics have been informed by multiple developments of sorption-type HPWHs, such as one approach based on a single-effect vapor absorption cycle (NH_3/H_2O), which was successfully developed and demonstrated in multiple U.S. field trials to reduce fuel consumption by 50% or greater with a projected UEF of 1.20 (1.08 on a primary energy basis) [1]. Another emerging approach described in this paper is based on a vapor adsorption cycle with enhanced chemisorption, with an NH_3/salt working pair. In this paper, lessons learned from parallel and prior sorption-type HPWH developments are provided and then the authors focus on the latter and review the development of a novel adsorption-type HPWH, using a nested buffer tank/heat exchanger approach driven by an integrated compact steam boiler, a collaboration between technology developers, with a hybrid design approach with 2 kW output sorption module and 12 kW auxiliary steam boiler. Performance goals are $\geq$1.25 UEF, target first hour rating of 284 L of hot water or greater, and a combustion system with less than 14 ng NOx/J output and compatible with 30% hydrogen/natural gas blended fuel, and capacity for typical 4-5 occupant North American homes.

2. Technology Review - Description of Residential Sorption-type HPWHs

For thermally-driven heat pumps (TDHPs) overall, inclusive of not just sorption-type machines but also mechanically-driven vapor compression cycles (e.g. engine-driven) and thermal compression machines (stirling-type, thermoacoustic, etc.), it is sorption-type machines that have the greatest potential be scaled down to sizes appropriate for residential applications (< 25 kW output, often < 5 kW for hot water). This is for many reasons, but for practical concerns, this is primarily due to challenges in cost-effectively scaling down engines for work-activated TDHPs and economies of scale necessary for thermal compression-type machines with commonly high operating pressures (> 50 bar) [3]. Sorption-type TDHPs are commonly used in heating-focused applications, in air-to-water/brine configurations most commonly, as supplements or replacements for water heaters, boilers, and/or furnaces. For these systems, the two primary types of sorption heat pumps are explained as follows:

- **Vapor Absorption** heat pump cycles utilize thermal energy to drive a heat-pump cycle where a refrigerant is cyclically absorbed and desorbed from a secondary fluid (absorbent). While the refrigerant is still compressed by an electro-mechanical pump (solution pump), it is a liquid in solution rather than a vapor – in the case of the predominant vapor compression cycles. Absorption-type heat pumps are an attractive alternative, as lifting the pressure of a liquid versus a vapor requires significantly less energy (1%-2% for standard conditions). Thus, while the job of refrigerant compression is performed by a relatively small, low-power solution pump, the primary input to the process is thermal energy required to drive the refrigerant vapor from its absorbed state in the desorber (or "generator"), taking a low-temperature refrigerant/sorbent mixture and providing a high-temperature, vapor refrigerant. The most common working fluid pairs are for absorption machines specializing in heating versus cooling, NH_3 (refrigerant) and water (absorbent) for the former and water (refrigerant) and lithium bromide (absorbent) for the latter. For heating applications, regeneration temperatures commonly range from ~115°C (single effect), ~150°C (GAX), to > 175°C (double effect). With significant developments by multiple manufacturers, developments of TDHPs using the vapor absorption cycle were summarized in 2019 by GTI Energy [3].

- **Vapor adsorption** heat pump cycles also referred to as solid sorption cycles, are the adhesion of a gas or vapor (the adsorbate) to form a thin film on a solid surface (adsorbent). Typically, adsorbents are mounted to a heat exchanger that heats and cools the solid. There are many different types of adsorbents, including silicon dioxide, carbon-based compounds, salt matrices, and synthetic compounds such as zeolites. Adsorption is a batch process, a discontinuous process that can continue until a balance between the adsorbent and the adsorbate is achieved. Regeneration temperatures trend lower than vapor absorption overall, depending on cycle and working fluid/sorbent pair, from as low as ~60°C to ~150°C, concerning common open and closed cycle architectures [3]. The adsorption cycle can be applied for multiple end uses, including space conditioning (both heating and cooling) and refrigeration.

As noted, NH_3 is a common refrigerant for sorption-type TDHPs designed for heating applications, used in nearly all of the prototypes and products summarized in the prior section. The table below provides a summary of the broad advantages and disadvantages of TDHPs using NH_3 as a refrigerant, for vapor absorption versus vapor adsorption type cycles. As noted previously and in other efforts [3], the performance advantages of vapor absorption cycles, particularly in heating applications, are well-documented, as are the operational and reliability challenges [10]. TDHPs using the vapor adsorption cycle do have a reduced capacity and efficiency but have significant potential for improved reliability.

