Unleashing delivery capacity: Approaching the technically achievable limits for water delivery capacity from a standard tank size

William Doktycz, University of Tennessee, Knoxville
Kyle Gluesenkamp, Bo Shen, Melanie Moses-Debusk, James Manley, Brian Kolar
Oak Ridge National Laboratory

ABSTRACT

Many consumers would benefit from a higher delivery capacity water heater, but face constraints such as limited space. In addition, many homeowners lack natural gas and would like to convert their existing 240 V water heater to 120 V, to quickly and inexpensively free up a 240 V outlet for other consumer priorities. A barrier to increasing consumer choice in this way is the low delivery capacity and large size of existing 120 V products. This work reports experimental results of a prototype that delivered a first hour rating (FHR) of 67.5 gallons, unprecedentedly high considering the 40-gallon tank size and only using the power available from a standard 120 V (~1.5 kW) outlet. Such performance presents consumers with expanded water heating options that can free up electrical panel capacity for other loads such as additional air conditioning units, induction cooktops, power for renovations, or other new loads while avoiding costly electrical panel upgrades. This work reports the test setup, measures implemented to maximize delivery capacity, control strategies used, and evaluation results. The measures implemented to achieve the performance 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 without increasing product volume.

Introduction

In the United States water heating contributes nearly 20% of total residential energy consumption (EIA 2020). Electricity is used by nearly half of the U.S. water heater market (46%), typically in the form of electric resistance storage water heaters (ERWHs). They require a dedicated 240 V outlet drawing up to 5.5 kW, a significant contributor to peak electricity demand. Heat pump water heaters (HPWH) have grown in popularity as a direct replacement for ERWHs due to their improved efficiency while maintaining similar performance. Despite the benefits, HPWHs only captured 4% of the U.S. water heater market in 2023 (Energy Star 2023).

Recently, a new type of water heater has entered the market using only the power from a standard 120 V outlet, approximately 1.5 kW. These low power HPWHs can be used to replace existing 240 V water heaters and inexpensively free up panel capacity for additional air conditioning units, induction cooktops, power for renovations, or other new loads while avoiding

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costly electrical panel upgrades. Unfortunately, they require enlarged tanks to compensate for their reduced heating capacity.

Market studies have found that the low delivery capacity and consequently large tanks have limited the application of 120 V HPWHs. A study by Slipstream (2024) recommended avoiding installing them in houses with more than four people. They also suggested upsizing former gas water heaters by two sizes (typical size categories are 40, 50, 65, and 80 gallons) when replacing them with a shared circuit 120 V HPWH. This statement was also echoed by an independent study carried out by the New Buildings Institute (BTO 2023). This limits retrofit feasibility because many water heaters are installed in space-constrained locations such as closets and crawl spaces, a significant concern given that approximately 80% of U.S. water heater sales are replacements or retrofits (DOE 2009). Separate studies by both Butzbaugh (2024) et al. and Slipstream (2024) found that hot water runouts still occurred on 5-6% of days despite increased tank size. These studies suggest that the limited delivery capacity of 120 V HPWHs necessitates larger tank sizes, which together constrain their installation potential.

Improving tank effectiveness presents a viable option to improve the delivery capacity of a water heater constrained by power consumption. A common method to do so is to increase the energy density of the storage medium by using phase change materials. Rendall et al. (2023) showed that this method improved the one-hour delivery capacity of a HPWH by 27.7%. Although, adding PCM capsules to the tank increases cost and presents leakage risks. Another method to improve tank effectiveness is to improve tank stratification, the layering of fluid due to differences in density. Stratifying the water tank enables useful hot water to float near the draw port, increasing hot water delivery. Currently, only electric resistance water heaters stratify by using the upper heating element to heat the top of the tank first. Conversely, HPWHs heat the tank evenly because they often use condenser coils that wrap around the outside of the tank spanning its height. This prevents useful hot water from being created during hot water draws thus lowering delivery capacity.

To demonstrate the benefits of stratification, a simple one-hour delivery comparison can be made. Two HPWHs are compared, one with a tank that mixes perfectly during reheating representing a commercially available HPWH and the other a tank that stratifies perfectly during reheating. Both water heaters have a 40-gallon (151.4 L) tank and a heater that delivers 4.3 kW to the tank. Both tanks start fully heated at an average temperature of 125°F (51.7°C). To start the one-hour delivery analysis, a 3 GPM (11.4 L/min) draw with 58°F (14.4°C) supply water is initiated until the temperature drops. It is assumed both tanks stratify perfectly during the initial draw. Thus, both tanks will deliver at least 40 gallons of hot water. Both tanks then recover for the remainder of the hour before another 3 GPM (11.4 L/min) draw is initiated at 60 minutes for any water heated to the delivery temperature of 125°F (51.7°C). For simplicity, both heaters run continuously for the entire hour therefore, the same amount of heat is transferred into each tank. The results of this analysis are demonstrated in Figure 1. During the first draw, the stratified arrangement was able to draw 46.9 gallons (177.5 L), 6.9 gallons (26.1 L) more than the 40 gallons (151.4 L) drawn by the mixed arrangement. After the tanks are allowed to reheat, the stratified tank is able to draw another 19.5 gallons (73.8 L) while the mixed tank cannot draw since the tank was only able to reach 83°F (28.3°C). Thus, the theoretical one-hour delivery of the stratified tank is 66.4 gallons (251.4 L) and only 40 gallons (151.4 L) for the mixed tank despite the same amount of heat being transferred into the tank.

