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Emerging Technologies

Domestic Hot Water Distribution Heat Loss

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Acronyms

DCW – Domestic Cold Water

DHW – Domestic Hot Water

HPWH – Heat Pump Water Heater

TM – Temperature Maintenance

TMV – Thermostatic Mixing Valve

UA – Thermal transmittance (U, constant that determines how well an object transfers heat) multiplied by surface area (A)

Executive Summary

Domestic hot water (DHW) distribution heat loss is the heat wasted as DHW is delivered and circulated throughout a building and it accounts for about 30% of the total domestic water heating required in typical multi-family buildings[i]. In addition to being wasted heat energy, recirculated warm water presents design challenges and drives down the overall performance of heat pump water heating systems. The goal of this study is to create a method to predict the DHW distribution heat loss in buildings with central DHW heating systems and define strategies to minimize it.

After interviewing several designers and installers, it's clear that even though distribution heat loss has a significant impact on energy usage, it's not a chief concern in DHW system design. There are no uniform best practices for designers or installers to calculate and minimize heat loss, and the accuracy of calculated heat loss is rarely verified after installation, which would help improve future design and installation practices.

The first challenge we addressed was finding a simple method to predict distribution heat loss. A simulation program was created to better understand the DHW flow, temperature, and heat loss rate through every unique section of pipe in a DHW distribution system and a simplified heat loss calculator was also created to make it easy for a designer to input the required information while maintaining calculation accuracy.

While the calculator predicts the heat loss of an ideally insulated DHW system, the relative heat loss between an actual system and ideal system varies significantly between projects. The possible reasons for this were hypothesized through installer interviews and site photos, and design suggestions are outlined to mitigate these inconsistencies while providing more reliable DHW delivery at a lower rate of heat loss.

Further research is needed to weigh the impact of each factor that drives inconsistencies between calculated and actual heat loss. This can be accomplished through lab testing of specific piping configurations and accessories in addition to targeted monitoring studies that follow a project through design, installation, commissioning, and occupied phases.

If backed by proper research, there are several measures outlined in this paper that can significantly reduce the energy wasted in the DHW distribution system and increase reliability of DHW delivery without further complicating plumbing design or installation.

Understanding the DHW Distribution Loop

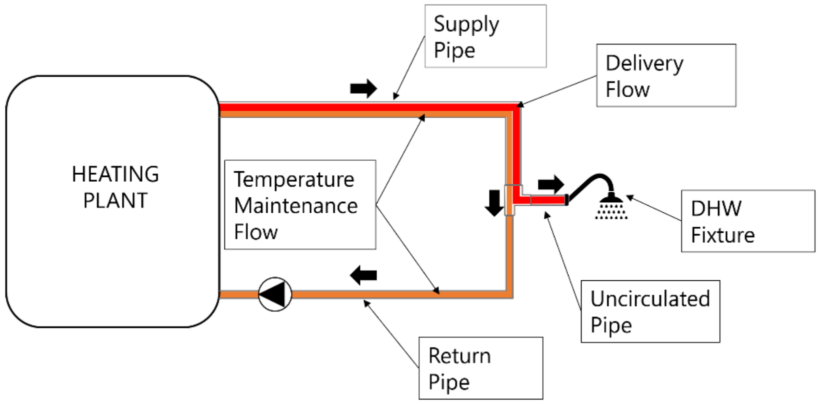


Figure 1. DHW distribution loop

DHW Distribution Loop Overview

The primary goal of a DHW system is to deliver hot water at a consistent temperature to every DHW fixture in the system that serves the building occupants, such as a sink or a shower head, in a reasonable amount of time. The equipment that heats and stores the DHW is called the heating plant. Since many large DHW systems have one central heating plant to serve the entire building, the DHW must travel a significant distance to each fixture through a supply pipe. If there is not consistent usage at the DHW fixture, DHW in the supply pipe becomes stagnant and begins to cool. To ensure recently heated water is always available to the fixtures, a DHW distribution loop is designed to consistently pump hot water through the supply pipe and return it back to the heating plant through a return pipe. See **Figure 1. DHW distribution loop** for an example of this loop. Since it is impractical to tap every fixture directly into the DHW distribution loop, there is a short uncirculated pipe that runs from the DHW distribution loop to each DHW fixture. The water in this pipe is not circulated, so it will cool down when the DHW fixture it serves is not in use.

