BONNEVILLE POWER ADMINISTRATION

Emerging Technologies

Improving Thermal Energy Storage to Reduce Installation Costs for Heat Pump Water Heating Systems

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Thermal Storage Performance in Heat Pump Water Heating Systems

Prepared for

Karen Janowitz, Project Principal Investigator

Washington State University Energy Program on behalf of Bonneville Power Administration

Prepared by

Scott Spielman, Adria Banks, Paul Kintner

Ecotope Inc.

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Definitions

Charging: Storing heating capacity by adding heat to a thermal storage device or storing cooling capacity by removing heat from a thermal storage device.

Discharging: Using stored heating or cooling capacity.

Thermal Storage: Equipment that allows the rate of heat generation to significantly differ from the rate of heat delivery to meet the load(s).

Sensible Energy Storage: Energy stored in the temperature difference between hot and cold.

Single-pass: A heat pump water heating system that heats water from cold entering city water to hot water for storage in a single-pass through the heat exchanger.

Thermocline: The transition region between the hot and cold portions of a stratified thermal energy storage tank.

Acronyms

HPWH: Heat pump water heater.

TES: Thermal energy storage.

Executive Summary

Thermal energy storage (TES) is one of the most expensive components in a heat pump water heater (HPWH) system – and the cost increases with the added TES volume. This report describes several strategies around TES that can reduce the costs of both the storage component and, as a result, the HPWH system.

By more thoughtfully designing storage tanks and connected piping, less storage can be used more efficiently to meet facility needs. Less storage requires fewer storage tanks, costs less, weighs less, and takes up less floor space, likely saving tens of thousands of dollars on each central HPWH system installation.

To realize saving of better performing pressurized TES, the findings from this report must be developed to update the Ecosizer[1] and allow designers to take advantage of increased thermal storage performance in sizing algorithms. Inputs for stratification, thermal losses, and drawdown factor can be added to the Ecosizer to capture TES performance more fully. Default choices including (1) (a) standard stock tank, (b) tank designed for use with single-pass HPWH, and (2) (a) single tank, (b) multiple tank parallel, (c) multiple tank series, can allow designers to quickly input designs and realize saving.

Additionally, unpressurized TES has potential to drastically reduce costs – it could decrease TES costs by a factor of 4. Unpressurized storage needs to be developed with a partner manufacturer to ensure the methods of exchanging heat between HPWHs, unpressurized storage, and potable water will lead to properly sized and installed systems. In addition to cost benefits, unpressurized storage allows for improved freeze protection, less wear on HPWH equipment, no expansion tank, and designs more suitable to high-rise buildings.

Background

TES is an essential component of all HPWH systems. It allows the rate of hot water generation to significantly differ from the rate of hot water usage.[i] Unlike some electric resistance and gas water heaters, which can be instantaneous, HPWHs need TES to function properly. All available HPWH systems today use pressurized potable water as the TES media, which typically costs between \$20 and \$35 per gallon. Energy is stored in the form of hot water, generated by the HPWH, and used by building tenants.

Historically, pressurized potable water has been used for TES in domestic water systems using gas or electric resistance water heating to allow a lower heating capacity to meet peak demands. In HPWH systems, TES can also be used to lower costs and provide beneficial services to the electric grid.

Installation costs can be reduced by properly designing TES so that fewer HPWHs are needed to meet the hot water load. This also reduces the electrical service required, which further lowers installation costs and puts less

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[1] The Ecosizer is an online tool, developed by Ecotope, that sizes thermal energy storage and heating water heater capacity for heat pump water heating systems. Link: https://ecosizer-calbem.ibpsa.us/sizer/

demand on the electric grid. Furthermore, fewer HPWHs also reduces peak power draw and demand charges, which lowers operating costs.

Because TES allows the rate of hot water generation to differ from the rate of hot water use, it provides opportunity for load shifting. An EcoPort (also called CTA-2045) connection allows utilities to take advantage of TES in HPWH systems by timing energy usage to improve electric grid operation.[ii]

Pressurized TES Tanks Need Design Changes to Improve Performance

The way storage tanks are used for gas and heat pump water heating are very different – and the pressurized TES tanks used today are built for gas.

Figure 1 shows the standard "stock" design of thermal storage tanks sold in the United States. This tank is specifically designed for use with a gas water heater with the bottom portion acting as a mixed buffer to prevent cycling and the top portion containing heated water ready for use. The storage volume is relatively small compared to heating capacity. A single-pass HPWH system needs a new design.