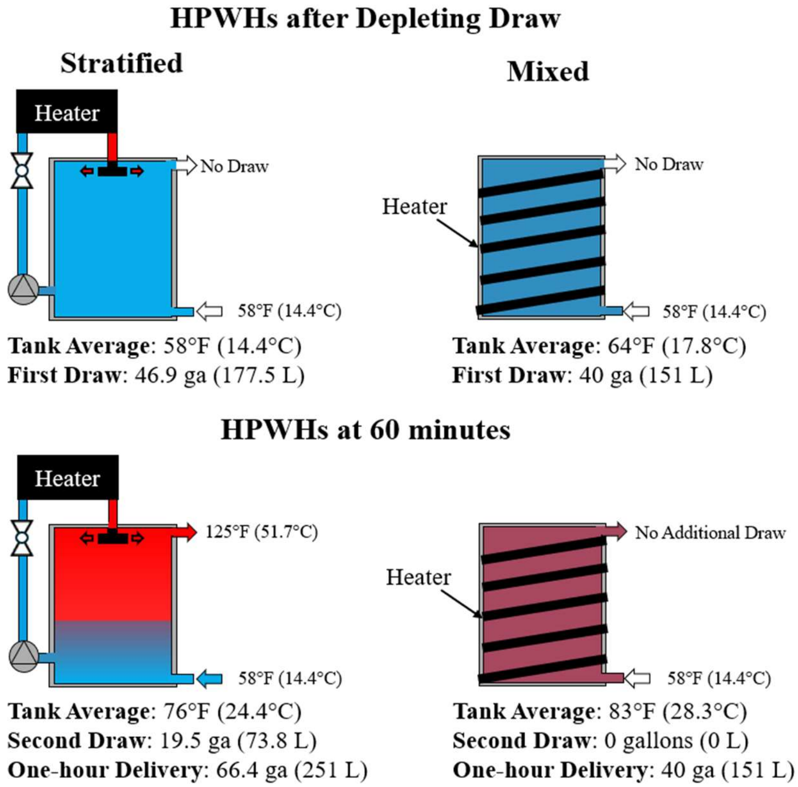

Figure 1. One-hour delivery comparison of perfectly mixed and perfectly stratified 40 gallon water heaters.

The goal of this study is to maximize the delivery capacity of a 120 V HPWH with a standard tank size while maintaining energy efficiency. To achieve this, the prototype incorporates a large compressor, a pumped loop with a plate heat exchanger to promote tank stratification, enlarged heat exchangers, and relatively thin insulation to maximize water storage volume without increasing overall product size. The 120 V prototype HPWH is evaluated using two draw profiles. A novel field-derived runout draw profile developed in our previous study is used to benchmark performance under real-world conditions (Gluesenkamp 2024). In addition, the First Hour Rating (FHR) draw profile defined in the US Code of Federal Regulations (10 CFR 430) is used to evaluate one-hour delivery capacity.

Prototype Description

The system being investigated is a dedicated circuit 120 V HPWH that uses a pumped water loop to heat the water and improve tank stratification. In contrast to most commercially available HPWHs, a brazed plate heat exchanger is used to condense the refrigerant rather than a wrapped tank condenser. A flow control valve in the pumped water loop is used to control the temperature of the water delivered to the top of the tank. A baffle is used to disrupt the water flow when it is reintroduced to the tank to minimize mixing. The pumped loop draws water from either the bottom or one of three ports in the middle of the tank at a maximum flowrate of 1.8 GPM (6.8 L/min). Switching to one of the middle ports during a draw enables the water heater to draw mixed temperature water rather than cold water to boost delivery capacity. A schematic of the system is shown in Figure 2.

