"Max-tech FHR": What is the maximum technically achievable water delivery capacity from a single 120 V plug?

Kyle Gluesenkamp, Bo Shen, Damilola Akamo, Melanie Moses-DeBusk, Ahmed Elatar, Ed Vineyard, and Brian Kolar, Oak Ridge National Laboratory

ABSTRACT

Affordable, direct drop-in replacements for existing gas water heaters that meet consumer expectations for hot water delivery will enable greater electrification of residential water heating. For many replacement scenarios, affordability includes a replacement option with like-for-like physical product dimensions. Consumer expectations presume a large delivery capacity adequate to prevent hot water runout. This work explores the technical potential for hot water delivery capacity for a heat pump water heater (HPWH) powered from a common 120 V receptacle. Delivery capacity in this work is quantified by two metrics: the first hour rating defined in the Code of Federal Regulations and a real-world draw profile that resulted in hot water runout during field studies of 120 V HPWHs. The work focuses on the "tall-and-slim" gas water heater product category with external product dimensions of 20 in. diameter and 60 in. height. Using the DOE/ORNL Heat Pump Design Model validated by experimental data to perform simulations, several measures were evaluated to maximize the delivery capacity of a 120 V HPWH. The 120 V HPWH was constrained by (1) external product dimensions of 20 in. diameter and 60 in. height, (2) electrical power of 1.5 kW (85% of the available power from a dedicated 120 V, 15 A circuit), and (3) commercially available components. The measures implemented included a large compressor, a pumped loop with plate heat exchanger to maximize tank stratification, enlarged heat exchangers, and relatively thin insulation to maximize the water storage volume.

Introduction

Gas-fired water heaters have been prevalent in residential buildings across the United States for decades. To put this into context, approximately 60 million US homes have gas-fired water heaters; California has one of the highest percentage of homes—78%—with gas-fired water heaters to meet hot water demands, according to data from the US Energy Information Administration (EIA 2020). Such widespread adoption shows the popularity of gas-fired water heaters in satisfying the demands of households across the nation. Despite their widespread use, gas-fired water heaters face certain issues. The major challenges with these appliances are space constraints, venting, and the carbon emissions they produce, which exacerbate their effect on air pollution and climate change. In addition, the operation of gas-fired water heaters can pose safety problems such as the release of carbon monoxide and possible fire hazards if the appliance is not properly installed or maintained. Fluctuations in gas prices and supplies can cause customers to

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incur unpredictably high energy costs, resulting in budgetary concerns and financial strain, especially for low-income families.

To resolve these issues and ensure decarbonization of the energy infrastructure, interest is growing for replacing conventional gas-fired water heaters with electric water heaters, which are a more energy-efficient and cleaner alternative. To make the switch effective, certain issues must first be solved. For instance, most US homes do not have existing electrical connections for conventional 240 V electric water heaters, which limits their adoption. Therefore, a potential alternative to consider is a 120 V heat pump water heater (HPWH), which integrates an electric heat pump with a conventional water storage tank, significantly increasing energy efficiency and reducing energy demand (Willem, Lin, and Lekov 2017). However, commercially available 120 V HPWHs are not ideal for direct drop-in replacement for conventional gas-fired water heaters because of differences in size. They have a higher form factor (measuring 65 in. tall with a diameter >20 in.) than that of “tall and slim” gas units (measuring about 60 in. tall with a 20 in. diameter) (Gluesenkamp 2023), thereby imposing a space constraint during installation. Also, the average first hour rating (FHR) of the commercially available 120 V HPWH (35 gal) is far lower than that of the gas-fired water heater (75 gal). Optimizing hot water delivery capacity and resolving space constraints of 120 V HPWHs could speed up the electrification of water heating while meeting consumer hot water needs.