Flow in the DHW Distribution Loop

The DHW distribution loop contains two simultaneous DHW flows. The first flow is the water that is delivered to the DHW fixture, called delivery flow ($\text{Flow}_{\text{Delivery}}$). The second flow is the water that is circulated to maintain the DHW distribution loop temperature, the temperature-maintenance flow (Flow_{TM}). The delivery flow and temperature-maintenance flow account for the total flow ($\text{Flow}_{\text{Total}}$) in the distribution loop.

The mixture of delivery flow and temperature-maintenance flow must reach the DHW fixture before it cools to an unacceptable temperature and must exceed a minimum flow rate (Flow_{Min}) to do so. If the DHW fixture is drawing 1gpm but the total flow must exceed 2gpm to reach the DHW fixture before it over-cools, the temperature-maintenance flow must make up the additional 1gpm to satisfy the 2gpm minimum flow rate. If the fixture is drawing more than 2gpm, the delivery flow will travel quickly enough on its own to avoid over-cooling. The delivery flow exits the loop through the fixture while the temperature-maintenance flow travels back to the heating plant through the return pipe to be reheated.

$$\text{Flow}_{\text{Total}} = \text{Flow}_{\text{Delivery}} + \text{Flow}_{\text{TM}}$$

$$\text{Flow}_{\text{Total}} \geq \text{Flow}_{\text{Min}}$$

DHW Distribution Heat Loss

All the heat loss in the DHW loop is heat being transferred from the DHW to the surrounding air or building materials that come in contact with the pipe. Delivery flow will experience Delivery Heat Loss (Q_{Delivery}) as it travels to the fixture, while the temperature-maintenance flow experiences Temperature Maintenance Heat Loss (Q_{TM}) throughout the entirety of the loop, as illustrated in Figure 2. DHW distribution heat loss.

To make up for the delivery heat loss, the delivery flow must leave the heating plant at a higher supply temperature (T_{Supply}) than is required at the fixture for use (T_{Usage}). Temperature-maintenance flow and delivery flow leave the heating plant as a uniform mixture, so they have the same supply temperature. Temperature-maintenance flow cools as it travels through the entire DHW distribution loop and returns to the heating plant at a lower temperature (T_{Return}).