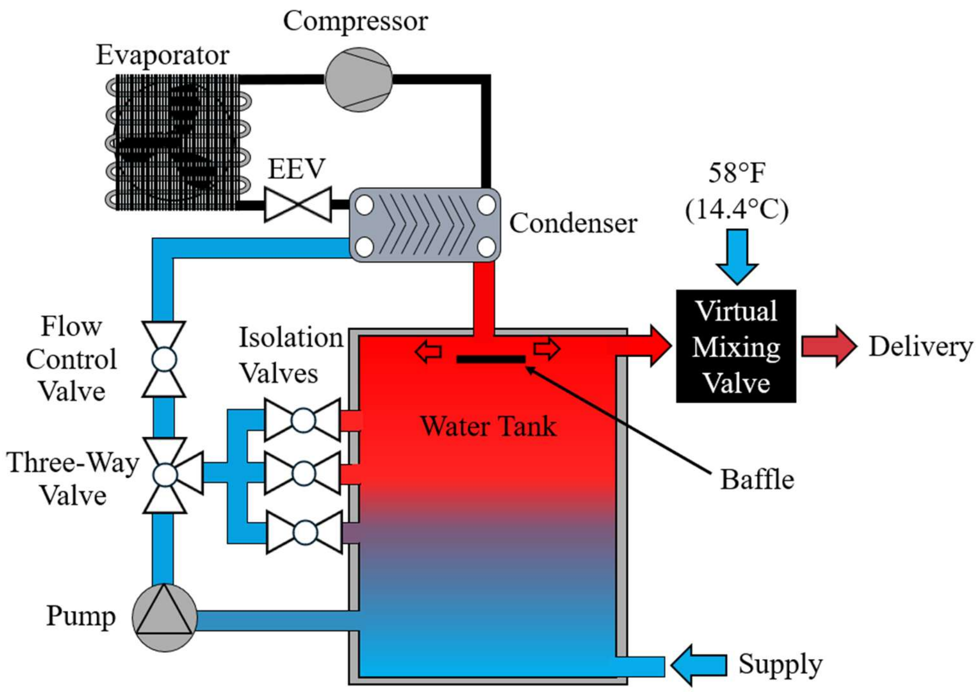

Figure 2. Simplified schematic of prototype system.

A virtual mixing valve is used to mix overheated (greater than 130°F (54.4°C)) tank water with tap water ensure a consistent delivery temperature and avoid scalding. A regular mixing valve could not be used since the tank cannot be pressurized. The mixing valve is 'virtual' because it only calculates the volumetric flowrate of 58°F (14.4°C) water required to mix with tank water to achieve a set flowrate of 120°F (48.9°C) water and does not actually add any makeup water. The virtual mixing valve reads the supply flowrate and the outlet temperature sensor to control the position of the Belimo valve at the tank supply to maintain a constant outlet temperature and flowrate.

The protype system's heat pump is equipped with an enlarged compressor that maximizes the heating capacity achievable from a standard 120 V circuit. The 12,000 Btu/hr (3,517W) rotary compressor uses R134a as the refrigerant. The condenser is a brazed 36-plate heat exchanger. The evaporators used are two large aluminum fin and tube heat exchangers. A 9.8 in (250 mm) diameter, 37 W fan is used to pull air through them. A 260-step electronic expansion valve is used to maintain 10°F (5.6°C) of suction superheat. A 1/15 HP (70 W) pump is used to circulate water from the bottom of the tank through the condenser using ½ in brass tubing insulated by 1 in foam insulation. Details about the components used in the prototype are shown in

Table 1.

Table 1. List of components used to construct the prototype 40 gallon (151.4 L) 120 V HPWH.

Name	**Type**	**Size**	**Specification**
Tank	Unpressurized	18.5 in OD x 40.25 in H 40 Gallon	Low density polyethylene
Insulation	Foam	1 in	N/A
Hydronic Tubing	Brass	½”	1” foam insulation
Pump	Circulator Pump	1/15 HP, 70 W	Bell & Gossett
Flow Control Valve	Belimo	½”	LRX24-MFT
Compressor	Rotary compressor	12,000 Btu/h (3,517 W)	RJSF250E1WKT
Condenser	Brazed Plate Heat Exchanger	3.01 X 12.52 X 1.89 inches, or 7.08 ft^2	28-plate
Evaporator	Finned Tube	Two, 15” H x 10” W x 1.5” T	Aluminum
Expansion Valve	Electronic Expansion Valve	260 Steps	10°F (5.6°C) Superheat
Fan	Axial Fan	250mm	37W
Mixing Valve	Virtual Mixing Valve	N/A	Maintains 120°F (44.4°C)
Refrigerant	R134a	N/A	N/A

The prototype system is equipped with sensors to measure and control the water heating performance. Temperature sensors were placed to measure air, water, and refrigerant temperature in prominent locations. To reduce the risk of refrigerant leakage, temperature sensors in the refrigerant circuit were surface mounted. Pressure sensors were placed in the refrigerant circuit to measure the high side pressure, low side pressure, and pressure drop across the condenser. One flow meter was placed at the tank inlet to measure and provide feedback for water draws. A second flow meter is used to measure the flow rate of water in the recirculation loop. Figure 3 shows a picture of the prototype and a schematic indicating sensor placement.