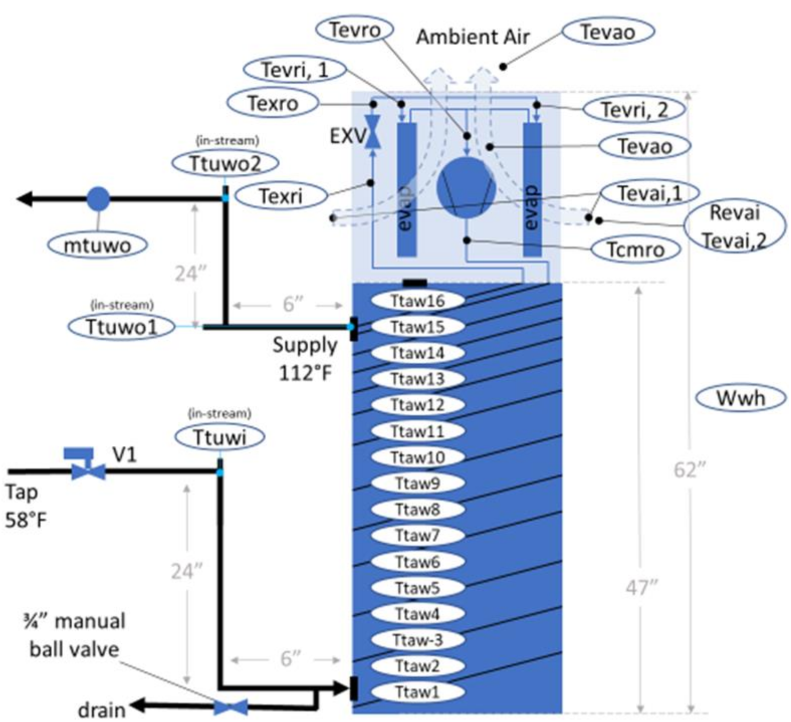
For a storage tank with a heater, the maximum hot water deliverable in one hour can be calculated straightforwardly with the following idealized assumptions: 1. assume that the tank begins at the delivery temperature, 2. assume all the water in the tank is delivered in one hour (zero losses by heat transfer to ambient, and zero lost by mixing with colder water), and 3. assume that all the heating capacity delivers water using single-pass heating from the tap temperature to the delivery temperature. For typical conditions of 58°F (14.4°C) tap water, 125°F (51.7°C) supply temperature, and 67.5°F (19.7°C) ambient air temperature, and using 4.18 kJ/kg-K as the specific heat of water, the maximum gallons of water deliverable in one hour is $V_{tank} + 6.12 \times Q$, where V_{tank} is the volume of the tank in gallons, and Q is the heating capacity in kW. In other words, every gallon of tank volume, plus 6.12 gal per kW of heating capacity, can be delivered in an hour. The maximum electrical power available from a dedicated 120 VAC circuit (12 A of the rated 15 A) is 1.44 kW. With an electric resistance heater, this means 1.44 kW (4.9 kBtu/h) of heating capacity, yielding up to $V_{tank} + 8.81$ gal in one hour. With a Carnot heat pump powered by 1.44 kW, the heating capacity is amplified by a factor of the Carnot heating COP. The Carnot COP is 10.2 when pumping heat from 67.5 to 125°F, resulting in a heating capacity of 14.6 kW (49.8 kBtu/h). Thus, a 120 VAC Carnot heat pump could deliver $V_{tank} + 89.6$ gal of hot water in one hour. If we assume a 40 gal tank, this is a maximum theoretical one-hour delivery capacity of 129.6 gal.

However, reality differs from this idealized scenario. Thus, this work explores modeling and simulation strategies, new design approaches, and experimental evaluation to improve the performance of 120 V HPWH technologies. The goal for delivery capacity is based on data obtained from the field study of hot water use behavior of installed 120 V HPWHs in multiple homes across California (BTO 2023). A unique modeling tool developed at the Department of Energy’s (DOE’s) Oak Ridge National Laboratory (ORNL)—called the DOE/ORNL Heat Pump Design Model (HPDM)—was used to simulate the experimental runout event. Also, simulation was used to explore and test several strategies to enhance performance of the 120 V HPWH system, including the FHR and the 24 h Uniform Energy Factor (UEF). The successful accomplishment of this work will provide a path forward in the engineering design and optimization of 120 V HPWH systems through the dissemination of new insights related to control strategies and hardware design, ultimately improving the state of the art.

Experimental Setup

An experimental test facility used in this study was designed to accurately measure hot-water delivery capacity and performance during hot water run-outs. ORNL obtained a commercially available 120 V HPWH system and instrumented it as shown in Figure 1. Temperature sensors were placed in key locations throughout the system to monitor temperatures, including air, refrigerant, and water. To avoid cutting refrigerant lines, all refrigerant sensors were surface-mounted. An inlet flowmeter was used to measure the water flow rate on the downstream end of the setup. The instrument types and their respective measurement uncertainties are listed in Table 1. Six measurement locations prescribed by the Code of Federal Regulations (CFR) standard test procedure (10 CFR 430) were installed inside the water tank along with 10 additional thermocouples, as shown in Figure 2. A LabVIEW data acquisition system was used to record measurements.

The measurement nomenclature in Figure 1 is important to note. The first letter represents the type of measurement, the second and third letters represent the relevant component, the fourth letter denotes the fluid being measured, and the fifth letter denotes the direction or location. For example, Texro denotes the temperature (measurement type) at the expansion valve's (component's) refrigerant (fluid) outlet (location).