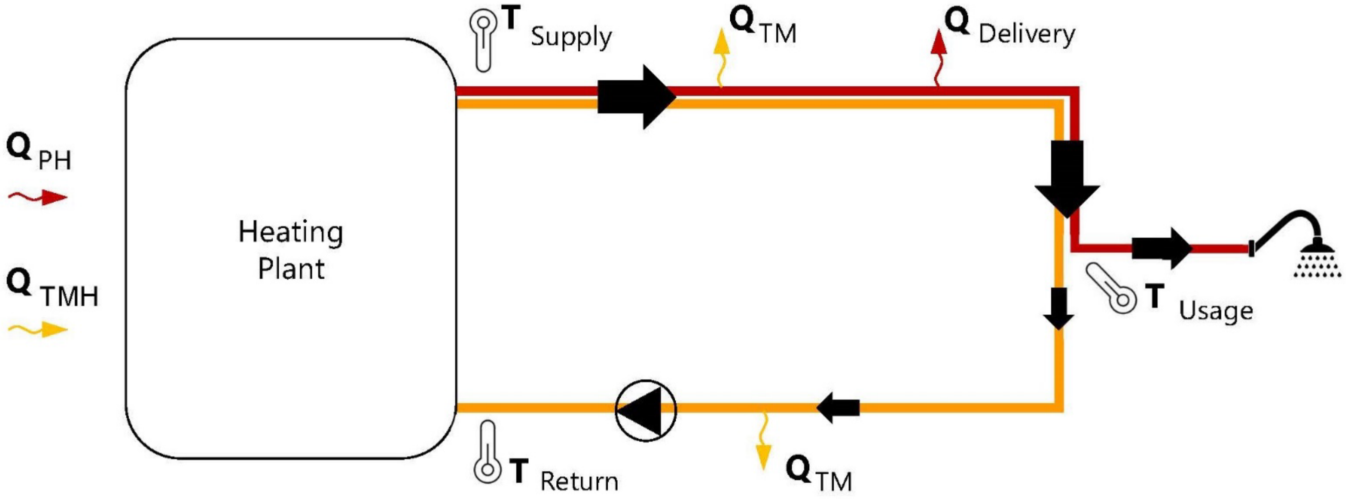


Figure 2. DHW distribution heat loss

Even though the delivery flow and temperature-maintenance flow are part of a uniform mixture with the same temperature and flow velocity, they make up different portions of the pipe's total volume, so they have independent flow rates that drive different heat loss rates. The temperature maintenance heat loss and delivery heat loss combine to make up the Total Heat Loss (Q_{Total}) in the DHW distribution loop. In any section of pipe, the portion of temperature-maintenance flow that makes up total flow is equal to the portion of temperature maintenance heat loss that makes up total heat loss. The relationship between each type of flow and heat loss in any section of pipe can be characterized by the following equations and visualized in Figure 3.