> *The way storage tanks are used for gas and heat pump water heating are very different –and the pressurized TES tanks used today are built for gas.*

Figure 1. Stock thermal storage tank

Figure 2 shows how piping is connected in a gas system. Note how both connections to and from the gas water heater are on the bottom side of the storage tank. This piping configuration will not work for single-pass HPWHs because they are designed to slowly heat TES tanks from the top down while maintaining stratification.

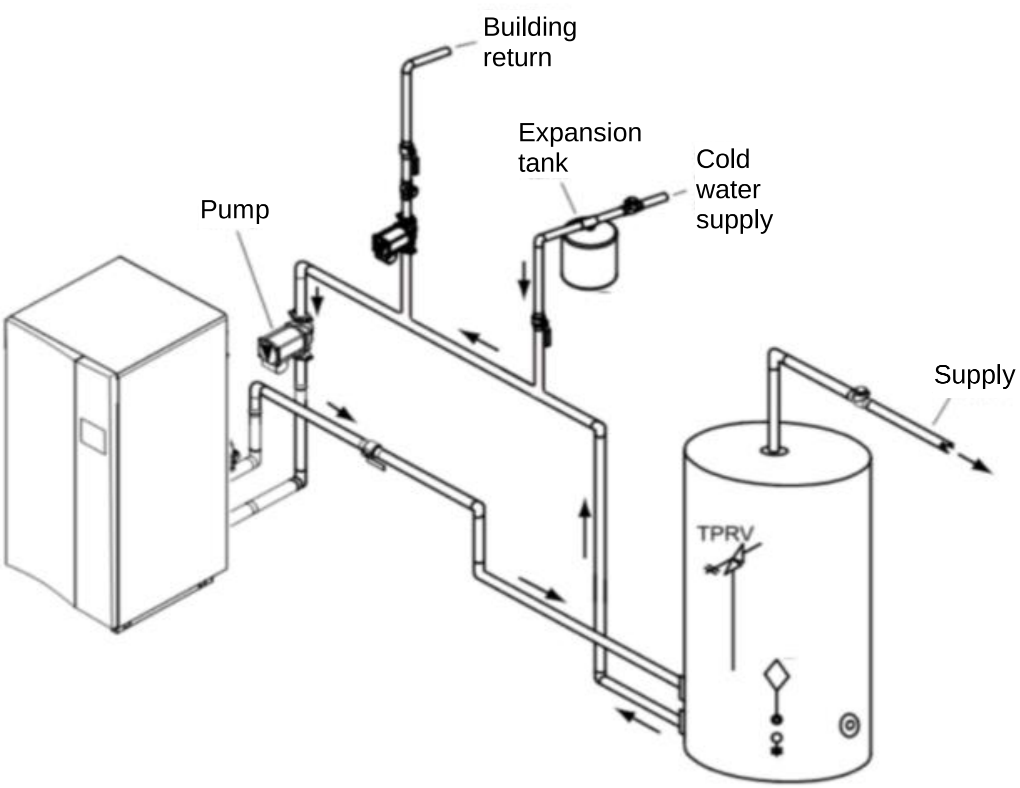

Figure 2. Gas boiler and storage piping configuration

Figure 3 shows a TES designed to work with single-pass HPWHs. Using this tank design would increase thermal storage performance by providing good stratification and nearly 100% drawdown factor (explained further under *Factors that Influence Thermal Energy Storage Performance*). It's also a simple design that should not cost much more than standard "stock" storage tanks to produce.

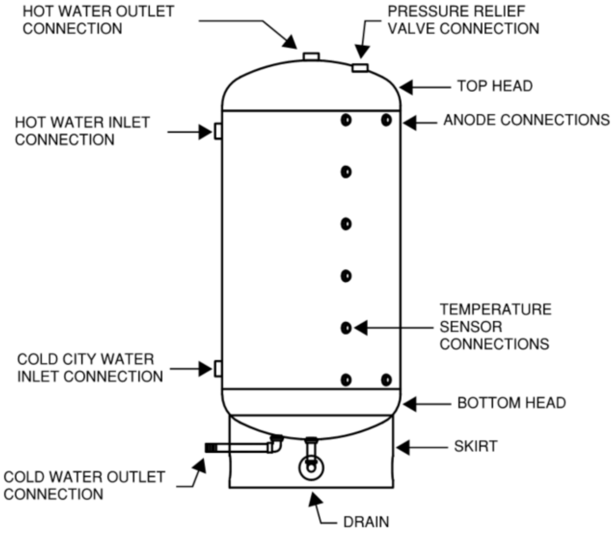

Figure 3. Tank designs to improve TES performance

To understand TES performance, stratification, thermal losses, and drawdown factor must all be considered.