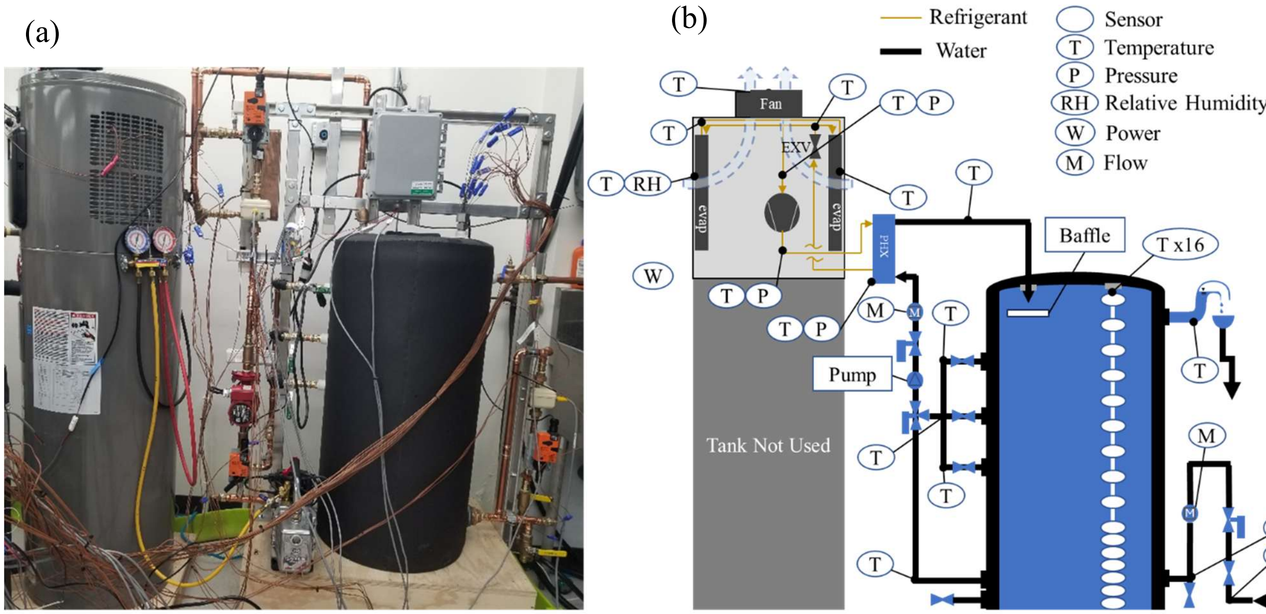

Figure 3. (a) Photograph of fabricated 40 gallon (151.4 L) prototype HPWH (prior to insulation). (b) Detailed prototype system schematic including sensor locations and types.

The temperature distribution within the storage tank was measured using 16 thermocouples positioned as shown in Figure 4. Six of them (TC3, TC7, TC9, TC11, TC13, and TC15) were placed such that the center of six equal 6.7 ga (25.4L) segments are measured. These are used to calculate the average tank temperature in accordance with 10 CFR 430. Seven more thermocouples (TC1, TC5, TC8, TC10, TC12, TC14, and TC16) are located between each of the six segments to give more resolution to the tank temperature distribution. The last three thermocouples (TC2, TC4, and TC6) are located within the first 10.1 ga (45.8L) to measure the water temperature every 1.7 ga (6.4L) when combined with TC1, TC3, and TC5.

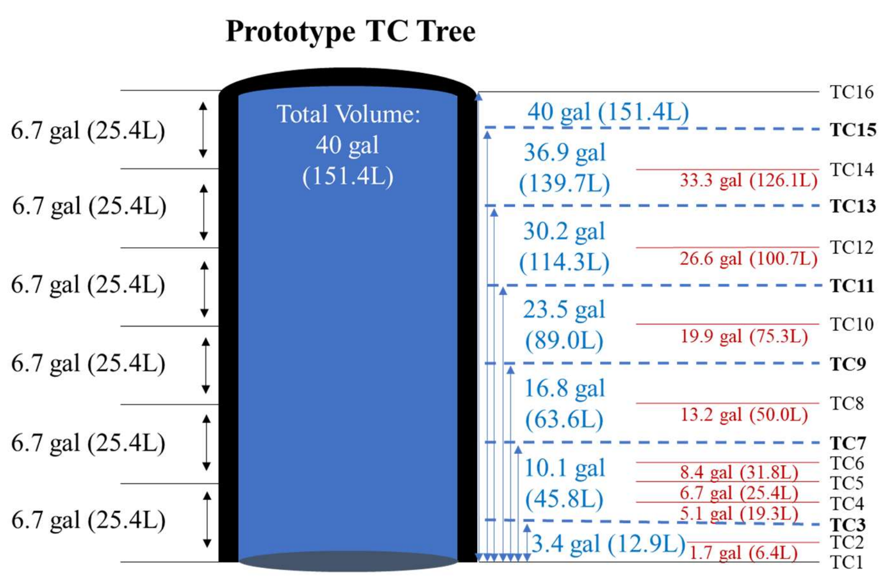

Figure 4. Prototype system tank thermocouple placement used to monitor tank temperature and stratification.