Table 1. Qualitative Comparison of NH_3-based Absorption and Adsorption type TDHPs

	NH_3 Absorption TDHPs	NH_3 Adsorption TDHPs
Unique Advantages	Continuous Process, has higher efficiency, ability to modulate capacity	Fewer moving parts for improved reliability, NH_3/salt pair has added capacity from chemisorption effect*
Unique Disadvantages	Pumps with dynamic seals are common failure points; corrosion and non-condensable gases must be managed	As batch process, cyclic & seasonal efficiency/capacity is poorer than absorption in general, commonly by 10%-15%
Common Advantages or Disadvantages relative to other TDHPs	Advantages: Can operate well in cold climate applications, NH_3 has GWP = ODP = 0.0, no issues with freezing climate installations	
	Disadvantages: Hazards associated with NH_3 as B2L refrigerant, compatibility challenges with common materials (e.g. copper/copper alloys)	

*This is primarily an improvement over other common adsorption working fluid/sorbent pairs

Before describing the design of the current HPWH, it is useful to review the features and outcomes of the vapor absorption-type HPWH. In this prior effort, a technology developer, GTI Energy, and multiple manufacturers were successful in developing and demonstrating a retrofit-ready GHPWH unit with a target total installed cost of $1,800 and with Ultra Low NOx certification (< 10 ng NOx/J output). The system used an integrated design, with a 3 kW nominal output NH_3/H_2O single effect absorption cycle atop a 227 L to 302 L tank, driven by a custom 2 kW premix gas burner with a nominal 1100 W heater for supplemental high capacity heating. The ~0.5 kg NH_3 was well below the 3 kg limit allowing for indoor installations and, following initial proof-of-concept developments [11-14], successive demonstrations were performed with ~30 units built, roughly half of which were installed in field environments. In the most recent, five-site demonstration in the Los Angeles area between 2019-2020, the per-site energy and GHG emissions reductions were 50% or greater over a 12-month monitoring period as compared to a measured baseline. Operating COP_{Gas} was consistently 1.25-1.60, electric power demand was 0.2% - 2.0% of total output, and end users surveyed indicated satisfaction with the hot water capacity delivered at average temperatures of 52°C [1]. Laboratory testing of the current pre-production generation of GHPWHs demonstrated a path to achieving 1.20 UEF certification. Subsequent analysis and modeling of the potential interactive effects between the GHPWH and the home's HVAC equipment revealed a minimal impact on false loading, substantially less than the impact of eliminating the natural draft baseline water heater product or an electric-type HPWH, and suggestive that a ducted evaporator is neither necessary nor cost-effective [1]. With a photo of a demo unit and the overall field performance compared to baselines in Figure 1, these efforts have aided in demonstrating the technical and market feasibility of sorption-type HPWHs.

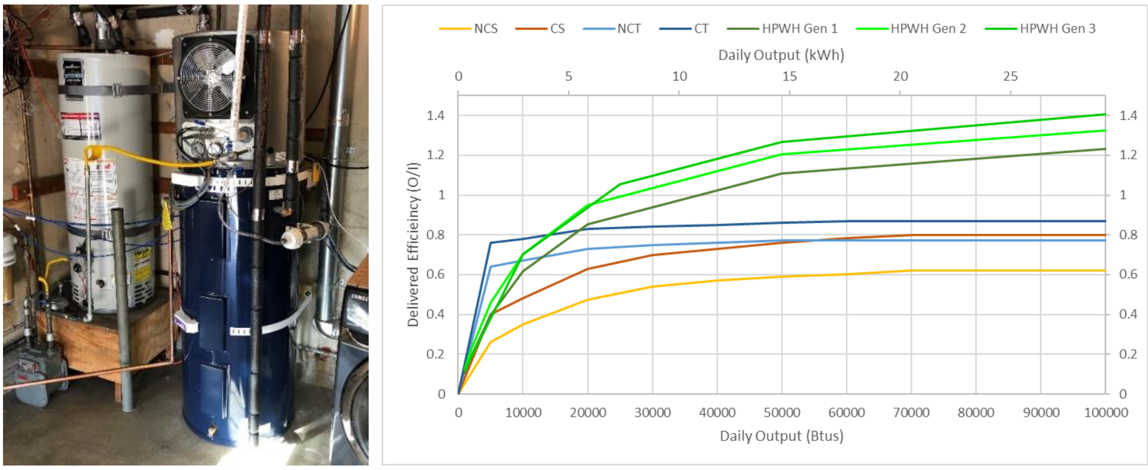

Fig. 1. Photo of Vapor Absorption-type Sorption HPWH in Prior Study and Performance Compared to Non-condensing Storage (NCS)/Condensing Storage (CS) and Non-condensing Tankless (NCT)/Condensing Tankless (CT) Baselines [1]

In developing this sorption-type HPWH, this team determined the performance criteria necessary to meet the original 1.30 Energy Factor (E.F.) and subsequent 1.20 UEF targets, which were as follows [1, 15]:

- *Average Heat Pump Cycle* COP_{Gas}*:* The time-averaged COP_{Gas} of the heat pump cycle needed to exceed 1.65, defined as the ratio of heat recovered from the heat pump cycle (absorber, condenser, flue gas heat recovery) to fuel inputs.
- *Average System COP* (COP_{System})*:* The time-averaged system COP needed to exceed 1.50, defined as the total heat delivered to the storage tank as a ratio of total energy inputs (electricity and fuel inputs). This is often approximately equal to the "recovery efficiency" term as defined in the standard test procedure.
- *Average combustion efficiency ≥ 95%* ($T_{flue\ gas} \leq$ 90 °F)*:* This is a time-average of the net combustion efficiency of the process, on a flue-loss calculation basis.
- *Average* $T_{delivered}$ *of hot water* $\geq T_{tank,\ initial}$*:* To avoid detrimental corrections in the calculation procedure, it is advantageous for time-averaged delivered outlet water temperatures to be at or above the starting average temperature of the storage tank.
- *Standby Heat Losses:* Using the UA term defined in the procedure as a benchmark, a factor of 2.5 Btu/hr-°F or less is prescribed.
- *Power Consumption:* Active and standby power consumption targets were less than 120 W and 10 W respectively.
- *Controls Trigger Early Recovery:* More an artifact of the hot water draw pattern used to yield the UEF metric determination, the product was required to initiate a recovery within the first draw cluster.

While these metrics will not universally apply to all sorption-type HPWHs, nor do they represent the unique set of criteria to meet a 1.20 UEF goal or greater, however, this approach of breaking down these key criteria of HPWH functionality will serve useful in the optimization of the presently described HPWH and others as well.

2.1. Description of the Adsorption-type HPWH Concept

Shown in the diagram and rendering, in both Figures 2 and 4 subsequently, the novel sorption-type HPWH described in this paper embeds a nominal 1 kW output vapor adsorption cycle within a buffer storage tank. The sorption module reactor is driven by a compact steam generator, dubbed a "burner/boiler", which regenerates the sorbate and delivers heat to the buffer storage (via heat recovery). The burner/boiler can also generate hot water directly ("boost" heating). The reactor design uses the NH_3/salt working pair and, as previously developed for space heating applications [16, 17], is modified for this application. The reactor includes calcium chloride, a widely known salt in use in various industrial applications and the adsorption bed uses a shell-and-tube type design as described previously, with the cycling and varying of heat delivery of the batch process evened out by the buffer tank [18]. As shown in the simplified schematic in Figure 2, the heat-driven adsorption HPWH consists of a reactor, a receiver, an evaporator, and a burner-boiler integrated into a 189 L buffer tank. The heat to the buffer tank is delivered either through a sorption cycle or via auxiliary combustion (“boost” heating), which indirectly delivers heat to the potable water. The sorption cycle and direct-firing can operate both in parallel and in series. In direct-firing mode, the steam generated in the burner-boiler and the remaining heat in the flue gas is recovered to heat the buffer tank directly. The direct-firing mode is utilized during high load periods when the buffer tank temperature drops below set-point during a draw.

In the sorption mode, the heat to the buffer tank is delivered in three different phases: (1) Desorption, (2) Cool-down, and (3) Adsorption. In the desorption phase, the steam generated in the burner-boiler enters the reactor. It condenses in the reactor, releasing heat to the reactor, with the liquid water returning to the boiler. The reactor's temperature increases to a level where ammonia is desorbed from the salt matrix. The desorbed ammonia vapor condenses on the reactor walls and heats the buffer tank with the heat of condensation before returning to the receiver and evaporator through gravity. The communication tube in the buffer tank helps with steam volume expansion. The desorption phase was sized to deliver heat to the buffer tank at 1.5 kW for 20 mins.

In the cool-down phase, the burner-boiler is inactive; the pump circulates water from the buffer tank through the reactor to cool down the salt matrix to the equilibrium pressure. The cool-down phase was designed to last 5 minutes and deliver 0.15 kWh of heat to the buffer tank through sensible heat recovered from the reactor.

In the adsorption phase, similarly, the burner-boiler is inactive. Low-grade heat from the ambient is utilized to heat the ammonia to the gas phase in the evaporator. Ammonia vapor flows through the receiver to the reactor and is absorbed into the salt matrix. The pump circulates water from the buffer tank through the reactor to heat the tank with the heat of adsorption. The adsorption phase was sized to deliver heat to the buffer tank at 0.49 kWh for 95 minutes.