Factors that Influence TES Performance

Unlike heating equipment that uses energy, TES performance cannot be defined by heat output over the input energy usage. TES equipment does not use energy, it stores energy like a battery.

To understand TES performance, stratification, thermal losses, and drawdown factor must all be considered.

> *TES systems should be carefully designed to increase stratification so that HPWH systems can use less storage to meet project needs.*

Stratification

Due to its lower density, hot water floats above cooler water. This phenomenon, called stratification, provides three significant benefits to TES.

1. Stratification allows less TES to meet the building needs.
2. Stratification allows a partially charged TES system to provide hot water.
3. Stratification improves HPWH efficiency.[2]

A thermocline exists at the interface between hot and cold water where the temperature transitions. The smaller the thermocline region, the closer the tank will be to a perfectly stratified tank. TES systems should be carefully designed to increase stratification so that HPWH systems can use less storage to meet project needs.

Figure 4 and Figure 5 illustrate the significance of stratification. Both figures show the same 500-gallon storage tank with different temperature profiles. Figure 4 is well-stratified, with a small thermocline region. Figure 5 is poorly designed and not well stratified; the thermocline region takes up the whole storage volume. Each tank contains the same amount of energy, but the well-stratified tank can provide ~300 gallons of usable hot water at 120°F whereas the poorly designed tank can only provide ~150 gallons of usable water.

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[2] All air-to-water heat pumps including HPWHs heat more efficiently when incoming water temperatures are cold. Additionally, in a swing tank system, hotter, unmixed water offsets more electric resistance heating.