The table below shows the setpoints used to control the heat pump in the prototype. The tank setpoint of 130°F (54.4°C) represents the average tank temperature set at the beginning of each draw profile. To control the heat pump, compressor turns on if TC6 reads less than 115°F (46.1°C). It will then run until TC6 surpasses 130°F (54.4°C). The recirculation loop setpoint is set just below the target tank temperature at 125°F (51.7°C). This ensures that the tank cannot heat to the setpoint in a single pass. This second pass occurs at much higher flowrate overheating the top of the tank and increasing stratification. By default, the recirculation loop will draw from the port at the bottom of the tank, but it will switch to draw from one of the three ports in the middle of the tank based on a temperature setpoint. Prior testing indicated that the lowest draw port which lines up with TC12 provides the best delivery capacity results. Thus, the upper two draw ports were closed off. Further, when TC12 falls below 125°F (51.7°C), the recirculation loop will stop drawing from the bottom of the tank and begin to draw from lowest of the three middle ports. This ensures just the top of the tank will be heated improving stratification.

Table 2. Prototype heat pump and pumped loop controls.

Tank (°F, °C)	**Compressor On (°F, °C)**	**Compressor Off (°F, °C)**	**Recirc Target (°F, °C)**	**Inlet Selector (°F, °C)**
130 (54.4)	TC6 < 115 (46.1)	TC6 ≥ 130 (54.4)	125 (51.2)	TC12 <125°F (51.2)

Draw profiles

A field derived runout profile will be employed to benchmark the system performance using realistic conditions. It was created using field data from NBI's study of 120 V HPWHs. It is based on a real runout that occurred in a 120 V HPWH with a 65-gallon (246.1 L) storage tank (NBI 2023). The methodology for creating this draw profile is described by Gluesenkamp et al. (2024). During each draw, the inlet water temperature is set at 58 ± 2 °F (14.4 ± 1.1 °C) and the outlet water temperature is set at 120°F (48.9°C). Runout occurs once the outlet water temperature falls to 100°F (37.8°C). The draw pattern is shown in Table 3.

Table 3. Field derived runout draw profile (Gluesenkamp 2024).

Draw #	**Flow (GPM, L/min)**	**Start (s)**	**Stop (s)**	**Total Volume (gal, L)**	**Ambient Conditions**	
					Temp (°F)	**RH%**
	-	0	437	-	69 (21°C)	43
1	0.25 (0.95)	438	629	0.80 (3.03)	69 (21°C)	43
	-	6.0	924	-	69 (21°C)	43
2	3.74 (14.2)	925	1054	8.90 (33.7)	69 (21°C)	43
3	2.39 (9.0)	1055	1264	17.25 (65.30)	69 (21°C)	43
	-	1265	2719	-	68 (20°C)	45
4	4.43 (16.8)	2720	2784	22.05 (83.47)	67 (19°C)	46
5	2.55 (9.7)	2785	3474	51.40 (194.57)	66 (19°C)	47
	-	3475	3814	-	66 (19°C)	47
6	1.55 (5.9)	3815	3899	53.60 (202.90)	65 (18°C)	47
7	1.31 (5.0)	3900	5700	92.80 (351.29)	64 (18°C)	48

The FHR draw profile is used to measure the one-hour delivery of the water heater and is defined in 10 CFR 430. The tank begins preconditioned and the test begins once the compressor turns off. A 3 ± 0.25 GPM (11.4 ± 0.95 L/min) draw at 125 ± 5 °F (51.7 ± 2.8 °C) is then initialized until the draw temperature drops by 15°F (8.3°C). The water supplied to the tank must maintain a temperature of 58 ± 2 °F (14.4 ± 1.1 °C). The tank is then allowed to reheat for the remainder of the hour before another 3 ± 0.25 GPM (11.4 ± 0.95 L/min) draw is initiated. The test then ends based on the same temperature drop criteria (10 CFR 430).

Results and Discussion

The prototype 120 V HPWH was evaluated using two draw profiles. The first is a field derived runout profile used to assess real world performance. It consists of 7 draws with flowrates between 0.25 and 4.43 GPM (0.95 and 16.77 L/min), see Table 3. The second is the FHR draw profile used to assess one-hour hot water delivery. It consists of two 3 GPM (11.4L) flowrate draws both ending once the outlet water temperature drops by 15°F (8.3°C). The first draw occurs at the beginning of the test and the second at 60 minutes.

The prototype performed significantly better in the runout test than the larger, 65-gallon (246.1L) 120 V HPWH the draw profile is based on. The larger system ran out of hot water after drawing 54.2 gallons (205.2L) in 3925s (~65 minutes). The prototype system drew 79.9 gallons (302.5L), a 47% increase and lasted 5151s (~86 minutes), outperforming the larger HPWH by approximately 20 minutes and 25.7 gallons. The plot below shows the prototype runout performance (