This sorption-type HPWH is sized for residential water heating applications but may be suitably large for space heating, or "combi"-type applications as well. The burner/boiler has a design output of 2-12 kW, sized to regenerate the 3.0 L sorption module and provide excess heating in "boost" operating modes. The system contains approximately 1.2 kg of NH_3, which is sufficiently below the previously noted 3 kg limitation for indoor installations. For this "alpha" prototype, the storage tank is based on a 50-gallon (227 L) platform, however, subsequent versions are expected to be slightly larger to meet the design targets of 2 kW peak output from the sorption module and up to 12 kW peak auxiliary output from the steam boiler. In all cases, the efficiency target is ≥1.25 UEF, with an interim target of the middle tier of 1.15 UEF [9], and in all cases a target first hour rating of 284 L of hot water. To be competitive in all U.S. markets, the product is also targeted to have at least 14 ng NOx/J output emissions and be compatible with up to a 30% hydrogen/natural gas blended fuel.

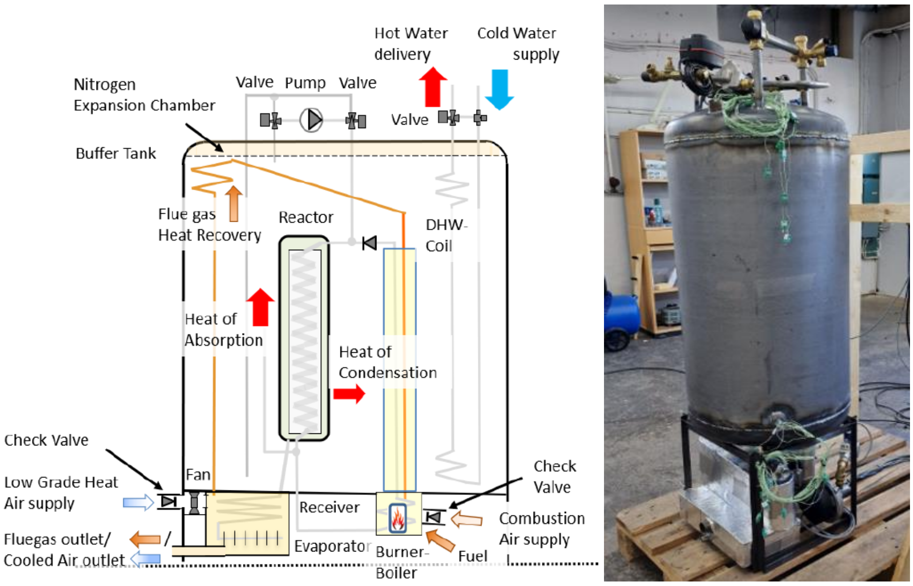

Fig. 2. Simplified Diagram of Concept Novel Sorption-Type HPWH and Prototype Under Construction

3. Progress in Novel Adsorption-Type HPWH Development

3.1. HPWH Design and Integration

A first “alpha” prototype with the design described was manufactured for preliminary testing in the second half of 2022. This design is based on several separate subsystem efforts in parallel, with the main focus on design, manufacturing, and showcasing a prototype that has a bill of materials that can meet the set cost targets within the target product category. The system is currently operational with a measured efficiency that is 15%-20% higher than direct-firing with a condensing-level efficiency. To improve on this performance, the authors note that system heat losses need to be better managed, for both direct-firing and heat pumping modes. With subsequent analysis, several pathways to remedy these performance gaps have been identified, including scaling up certain subsystems to optimize capacity versus these thermal losses. At the time of writing, the team continues to address these performance optimization challenges, with completion expected in 2023. Several aspects of this development are described in the subsequent section.

Guiding this design process is the challenging market of residential water heating, where an aggressive cost target is necessary for consumer acceptability [19]. The goal for this system, as a drop-in replacement in North America, would be competing with lower cost, lower performance existing water heaters but also assuring efficiencies well above levels of performance consistent with condensing-level efficiency. In addition to being considered as a replacement or alternative for existing lower efficiency water heaters, the product may also be considered as an alternative to both high-efficiency boilers and electrically-driven heat pump water heaters. With these factors in mind, the system configuration is intended to meet near-term efficiency and decarbonization goals, while retaining end user comfort in standard and extreme loading scenarios, while meeting a mass production manufactured cost of <$1,000 with an even lower cost as a long-term goal. While sizing described previously is for a proof-of-concept version of this sorption-based HPWH approach, designs and product families may evolve with greater/lesser levels of buffer storage, sorption module capacity, and burner/boiler capacity. Ultimately, it is the authors’ sense that the available market for a future product within the category is mainly driven by the cost of the appliance, which drives this optimization process overall, per the simplified representation in Figure 3.