Nomenclature

First letter—measurement		
	T	temperature
	M	mass flow rate
	P	pressure
	R	relative humidity
	V	volumetric flow rate
	W	power measurement
Second and third letters—component or circuit		
	ta	tank itself
	tu	tank, user circuit (draws and tap)
	th	tank, heat pump circuit
	ev	evaporator
	hx	plate heat exchanger condenser
	am	ambient
	cm	compressor
	ex	expansion valve
	wh	whole water heater
	fa	fan
Fourth letter—fluid		
	a	air
	r	refrigerant
	w	water
Fifth letter—direction/location		
	i	inlet
	o	outlet
	s	space

Figure 1. Piping and instrumentation diagram (left) for the 120 V HPWH baseline system and nomenclature for the measurement points (right).

Table 1. Instrument measurement uncertainties

Instrument type	Measurement uncertainty
Thermocouple	±0.5°C
Relative humidity sensor	±3%
Flowmeter	±1% of reading
Power meter	±2%
Pressure gauges	±0.5 psi

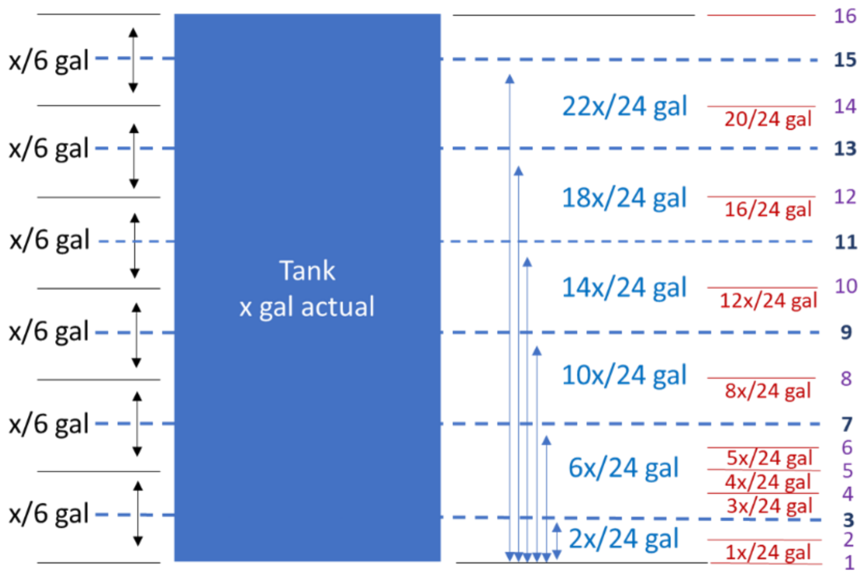


Figure 2. Layout of 16 thermocouples in the hot water tank. The six CFR-prescribed thermocouples are numbered 3, 7, 9, 11, 13, and 15 and are indicated by the dashed blue lines. The variable *x* indicates the actual tank volume. Heights of each thermocouple were set to correspond to the appropriate volume fraction of the tank.

Draw Profile for Hot Water Runout

A field runout event was emulated in the laboratory to recreate an event measured by the New Buildings Institute as part of an Advanced Water Heater Initiative field study (NBI 2023). The study was performed in a mild climate with a 65 gal 120 V HPWH located in a garage, named “Site 23” in the published study. The field study involved the installation of 120 V HPWHs in multiple homes across California and the collection of data on hot water usage behavior and customer satisfaction. Data in this study indicated Site 23 was a heavy hot water user site that reported hot water runout issues. The dataset was mined for a suitable runout event that could be emulated in the laboratory. The criteria used to identify a hot water runout event were: (1) hot water usage of >0.5 gal over a 1 min period and (2) hot water delivery temperature that dropped below 100°F for ≥30 s. The runout event shown in Figure 3 occurred during an evening in late March. The average psychrometric condition during this field event was 46% RH at 67°F.