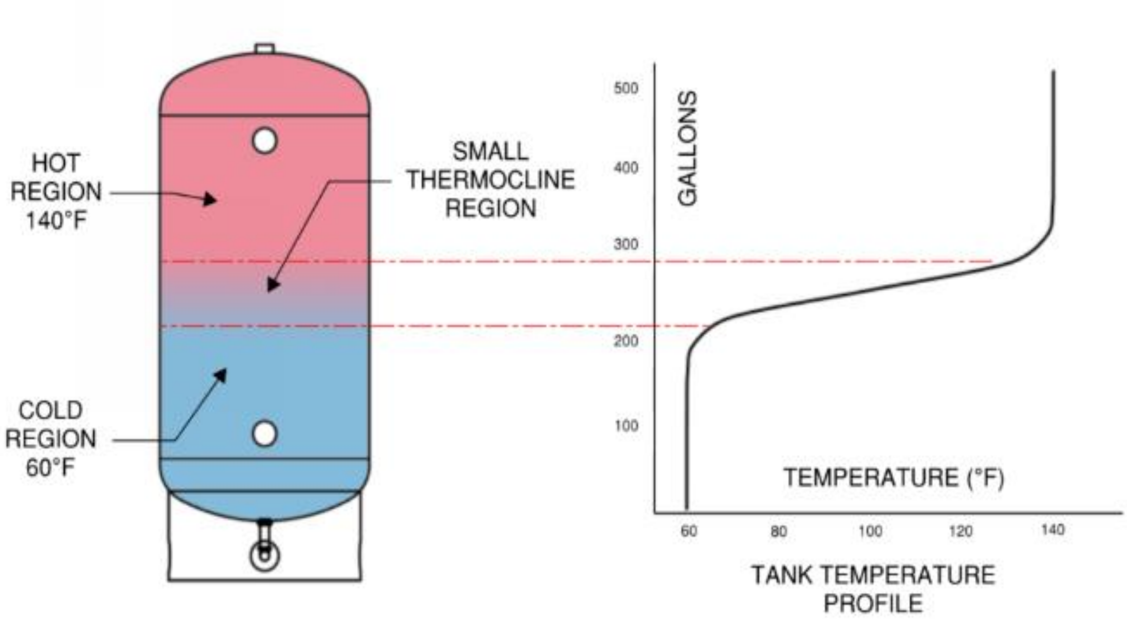

Figure 4. Well stratified tank and temperature profile

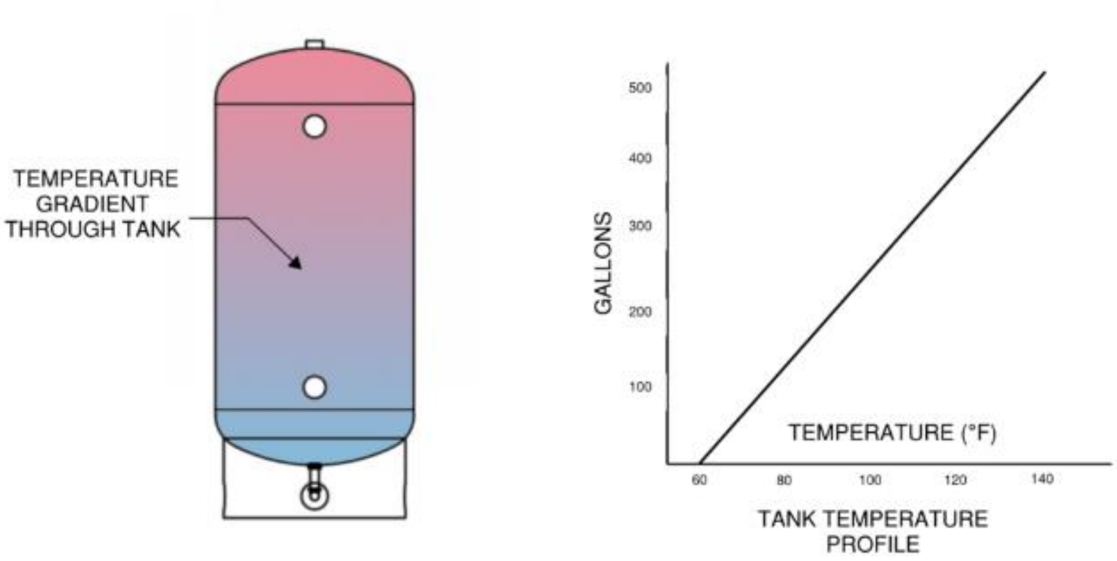

Figure 5. Poorly stratified tank and temperature profile

DESIGN CONSIDERATIONS TO INCREASE STRATIFICATION

The following three guidelines should always be followed to ensure storage tanks are designed to maximize stratification.[iii] [iv]

1. Provide horizontal inlets or baffles/sparges to redirect inlet flow from vertical to horizontal. Connecting outlets vertically will not disrupt stratification, only inlets.
2. Size pipe connections so inlet/outlet velocities are less than 3 feet per second at peak flow rates.

3. Provide hot inlet/outlet connections near the top of the tank and cold inlet/outlet connections near the bottom of the tank.

Other factors that influence stratification include:

- Larger temperature differences between hot and cold water increase stratification.
- Taller/skinnier tanks decrease the volume of water in the stratification region and reduce conduction between hot and cold water which expands the thermocline region. However, a tank that is too skinny will increase thermal losses.
- Thermal losses increase the width of the thermocline region and decrease stratification. More insulated TES tanks will hold heat and stratification better.

Thermal Losses[v]

Thermal losses are heat lost by conduction through tank walls to the ambient air. The heat lost was generated by the HPWH but cannot be delivered to tenants in the form of hot water and therefore reduces system efficiency. Additionally, thermal losses tend to degrade stratification.

Tanks offered today provide between R-12 and R-30 insulation. More research is needed to fully understand and optimize insulation for thermal and economic performance. However, at this point Ecotope recommends a minimum of R-18 insulation for HPWH systems.

Drawdown Factor

Drawdown factor is the percent of usable volume dictated by inlet and outlet placements.

For example, a tank with an outlet at the lowest point and inlet at the highest point on the tank has a 100% drawdown factor. However, the typical storage tank design shown in Figure 6 does not have an outlet at the bottom of the tank. The outlet is placed on the cylindrical portion of the tank above the bottom head which means some cold

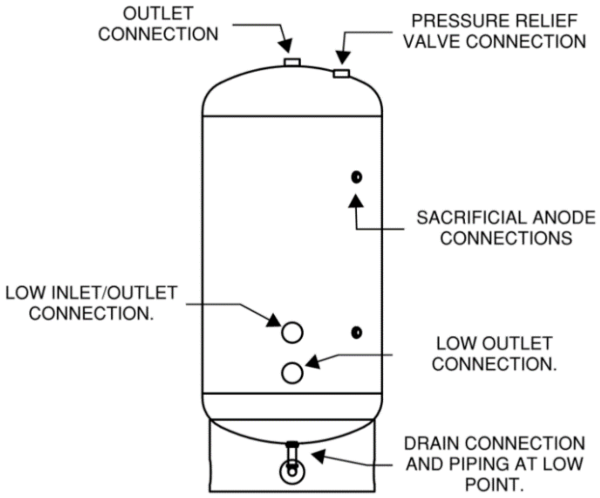

Figure 6. Typical Storage Tank Design

> *When the Ecosizer is updated to include TES performance characteristics from stratification, thermal losses, and drawdown factor, manufacturers who choose to optimize storage and size systems using the Ecosizer will reap the economic benefits of a higher performing system.*

water will always be left at the bottom of the tank. The typical drawdown factor for a side outlet is 80-85%.