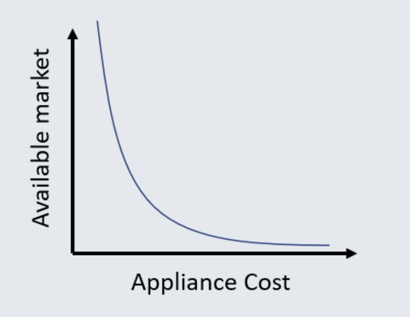

Fig. 3: Representation of Cost Driver

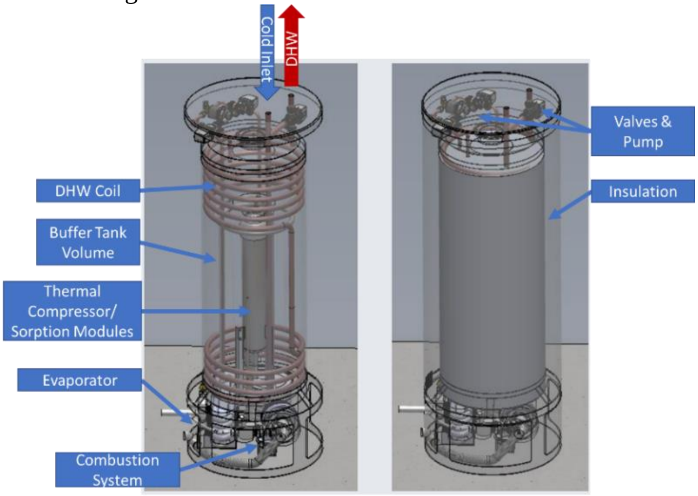

Fig. 4. Rendering and Identification of Key Components of Concept Novel Sorption-Type HPWH

3.2. Burner/Boiler Design and Demonstration

Based on preliminary design exercises, the burner/boiler will need to meet the following basic criteria for performance: greater than 93% overall effectiveness, greater than 83% overall fuel-to-steam efficiency, NO_x emissions of less than 14 ng/J output, CO emissions of 100 ppm air-free or below, and suitable modulation over full range over 2-12 kW. During start-up, the burner/boiler should rapidly reach steady-state steam circulation and the boiler segment should avoid dry-firing in all operational scenarios.

3.2.1. Combustion Design Lessons Learned from Prior Sorption-type HPWH Efforts

Similar to conventional boilers, direct-fired sorption machines commonly employ either "water-tube" or "fire-tube" designs for the desorber, the vessel where the heat source (combustion, typically) drives the boiler of the refrigerant from the sorbent, typically at a peak temperature/pressure for the cycle. In previous work by a subset of the authors in a separate and parallel effort, the aforementioned prototype development of small-scale absorption heat pumps [1] and commercially-available solutions employ "fire-tube" and "water-tube" designs respectively (see figure below). While the heat transfer coefficient of boiling ammonia/water solution differs from what is expected within low-pressure steam generation, by 10-25X, some lessons can be learned, specifically from the "water-tube" desorber design effort, which includes the following as applicable to a custom approach for premixed, modulating combustion within a compact desorber:

- Radial/cylindrical burners were superior in performance and emissions to up-fired approaches in the cylindrical combustion chamber, using a CFD-assisted design approach the ideal dimensions of the combustion chamber and burner were realized, which were a chamber radius approximately equal to the diameter of the burner.
- On downstream quenching, CO emissions, and stability issues, the height of the chamber (distance from the top of the burner, with a blank surface, from transition/exit from the chamber) was found to have a non-linear response. Increasing heights above a certain limit, the simulation suggested a favorable recirculation zone was weakened, leading to poorer heat transfer and flame liftoff. This allowed for an empirically-tuned gradual increase in the chamber height.
- On the burner surface, the impact of vertical distribution was mitigated by internal structures, preventing the "Christmas tree" effect – wherein fuel/air face velocities are greatest at the burner top and lowest at the bottom. The use of conical or parabolic inserts, in addition to revised perforated plate hole patterns, were all shown to improve this impact, further reducing quenching.
- For outdoor installations, several combinations of gas valves, blowers/mixers, and ignition controls were demonstrated to effectively modulate and ignite at down to -20°F, though not all components performed equally.

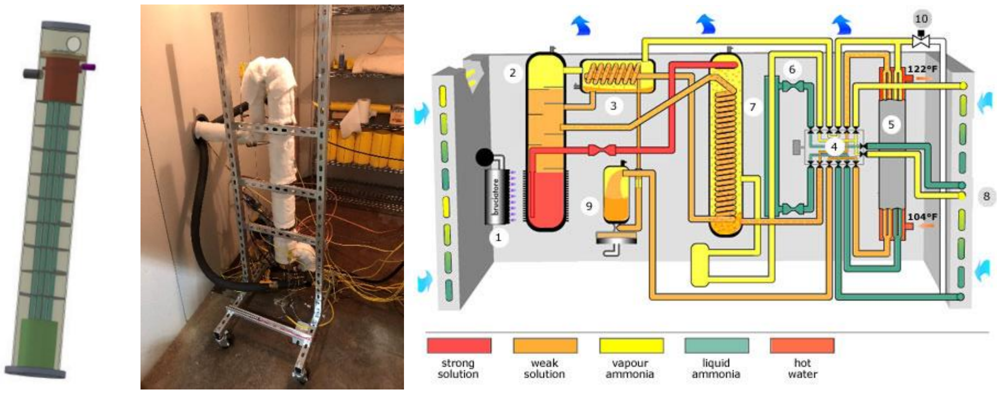

Fig. 5. "Fire-tube" Desorber Design/Testing (Left, Center) and "Water-tube" Desorber Design (Right, Desorber is #2) Examples (Image Source: [15], GTI Energy, Robur)