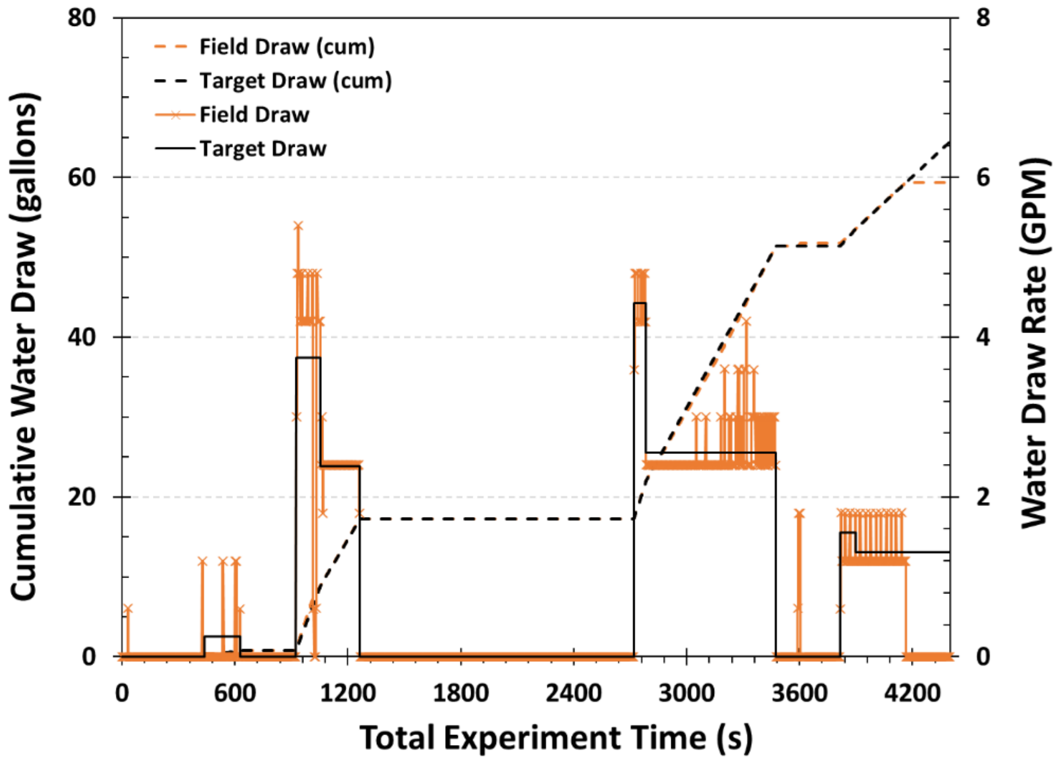


Figure 3. Field-measured hot water runout draw profile (orange line) with slightly simplified target draw profile (black line) used for the laboratory emulation experiment. The corresponding cumulative water usages (dashed orange and black lines) are graphed on the left *y*-axis.

The selected field hot water runout event occurred during a 20 min, 40 gal draw event, which took place 30 min after completion of a 5 min, 16 gal draw event. The most significant prior hot water draw had taken place 12 h before these events occurred. Thus, the research team used only 1 h before the runout event to create a draw profile to emulate in the lab following a compressor cut-out. To simplify flow control in the lab, the field-measured draw was simplified as shown in Figure 3 to four target draw events that each maintained cumulative water usage that was the same as that of the field event. Table 2 lists the detailed times and flow rates used for the emulated hot water runout in the lab.

Table 2. Flow rate conditions used for emulated hot water runout

Draw	Flow (gal/min)	Target time for emulated runout			Cumulative (gal)
		Start (s)	Stop (s)	Total (min)	
	–	0	437	7.3	–
1	0.25	438	629	3.2	0.80
	–	630	924	4.9	–
2	3.74	925	1,054	2.2	8.90
3	2.39	1,055	1,264	3.5	17.25
	–	1,265	2,719	24.3	–
4	4.43	2,720	2,784	1.1	22.05
5	2.55	2,785	3,474	11.5	51.40
	–	3,475	3,814	5.7	–
6	1.55	3,815	3,899	1.4	53.60
7	1.31	3,900	5,700	30	92.80

Modeling Approach

An accurate computer modeling tool is needed for HPWH engineering design and energy simulation to simulate the interaction between a stratified hot water tank and an HPWH system. The modeling tool for such purposes should be hardware-based, with detailed inputs such as heat exchanger geometry and compressor performance representations, that can reasonably predict the effects of changes in component sizes and heat exchanger configurations. In addition, the tool should have a computational speed fast enough to accommodate 24 h energy simulation and energy standard rating calculation needs. This work used the modeling approach described by Shen et al. (2018). To summarize, Shen et al. (2018) described detailed modeling methodologies and validated the prediction accuracies of a quasi-steady-state HPWH system design model. The development of a quasi-steady-state HPWH system model was based on a public-domain thermal system modeling platform, the DOE/ORNL HPDM (DOE/ORNL 2019), developed and maintained by ORNL. The HPDM has been a reliable, public-domain platform for design, optimization, and analyses of heat pump systems with varying complexities for both residential and commercial applications. The HPDM can model HPWHs in two typical configurations highlighted in Figure 4: (1) with forced water flow and a water-to-refrigerant heat exchanger, and (2) with wrapped-tank condenser.