An 80% drawdown factor on a 500-gallon tank means only 400-gallons of usable water. At $25 per gallon, that is approximately $2,500 lost value. Because the cost to add a lower outlet is less than $500, Ecotope believes tanks designed for use with HPWH systems should always provide a bottom outlet and drawdown factors of 95% or above.

Ecosizer Calculation[vi]

Currently the Ecosizer only includes drawdown factor in the TES sizing calculation. Figure 7 (from Ecosizer documentation) shows unusable volume calculated from the “Storage Efficiency” input. The current algorithm allows for different storage efficiencies to give the same result, which may be confusing to users. Conservatism in other parts of the calculation likely prevent under-sizing of storage, but more thought should be put into accurate accounting of TES performance. When the Ecosizer is updated to include TES performance characteristics from stratification, thermal losses, and drawdown factor, manufacturers who choose to optimize storage and size systems using the Ecosizer will reap the economic benefits of a higher performing system.

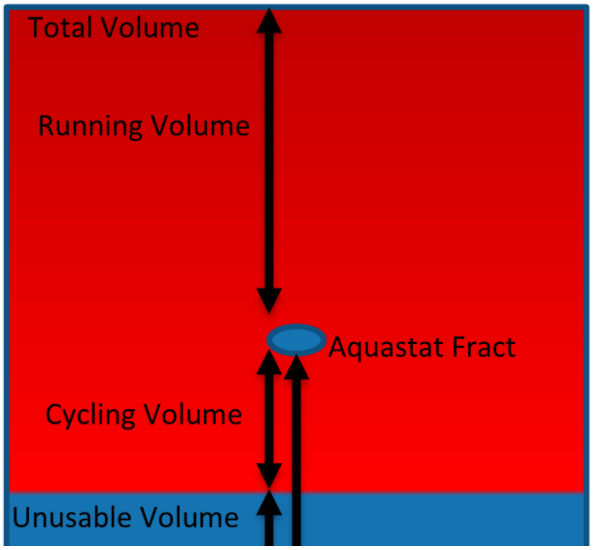

Figure 7. Storage Efficiency Ecosizer

Multiple TES Tanks – Parallel vs. Series Piping

When more than one tank is required, tanks can be arranged in series or parallel piping configurations – shown in Figure 8 and Figure 9 respectively.

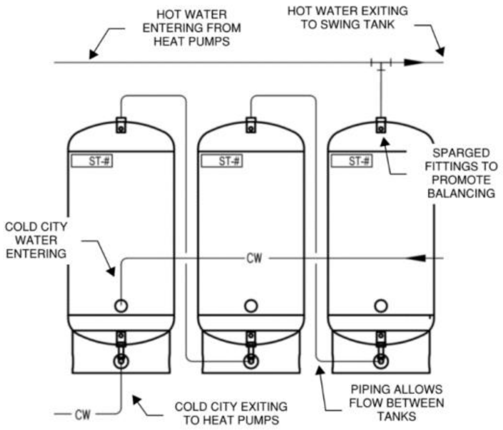

Figure 8. Series piping for multiple TES tanks

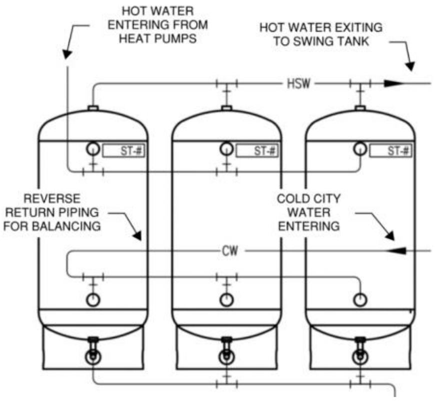

Figure 9. Parallel piping for multiple TES tanks

Although more research is needed to determine which piping configuration should be adopted as a standard, key advantages to each option are below.

Parallel Configuration:

1. Ability to isolate, drain, and perform maintenance on a tank without interrupting the system.
2. Potentially increases stratification through low inlet/outlet velocities and a tighter thermocline region across tanks.
3. Lower pressure-drop through storage system.
4. More consistent control setup with different numbers of tanks.

Series Configuration:

1. Different sized tanks can be used in the same system.
2. Simple balancing with just one set of inlets/outlets for the system.

Unpressurized TES

Unpressurized TES tanks have a direct connection to the atmosphere so the pressure inside and outside the tank are equal. Although they have not yet been used in HPWH systems, they are used in hydronic heating systems when large thermal storage is desired.