3.2.2. Burner/Boiler Testing Results

An experimental test stand was designed and built at GTI Energy to perform testing on the burner/boiler component of the novel sorption-type HPWH, as shown in the figure below. A custom-made, cylindrical, radiant-style burner was used in conjunction with off-the-shelf gas train components. The premix burner configuration was assembled using a fuel-air mixer with a nominal output of 27 kW and a turndown ratio of 5:1. During preliminary testing, combustion stability was difficult to maintain, with lean blowoff being the common mode of failure. This may have been caused by insufficient sealing of the burner base and entrainment of secondary combustion air into the burner/boiler, or insufficient drainage of condensate in the flue gas stream leading to abrupt changes in back pressure. Further investigation will be conducted to determine and resolve the flame stability issue.

Despite challenges with maintaining combustion stability, some valuable experimental data was gained from the preliminary testing during stable operation taking place over separate 15 minute and 20 minute periods. Due to the oversizing of the fuel-air mixer component, the firing rate was set to an average of 14.0 kW with excess air of 170% (air-fuel equivalence ratio of 1.7). Emissions testing results are summarized in Table 2, which indicates NO_x emissions well below the target but outstanding issues with the CO emissions, slightly above the target. For future testing, a new gas train will be assembled with a more appropriate modulation range that will better match the 2-12 kW operating range of the sorption module. The emissions values will be reassessed at excess air ranging between 140-150%, which is more common for boiler applications.

Table 2. Emission Testing Results.

Exhaust Species	Average Measured Emissions	Emissions Target
NO_x Emissions	1.8 ng/J; 1.5 ppm at 3% O_2 Corrected	14 ng/J; 20 ppm at 3% O_2 Corrected
CO Emissions	137.4 ppm, air-free	100 ppm, air-free

Fig. 6. Photo of Un-insulated Burner/Boiler Test Station

3.3. System Simulation and Projected Performance

The adsorption HPWH model was simulated as a stratified water buffer tank as an indirect Domestic Hot Water (DHW) system coupled with an adsorption heat pump and an internal Heat Exchanger (HX), as illustrated in the Figure 7 schematic. The sensible storage energy balance model were developed in Octave based on stratified sensible thermal storage divided into five volume segment nodes. Each equal volume segment is assumed to be thoroughly mixed. The heat loss capacity rate from the buffer tank to the ambient was specified for the bottom, top and zone as highlighted in Table 3, as heat loss capacity rate UA. The model constants and buffer tank properties highlighted in Table 3 were based on an off-the-shelf 50-gal indirect storage tank. The buffer tank was discharged (i.e., heating DHW) via the internal heat exchanger. All temperatures in the buffer tank were computed by solving a set of differential equation energy balance for each node given by:

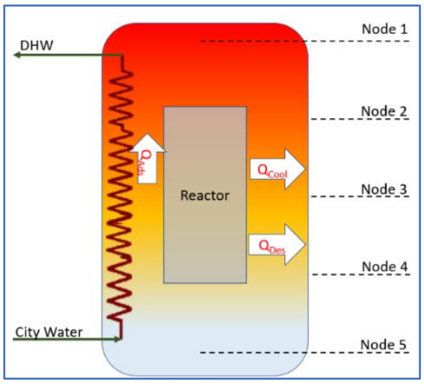

Fig. 7. The schematic for stratified water storage tank model with direct heating and internal heat exchanger.

$$\frac{V_w \rho_w C_{p,w}}{n_{tank}} \frac{\delta T_{i,j}}{\delta t} = k_{water} \frac{A_q}{H_w} n_{tank} \left[\left(T_{i+1,j} - T_{i,j} \right) + \left(T_{i-1,j} - T_{i,2} \right) \right] - \frac{UA_{hx}}{n_{hx}} \left(T_{i,j} - T_{i,j,hx} \right) - \sum \frac{UA_{loss}}{n_{loss}} \left(T_{i,j} - T_{amb} \right) + P_{heat} \quad (1)$$