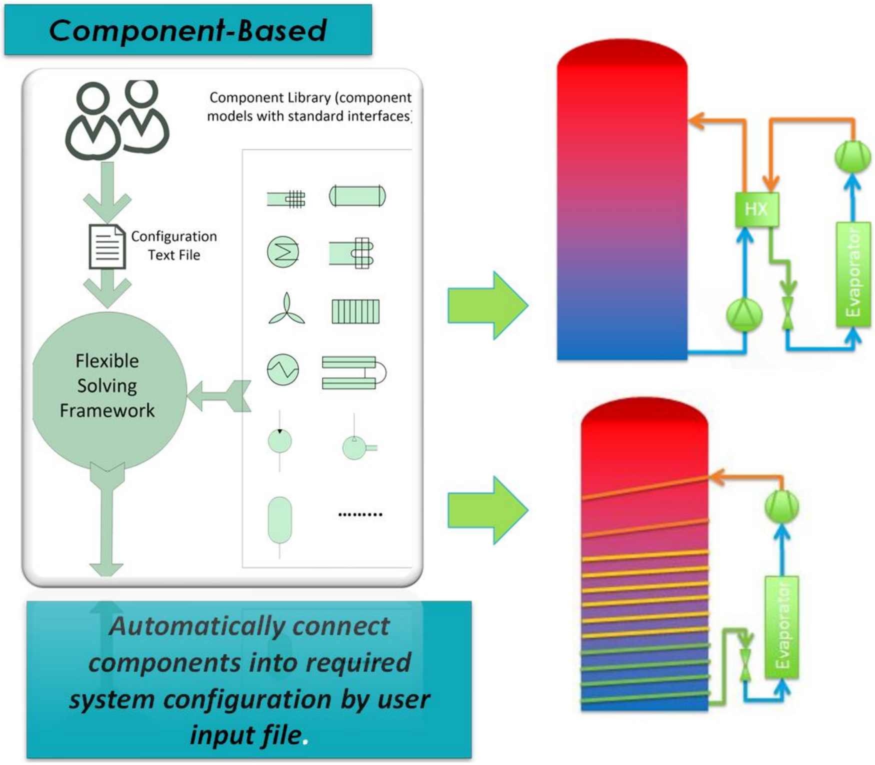


Figure 4. ORNL Heat Pump Design Model, used in this work to model HPWHs. The top right model is configured with forced water flow and a water-to-refrigerant heat exchanger, and the bottom right model is configured with a wrapped-tank condenser.

For air-to-refrigerant heat exchangers, HPDM employs a segment-to-segment modeling approach, dividing a single tube into numerous mini segments. Each tube segment considers individual airside and refrigerant-side entering states, accounting for possible phase transitions. Heat transfer calculations within each segment use the ε-NTU approach. Additionally, the evaporator model, akin to the functionalities of the segment-to-segment fin-tube condenser, can simulate the dehumidification process. The method proposed by Braun et al. (1989) is used to simulate cases of water vapor condensing on an evaporating coil, where the driving potential for heat and mass transfer is the difference between enthalpies of the inlet air and saturated air at the refrigerant temperature. Compressor performance is represented by an Air-Conditioning, Heating, and Refrigeration Institute 10-coefficient compressor map, facilitating the calculation of compressor mass flow rate and power consumption based on suction and discharge saturation temperatures. In cases where a compressor map is unavailable, constant volumetric efficiency and isentropic efficiency are employed for evaluating compressor performance, as depicted in Equations (1) and (2), respectively.

$$m_r = Volume_{displacement} \times Speed_{rotation} \times Density_{suction} \times \eta_{vol} \quad (1)$$

$$Power = m_r \times (H_{discharge,s} - H_{suction})/\eta_{isentropic} \quad (2)$$

where m_r is the compressor mass flow rate; $Power$ is compressor power; η_{vol} is compressor volumetric efficiency; $\eta_{isentropic}$ is compressor isentropic efficiency; $H_{suction}$ is compressor suction enthalpy; and $H_{discharge,s}$ is the enthalpy obtained at the compressor discharge pressure and suction entropy. Compressor shell heat loss, relative to the power input, is considered to simulate the refrigerant side and air side energy balance. The water tank model was enhanced from the EnergyPlus stratified water tank model, a one-dimensional model simulating water temperature stratification across up to 10 nodes. Each node serves as a control volume, maintaining uniform temperature and water property values. The model encompasses water piston flow (plug flow), representing bulk water movement from a make-up port to a supply port, heat conduction between water nodes, and natural convection up-flow and mixing. The model has been extensively verified for accuracy in simulating tank shell losses, placement of electric heater elements, and thermostats. The FHR quantifies the available hot water capacity of the water heater in gallons. It is influenced by several factors including the water tank's storage volume, the heat pump capacity, and supplemental resistance heating capacity. The test procedure initiates with a fully charged tank, with the tank supplying water at 125°F ± 5°F (51.7°C ± 2.7°C). Hot water is drawn at a flow rate of 3.0 ± 0.25 gal/min (11.4 L/min) until the supply water temperature drops to 15°R (8.3 K) below the maximum observed water supply temperature. The tank is considered recovered when the thermostat reduces heating of the tank, and any subsequent draw is terminated when the supply water temperature again decreases by 15°R. This process is repeated for 1 h. If a draw is ongoing at the hour's end, it is allowed to complete. If no draw is ongoing at the hour's end, a final draw is initiated and terminated when the outlet water temperature reaches the same temperature as that of the previous draw's termination. The UEF is defined in the standard (10 CFR 430). Different water draw profiles can be used, depending on water heater size. Typically, residential water heaters follow the medium water use pattern, comprising 12 water draws, as detailed in Table 3.