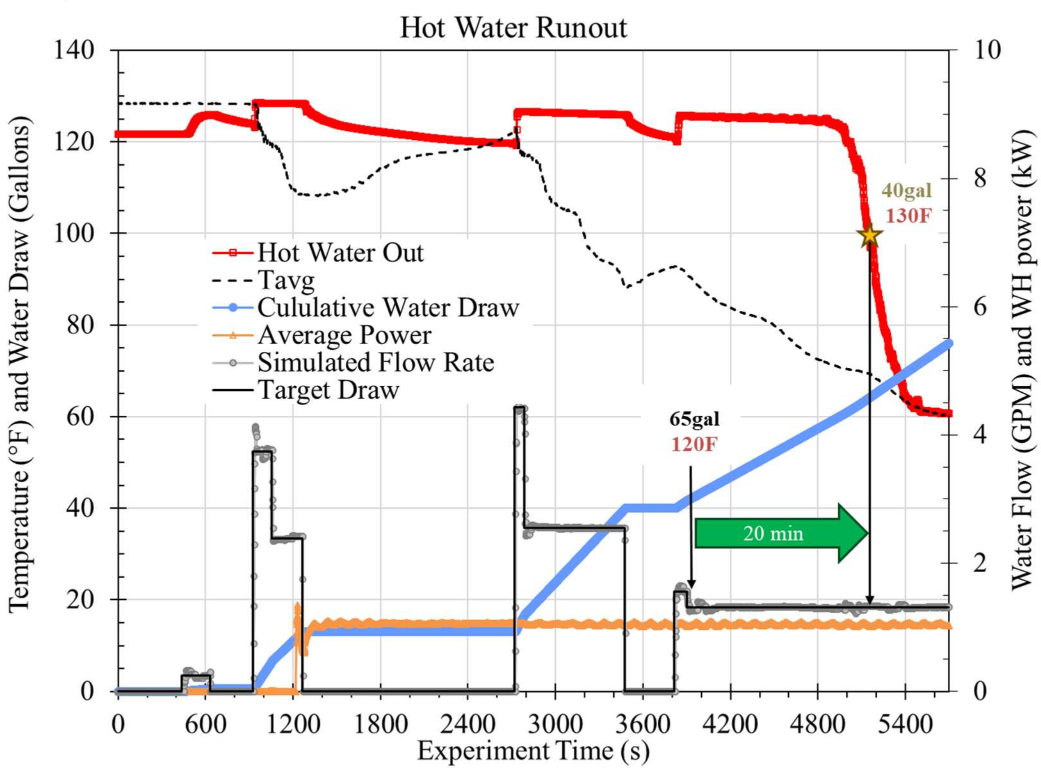

Figure 5).

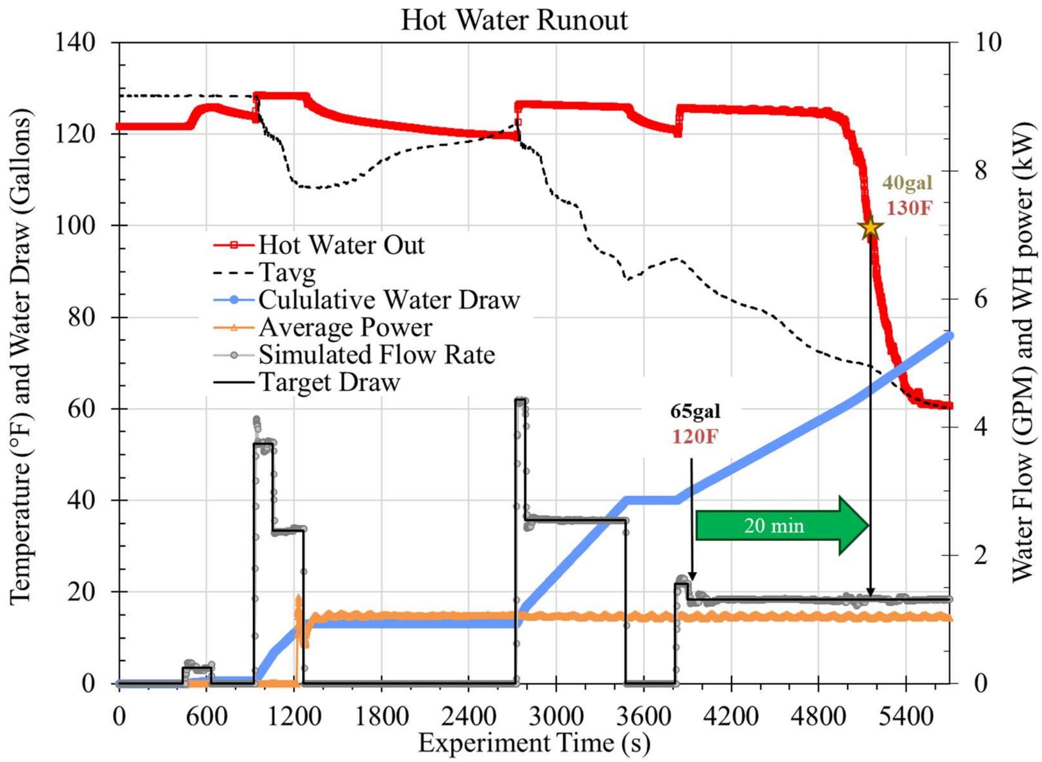

Figure 5. Prototype results compared to 65ga (246.1L) HPWH in a field derived runout test.