The internal HX heat transfer area is divided into five segment nodes. Each node was thermally coupled to the corresponding volume segments of the tank. The heat transfer coefficient between the heat exchanger and tank was calculated using H. Druck's correlation for immersed coil heat exchanger [20]. The energy balance for the heat exchanger at each node is given by:

$$\frac{V_{hx}\rho_{hx}C_{p,hx}}{n_{hx}}\frac{\delta T_{i,j}}{\delta t} = \dot{m}_{hx}\, C_{p,hx}\left(T_{i-1,j} - T_{i,j}\right) + \frac{UA_{hx}}{n_{hx}}\left(T_{i,j,tank} - T_{i,j}\right) - \frac{UA_{hx,loss}}{n_{hx}}\left(T_{i,j} - T_{amb}\right) \quad (2)$$

The heating of the buffer tank was either performed by sorption phases at fixed-volume nodes, as shown in Figure 7. The internal heating of the buffer tank was modeled like an electric resistance heater controlled by the average tank temperature (i.e., aquastat). The heat loss capacity rate from the buffer tank to the ambient was specified for the bottom, top, and each volume node, as summarized in Table 3.

Table 3. Constant model parameter.

Model Parameters	
Volume of tank [m^3]	0.19 (50 Gal)
Height of storage tank [m]	1.17
UA_a – Zone heat loss [W/K]	0.7
UA_u – Bottom heat loss [W/K]	0.3
UA_o – Top heat loss [W/K]	0.3
$V_{hx,internal}$ [m^3]	0.01
A_{hx} [m^2]	1.32
Time step – [sec]	10
Number of nodes	5
Max tank temp [°C]	72
Q_{des} – Desorption [kW, Minutes]	1500, 20
Q_{cool} – Cool down [kW, Minutes]	1800, 5
Q_{Ads} – Desorption [kW, Minutes]	315, 95

As illustrated in Figure 8, the model was validated with experimental data for an indirect DHW storage tank previously collected in the field by GTI Energy. The model's accuracy was within ± 15% of the experimental data's tank average temperature. The model's spatial average temperature was computed by averaging the temperatures of the five nodes. Similarly, the water storage temperature was measured in the field at five equally distributed intervals and averaged.

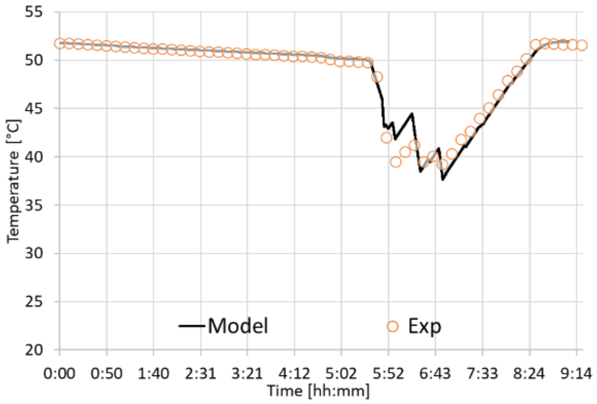

Fig. 8. Model validation with experimental data for average tank temperature.

Energy efficiency standards and labeling metrics (EES&L) for water heaters vary widely among countries [21]. In the USA, the Uniform Energy Factor (UEF) test procedure developed by the U.S. Department of Energy (DOE) is used for the energy efficiency of water heaters [22]. A higher UEF metric means a water heater is more energy-efficiency and will cost less to operate compared with other water heaters in the same category.

The UEF test is 24 hours long to simulate the use of a water heater over one day. For the medium draw profile in this work, the UEF consists of numerous water draws organized into three draw groups (series of water draws) at two predefined flow rates (1 and 1.7 GPM). The UEF characterizes the system's energy efficiency based on this characteristic hot water use pattern. The UEF has energy-based corrections for the tank's initial and final conditions and energy-based corrections for the outlet temperature differing from the nominal value.

The COP for the adsorption heat pump during the 24-hour model, the UEF test, was assumed at a constant value of 1.25 based on the UEF test condition requirement of 19.7 ± 0.6˚C [20]. The adsorption heat pump operated for a total of 9 hours and 30 minutes, as shown in Figure 9. The heat pump's runtime was divided into two segments, with 3 hours of non-operational period between them. Based on the estimated COP of the adsorption heat pump and the heat loss from the buffer tank, the system achieved a UEF of 1.1 in the model. As illustrated in Figure 9, the tank is vertically stratified, with hotter (lower density) water above cooler (higher density) water, as expected by the model for the stratified tank. Analysis of the tank temperature shows the effect of draws and charging location (i.e., adsorption heating phase) on the stratification.

As illustrated in Figure 10, the buffer tank temperature was set to and maintained at 70˚C (158˚F), compared to 48.9˚C (120˚F) in residential storage water heaters. The buffer was held at a higher temperature than the standard due to the indirect design of the DHW. A higher buffer temperature is required to maintain the DHW supply temperature of more than 43.3˚C (110˚F), accounting for the flow rate and heat transfer limitation on the heat exchanger, as shown in Figure 10 during the UEF testing.