Table 3. UEF medium use draw pattern (10 CFR 430)

Draw No.	Time during test [hh:mm]	Volume [gallons (liters)]	Flow rate [GPM (L/min)]
1*	0:00	15.0 (56.8)	1.7 (6.4)
2*	0:30	2.0 (7.6)	1 (3.8)
3*	1:40	9.0 (34.1)	1.7 (6.4)
4	10:30	9.0 (34.1)	1.7 (6.4)
5	11:30	5.0 (18.9)	1.7 (6.4)
6	12:00	1.0 (3.8)	1 (3.8)
7	12:45	1.0 (3.8)	1 (3.8)
8	12:50	1.0 (3.8)	1 (3.8)
9	16:00	1.0 (3.8)	1 (3.8)
10	16:15	2.0 (7.6)	1 (3.8)
11	16:45	2.0 (7.6)	1.7 (6.4)
12	17:00	7.0 (26.5)	1.7 (6.4)
Total Volume Drawn Per Day: 55 gallons (208 L)			

* Denotes draws in first draw cluster.

The DOE/ORNL HPDM was used to simulate a baseline 120 V HPWH with a 40 gal tank. Following are the key characteristics of the HPWH:

- Operating with a 120 V power supply, the system incorporates an R134a compressor delivering 12 kBtu/h capacity at 35°F evaporating and 125°F condensing temperatures.
- The compressor's isentropic efficiency is fixed at 60%, and its volumetric efficiency is fixed at 65%.
- The evaporator and fan are sized to achieve a 35°F evaporating temperature.
- The system maintains 10°F refrigerant superheat at the compressor suction and 10°F refrigerant subcooling at the condenser exit.
- Heat exchange between refrigerant and hot water occurs through a 15-plate double-wall brazed plate condenser (PHX).
- A pump circulates water flow at a rate of approximately 1 gal/min through the PHX; the pump consumes 50 W whenever the compressor is operational.
- The system does not incorporate electric heating elements.
- Thermal insulation on the tank is of a level that would result in a 90% energy factor if the tank were heated only by electric resistance.

Model Validation

As mentioned previously and shown in Figure 3 and Table 2, a hot water runout scenario was identified from a field study on a 120 V HPWH using a wrapped-tank condenser. Experiments were run on the wrapped-tank condenser baseline system in the laboratory. Key water temperatures, flow rate of the hot water draw, and HPWH power consumption are plotted in Figure 5.

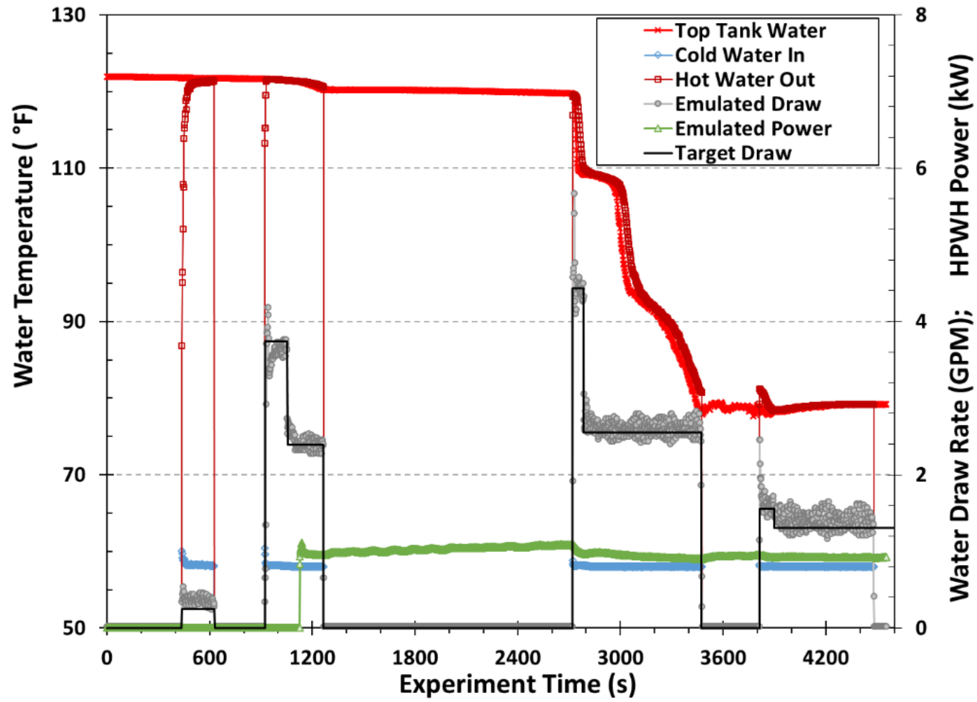


Figure 5. Measured results during the emulated hot water runout scenario. The target draw profile is also included for reference (black line).