There are numerous advantages to utilizing an unpressurized TES in HPWH systems:

- **Less expensive:** Unpressurized storage typically costs $5 to $10 per gallon, as opposed to $20 to $35 per gallon for pressurized storage.
- **Improved freeze-protection:** Propylene glycol can be used in the outdoor loop between the TES and HPWH which reduces the amount of heat trace required. Heat trace may still be needed on the HPWH condensate pan and condensate pipe. However, condensate heat trace can more easily be integrated into the HPWH by the manufacturer.
- **Expansion tank not needed:** Both air and water are present inside the tank allowing the water level to rise and fall as the storage expands and contracts. Eliminating the expansion tank, which can be quite large for pressurized systems, reduces equipment cost, installation time and complexity, and required physical space.
- **Isolates HPWH from city water:** City water must be kept pressurized to serve the building, so when unpressurized storage is used, the HPWH cannot heat the city water directly. Instead, the HPWH heats the unpressurized storage, which then heats city water through a heat exchanger. Indirectly heating city water protects the HPWH's internal heat exchanger which will increase its usable life and allow a single walled heat exchanger to be used inside the HPWH.
- **Advantages in high-rise design:** Pressure relief valves on pressurized TES tanks are set at 125 psi. However, in high rise buildings booster pumps are sometimes required to boost pressure over 125 psi to serve upper floors in the building. In unpressurized TES, a heat exchanger is used between the TES and the pressurized water, so higher pressures are not problematic.

Heat exchangers must be used to transfer energy from the heat pump to the unpressurized storage, and then from the unpressurized storage to the potable water. The heat exchangers can be copper coils located directly in the unpressured TES tank (Figure 10) or brazed plate heat exchangers with pump (Figure 11). The brazed plate heat exchanger with pump offers better controllability but is more complex and expensive.