The prototype achieved an exceptional FHR* thanks to effective tank stratification. The average tank temperature began slightly above the intended setpoint at 133°F (56°C) with the top of the tank near 135°F (57°C) and the lower portion at 129°F (54°C). Figure 6 shows the tank temperature sensors during the FHR draw profile. The tank stratification can be seen once the first draw ends, around 20 minutes. TC14-10 climb one at a time due to the pumped loop drawing from the middle of the tank and delivering hot water to the top of the tank enabling a significant second draw. The first draw deposited 51.8 gallons (196.1 L) of hot water, 11.8 gallons (44.7 L) above the tank volume. The second draw added another 15.7 gallons (59.4 L) due to effective stratification during reheating. This is far more than would be expected by a typical HPWH that does not have backup resistance elements. The FHR* total is 67.5 gallons (255.5 L), 27.5 gallons (104.1 L) above the tank volume.

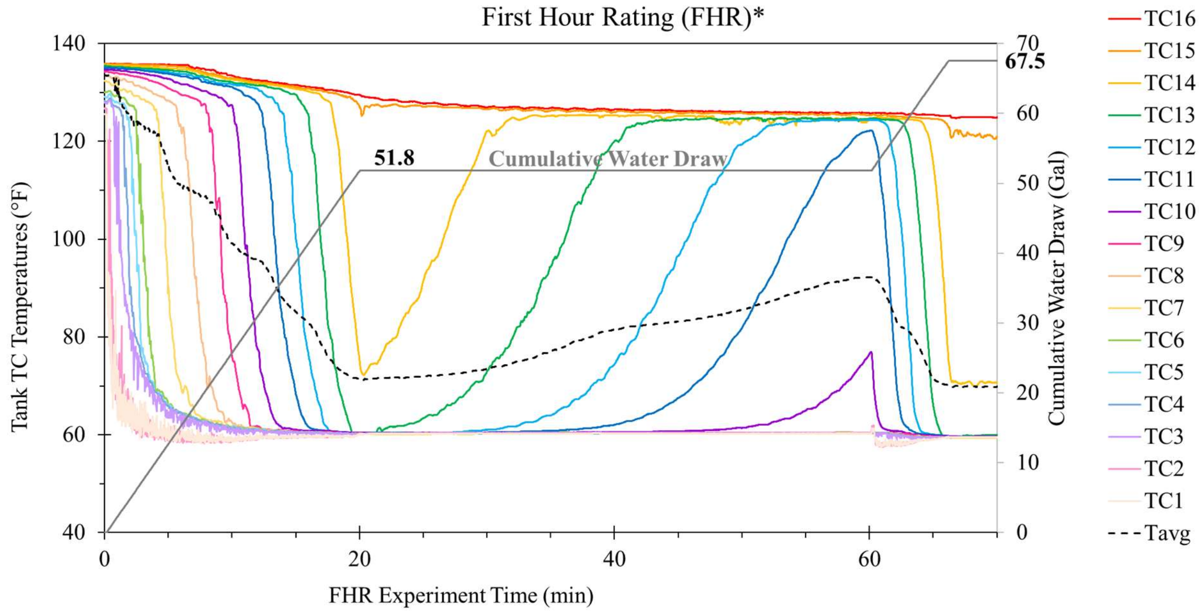

Figure 6. Thermocouple tree within prototype tank during FHR* draw profile. *The ambient conditions and flowrate were outside what is required in 10 CFR 430. The average air temperature was 65.5±1.1°F (18.6 ± 0.6°C), the relative humidity was 27.0 ± 1.7, and the flowrate was 2.59 ± 0.15 GPM (9.8 ± .6 L) during the FHR test.

Figure 7 shows a comparison between the prototype 120V HPWH and other commercially available water heaters with similar tank volumes (less than 42 gallons (159 L)) on the basis of FHR and input power. The 40 gallon (151.4 L) prototype 120 V HPWH outperforms all 240V HPWHs and ERWHs in delivery capacity despite using less than half of the input power. Compared to just 120 V HPWH, it delivers more than 20 additional gallons (75.7 L) while using slightly more power due to the pumped loop. Its delivery capacity is competitive with most gas water heaters especially those with burners less than 40 MBtu/hr (10.25 kW).