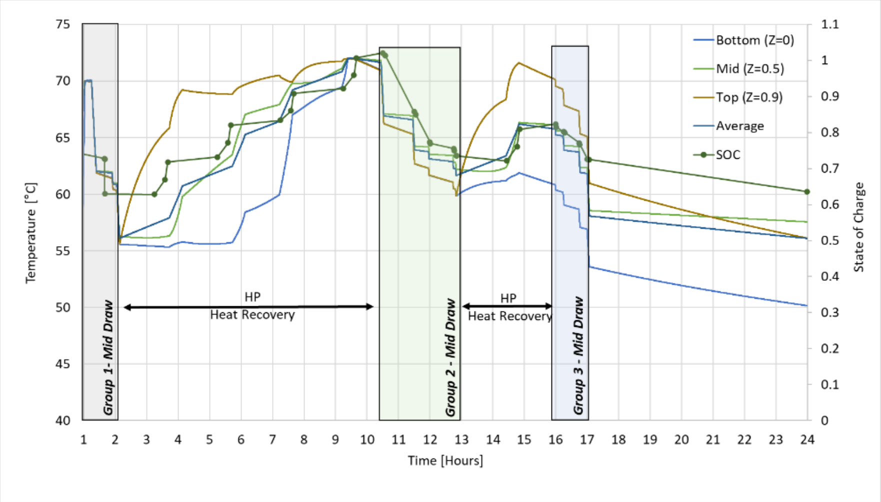

Fig. 9. Uniform Energy Factor (UEF) simulation of adsorption HPWH for 24 hours at medium draw level.

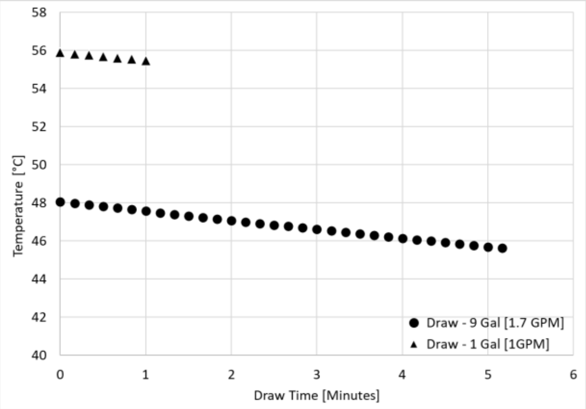

Fig. 10. The effect on DHW supply temperature for the indirect system during the UEF simulation.

4. Conclusions and Next Steps

In this paper, the authors described a novel sorption-type heat pump water heater, sized for residential applications in North America with a hybrid design, of both up to 2 kW peak output from the sorption modules and up to 12 kW peak auxiliary output from the steam boiler, with an efficiency target of $\geq$1.25 UEF and a target first hour rating of 284 L of hot water. The context of this development is described, in terms of the residential high-efficiency water heating market and the design and performance of sorption-type HPWHs in general. Progress on several aspects of the design and development are described, including a) the development and testing of a compact steam boiler loop to drive the desorption process, designed for 14 ng NOx/J output and compatible with up to a 30% hydrogen/natural gas blended fuel, b) immersed sorption modules within the buffer storage tank for water heating with a $COP_{gas} > 1.40$ using limited moving parts, and c) heat exchange and preliminary system controls, per empirically-calibrated simulation, to meet UEF targets and high usage hot water patterns typical for 4-5 occupant homes. While these remain performance targets as development and testing are ongoing, a path to reaching these goals is briefly described as are efforts to calibrate a performance model of the novel sorption-type HPWH. In the coming months, the authors anticipate refining system components through successive experimental development, assessing performance in succeeding generations of HPWH prototypes, and if successful in meeting targets, proceeding to initial field trials in the U.S.

List of Acronyms/Nomenclature

CO	Carbon Monoxide
COP	Coefficient of Performance
CFD	Computational Fluid Dynamics
DHW	Domestic Hot Water
GAX	Generator Absorber Exchange
GHG	Greenhouse Gas
GHPWH	Gas-fired Heat Pump Water Heater
GTI	Gas Technology Institute
HPWH	Heat Pump Water Heater
HVAC	Heating, Ventilation, and Air-conditioning
NEEA	Northwest Energy Efficiency Alliance
NOx	Oxides of Nitrogen
TDHP	Thermally-Driven Heat Pump
UEF	Uniform Energy Factor
heat	Heat input
hx	Heat Exchanger
n	Nodes
UA	Heat Transfer coefficient (W/K)
V	Volume (m^3)
Cp	Heat Capacity (kJ/kg K)
T	Temperature (°C)
k	Thermal Conductivity (W/m K)
A	Area (m^2)
P	Heating Power (W)
ρ	Density (kg/m^3)

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