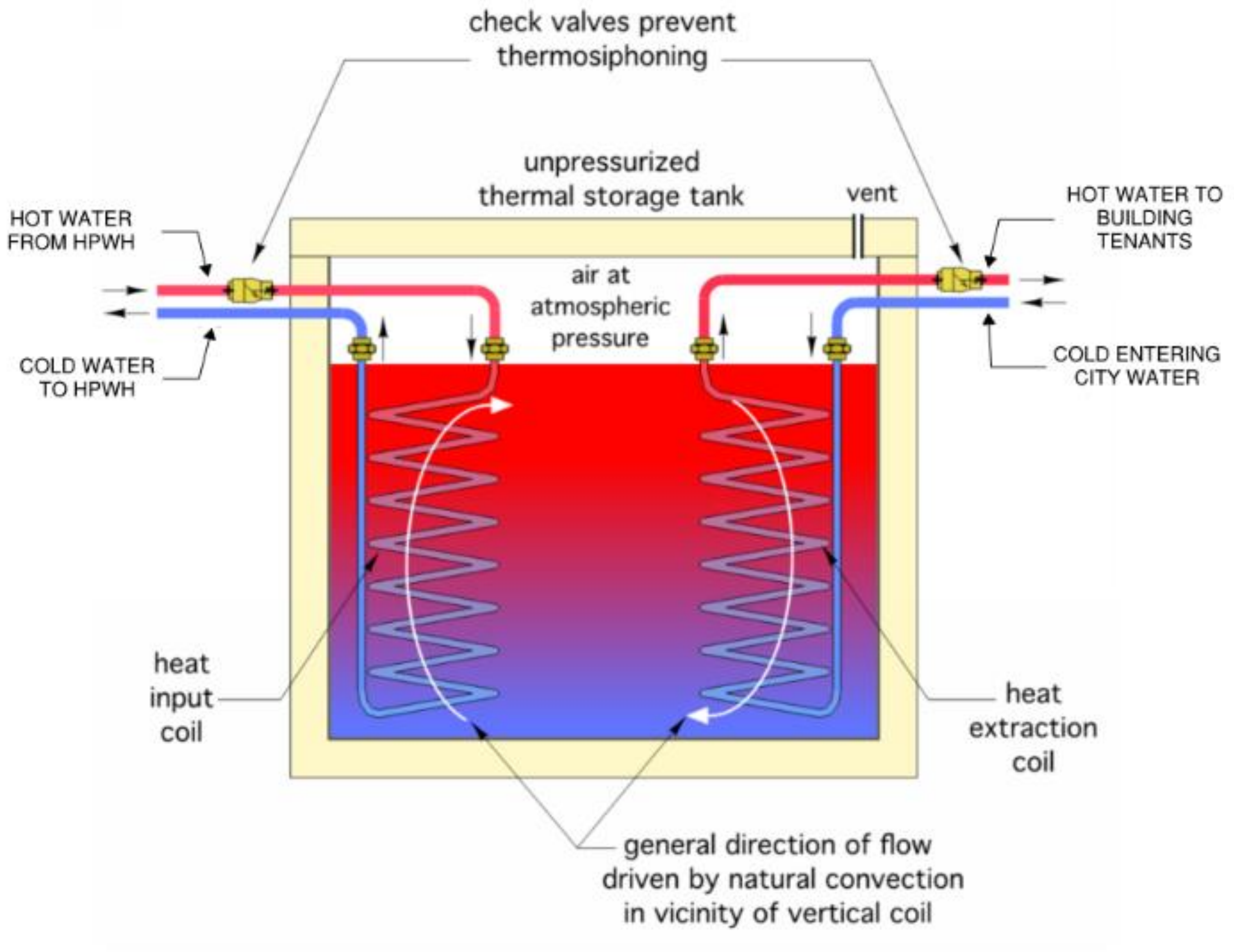

Figure 10. Unpressurized TES with copper coil heat exchangers. Courtesy of John Siegenthaler HYDROsketch

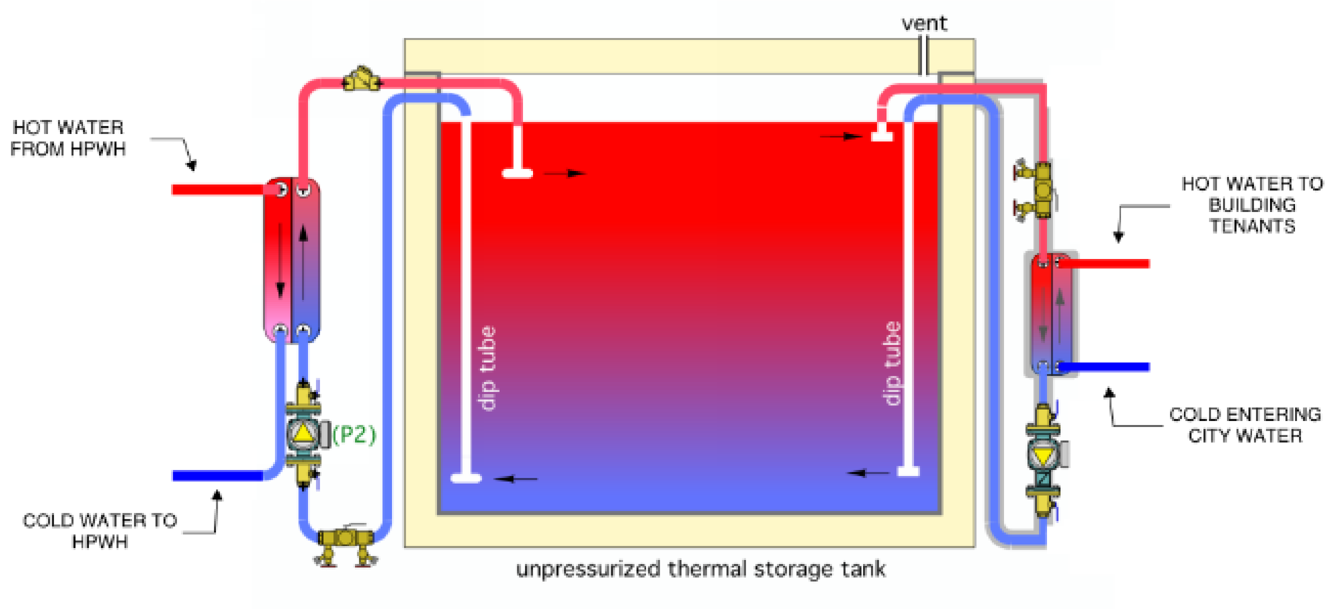

Figure 11. Unpressurized TES with brazed plate heat exchangers. Courtesy of John Siegenthaler HYDROsketch

Future Research

Further research needs to be done to optimize TES design. Small changes in fitting placement and piping design can provide significant increase in TES performance of pressurized systems. Research can help quantify those benefits and create an economic case for tank manufacturers to start building tanks designed for use with HPWHs. To further reduce TES costs, easily deployable unpressurized TES should be developed for HPWH systems.

A key to improving TES system designs is to include detailed monitoring that can be used to understand performance of installations. Ecotope has developed an algorithm that can plot temperature profiles using temperature sensors installed as part of measurement and verification (M&V) projects. The temperature profiles can be used to compare TES performance in installations with different designs.

For each timestep, the algorithm plots the temperature of each temperature sensor on the x-axis and the position of each temperature sensor relative to the center of the thermocline on the y-axis, known as the volume fraction. Volume fraction is the fraction of the total tank volume. In a 500-gallon tank, a volume fraction of 0.2 means the temperature sensor is 100 gallons above the center of the thermocline. Volume fractions can be negative if the temperature sensor is below the thermocline when the point is recorded. A negative 0.2 volume fraction in a 500-gallon tank means the temperature sensor is 100 gallons below the thermocline.