This scenario was adopted to validate the model. A baseline model was run for a PHX-based system using model inputs from the laboratory-measured initial tank water node temperatures, ambient temperature, humidity, and draw patterns. Figure 6 illustrates the comparison of results in the experiment and the model. Because of the different condenser configurations (forced flow PHX versus wrapped-tank condenser), the simulated temperature fluctuation of the PHX is larger than that of the field wrapped-tank condenser configuration. However, both the simulation and experiment reach the same runout moment when the tank top temperature drops below 90°F around 3,200 s, and they show a ±10% variation in HPWH power consumption. Therefore, the simulated results are deemed reasonable representations of the FHR and UEF.

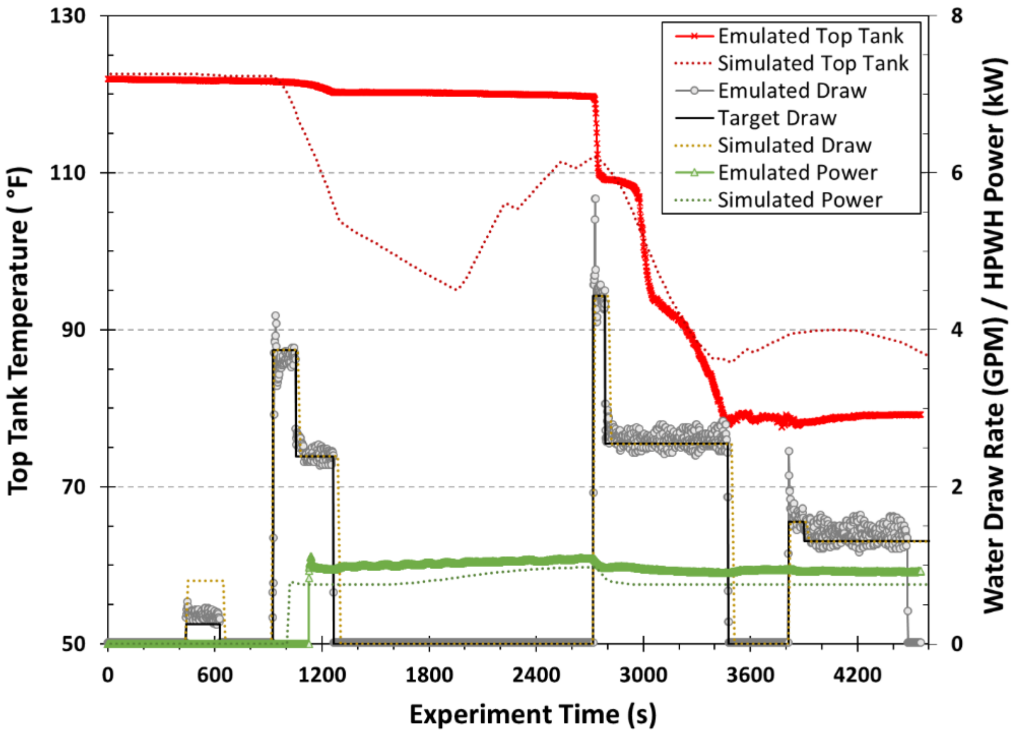


Figure 6. Comparison of simulated runout scenario results (dotted lines) compared with experimental results (markers) for temperature at the top of the tank (left axis), HPWH compressor power, and water draw rate. The target draw rate is also shown (solid black line).

Results and Discussion

Using the model developed in this work, the following strategies were explored to enhance the FHR:

Case 1: *Baseline*: A thermostat located in the tank at 70% of the tank height provides on/off control of the heat pump with a setpoint of 125°F and a 5°F deadband (i.e., when the temperature falls below 120°F, the heat pump activates until the temperature reaches 125°F).

Case 2: *High initial tank temperature*: A thermostat positioned at 70% of the tank height has a setpoint of 140°F with a 5°F deadband. During the FHR test, water draws continue until the supply water temperature drops below 110°F. This deviates from the strict FHR procedure to demonstrate the increase owing to hotter water storage.

Case 3: *Mixing valve addition*: Building upon Case 2, a mixing valve is installed at the supply port to maintain a supply water temperature of 112°F by blending the tank top node with city makeup water at 58°F. The mixing valve, combined with a hot water storage temperature of 140°F, aims to raise the FHR of the supply water above 110°F.