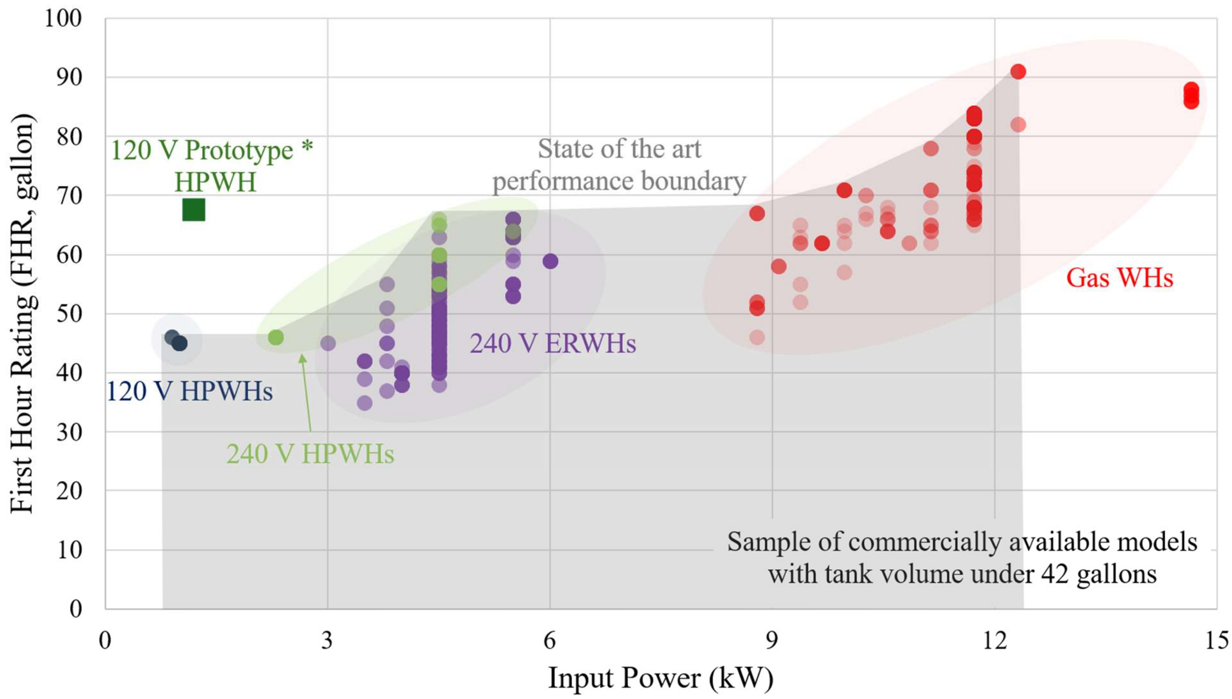

Figure 7. 40-gallon (151.4 L) prototype compared to commercially available water heaters with similar sized water tanks (less than 42 gallons (159 L) (AHRI 2026; Energy Star 2026). * Ambient conditions were outside what is required in 10 CFR 430 for the FHR test. The average air temperature was 65.5±1.1°F (18.6 ± 0.6°C), the relative humidity was 27.0 ± 1.7, the flowrate was 2.59 ± 0.15 GPM (9.8 ± .6 L) during the FHR test.

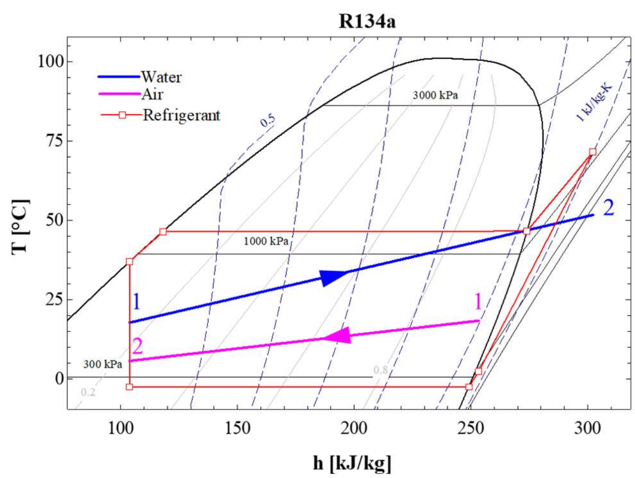

Figure 8. Pinch point diagram of heat pump heat exchangers during single pass operation.

The efficiency of the system was evaluated by analyzing the coefficient of performance (COP) of the cycle during both the first pass and second pass of water from the bottom of the tank through the condenser. During the first pass (58°F return 125°F supply), the coefficient of performance (COP) is 3.14. This is lower than expected but can be explained by ineffective evaporators and heat loss in the refrigerant system. Figure 8 shows a time averaged pinch plot analysis of the heat exchangers in the prototype system during the first pass. The plot shows that the condenser has extremely high effectiveness, with a closest approach of less than 1°F (0.5°C) at the pinch. In contrast, the closest approach at the pinch in the evaporator is 14.7°F (8.2°C), indicating room for improvement. Additionally, the performance of the system drops considerably to a COP of 2.55 during the second pass (~110°F return and +130°F supply) of water through the condenser. The hot water entering the condenser drives the refrigerant pressure up, reducing the thermodynamic efficiency of the system.

Conclusion and Future Work

In this work, we have reported the experimental results of a 120 V dedicated circuit HPWH. The 40-gallon prototype featured 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 without increasing product volume. It was tested using two draw profiles, a field-derived runout profile and FHR. The prototype outperformed the 65-gallon 120 V HPWH the runout draw profile is based on by 20 minutes, providing 47% more hot water. It also achieved an unprecedented FHR* of 67.5 gallons, above commercially available 240V ERWH and 240V HPWH with similar tank volumes despite the lack of input power. Analysis indicates that inefficiencies in the heat pump can be addressed by improving evaporator effectiveness and eliminating the second pass of water through the condenser. As a part of future work, the team plans to package the unit to match a standard form factor and further increase FHR while also evaluating the Uniform Energy Factor draw profile, the US standard for overall system efficiency.

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