Figures 12, 13, and 14 show temperature profiles developed from tank temperature data using the algorithm. Plotted points are in a color scale from blue to red. Bluer dots are from temperature sensors lower in the tank. Redder dots are from temperature sensors higher in the tank. Figure 12 is developed from a single tank using lab test data. Figure 13 and Figure 14 are from field M&V sites showing a series and parallel system respectively.

The plots shown in Figures 12 through 14 can be used to calculate a stratification coefficient. Stratification coefficient is the stratification performance compared to a perfectly stratified tank.

However, storage size, piping configuration, insulation, and time of charging and discharging all affect stratification coefficient. The systems plotted in Figures 12 through 14 are different enough that more data from more sites is needed before confident conclusions can be drawn and changes to the Ecosizer can be made. Creating similar plots for future installations will help assess different TES strategies to build a case for improving TES tank designs and improvements to the Ecosizer.

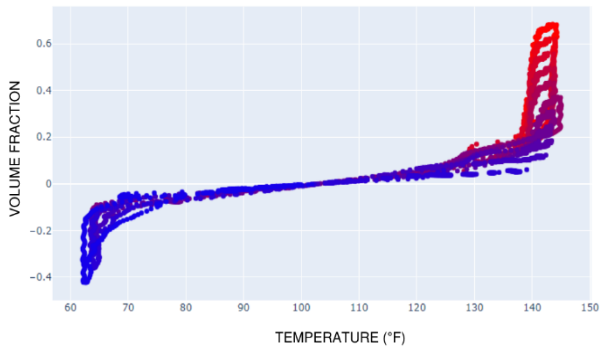

Figure 12. Temperature profile developed from single tank using lab test data

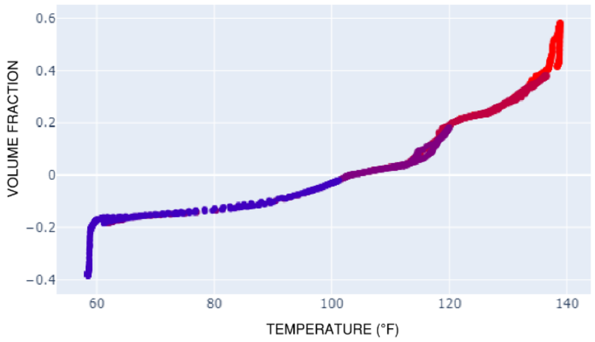

Figure 13. Temperature profile developed from series piped system using M&V data

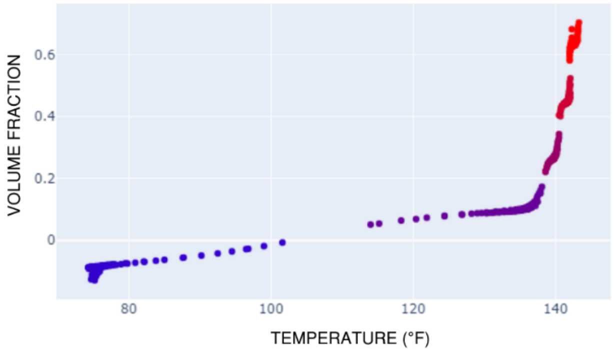

Figure 14. Temperature profile developed from parallel piped system using M&V data

Conclusions

Ecotope sees several next steps to refine TES design which will reduce HPWH system cost and increase adoption. Improving pressurized storage design and developing unpressurized storage will reduce HPWH system cost and increase adoption.

The Ecosizer should be updated with new inputs for stratification, thermal losses, and drawdown factor to provide more detail on TES design. With data collected from M&V sites and lab testing, Ecotope can assess the effects of different design configurations and create default inputs for typical designs – allowing designers to quickly input designs and realize savings.

In parallel, Ecotope needs to partner with a manufacturer to develop unpressurized TES. Unpressurized storage, while not currently in use, has potential to substantially reduce cost and open the HPWH market in a significant way. In addition to reducing cost, unpressurized storage can allow for improved freeze protection, less wear on HPWH equipment, no expansion tank, and designs more suitable to high-rise buildings.

In HPWH system installations today, TES is either the most expensive component, or the second most expensive component after the HPWH itself. More thoughtfully designed TES, and an updated, more accurate Ecosizer algorithm can bring TES costs down by tens of thousands of dollars off each HPWH installation. That, in turn, should dramatically increase adoption of these energy efficient hot water solutions.

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