Case 4: *Enhanced control with dual sensors*: Continuing from Case 3, two sensors positioned at 70% and 10% heights, respectively, and each weighted at 50%, are used to indicate the average tank temperature for quicker response and improved control.

Case 5: *Circulation location adjustment*: Building upon Case 4, the circulation location is switched from the bottom to 50% height if the top tank water temperature falls below 135°F

(Figure 7). This adjustment ensures heating primarily at the tank top if the system struggles to catch up.

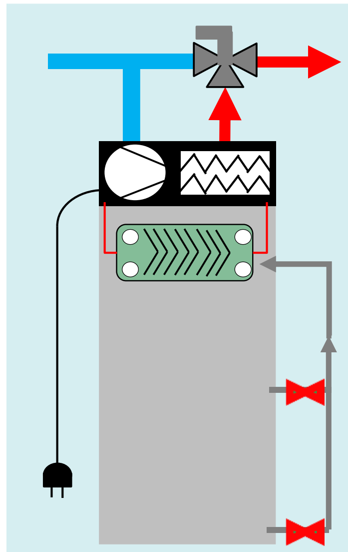


Figure 7. Circulation location adjustment.

Figure 8 depicts the resulting FHRs and UEFs for these cases. It's important to note that when simulating UEFs, the compressor is relatively oversized for the medium UEF draw pattern, leading to brief compressor run times. Therefore, a 10% energy penalty was applied to account for cyclic degradation losses.

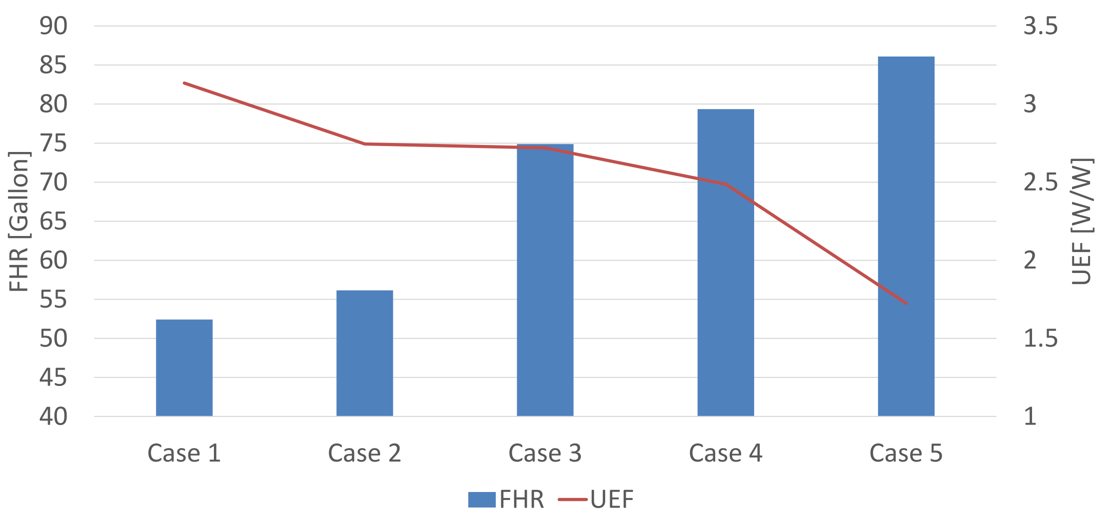


Figure 8. FHRs and UEFs of various strategies applied in Cases 1–5.

From Case 1 to Case 5, the FHR is increased from 52 to 85 gal. The most helpful measure was to heat water to 140°F using a mixing valve. However, these strategies degraded the UEF from 3.13 to 1.72, with the largest penalty coming from the circulation location adjustment.

Conclusion and Future Work

In this work, we have reported the experimental and simulation studies to achieve performance improvement for a 120 V HPWH. For the baseline system evaluation, hot water runout was emulated using experimental and simulation studies based on field data. Both experimental and simulation modeling reached identical runout moments when the top of the tank temperature dropped below 90°F with acceptable variation in power consumption. Hence, the simulation tool is a viable predictor of the FHR and UEF of the HPWH system. Also, the simulation tool provided key insights regarding the systems' elements and control strategies for optimization of the 120 V HPWH system performance, including an increase in water delivery capacity. These strategies include the addition of mixing valves at the supply port of the HPWH, use of multiple sensors throughout the cross-section of the HPWH system for improved control, and circulation location adjustments, among others. As part of future work, the research team is adopting the key control strategies and hardware design from the simulation studies to develop the next generation 120 V HPWH prototype with higher FHR and ENERGY STAR-qualified UEF.

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