$$Q_{Total} = Q_{Delivery} + Q_{TM}$$

$$Q_{TM} / Q_{Total} = Flow_{TM} / Flow_{Total}$$

$$Q_{Delivery} / Q_{Total} = Flow_{Delivery} / Flow_{Total}$$

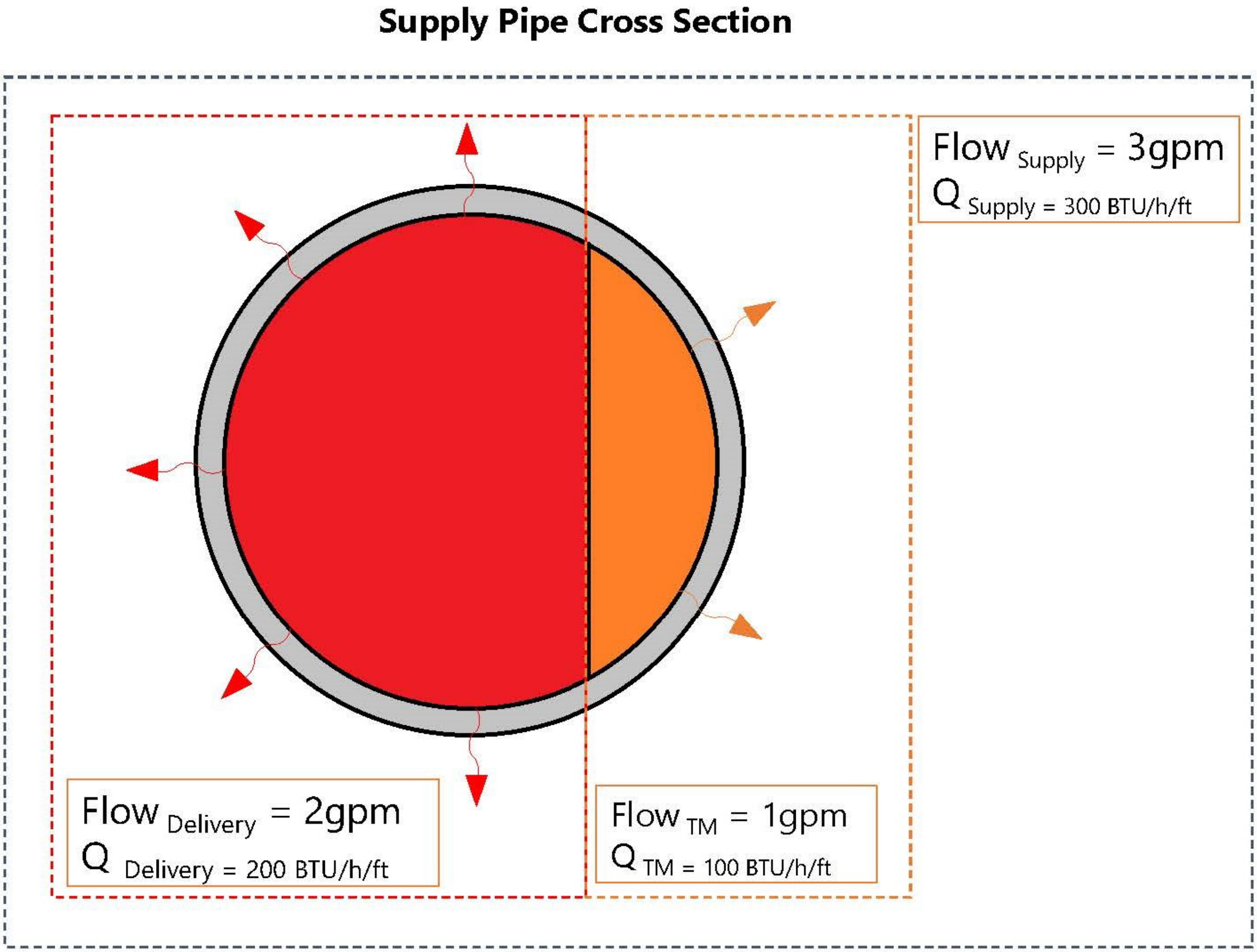


Figure 3. Ratio of TM and delivery

Dedicated Heating Plants

It is important to quantify the temperature maintenance heat loss and delivery heat loss separately because the temperature-maintenance flow is heated with dedicated Temperature Maintenance Heating equipment in some applications. The delivery flow is then heated with larger Primary Heating equipment. In this case, Primary Heating (Q_{PH}) makes up for delivery heat loss, while the Temperature Maintenance Heating (Q_{TMH}) makes up for temperature maintenance heat loss, as illustrated in Figure 4.

Circulated Branches

All descriptions up to this point have considered a single loop serving a single DHW fixture to establish a clear understanding of the flow and heat transfer in the loop. In practice, a large DHW distribution loop will serve several fixtures with several smaller loops circulating throughout the building, as illustrated in Figure 5. Each smaller loop that serves a group of fixtures is called a branch.

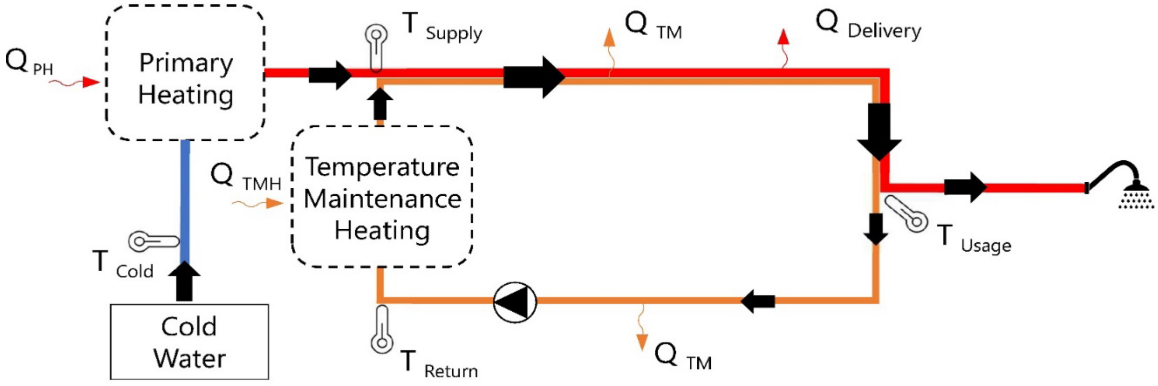


Figure 4. Dedicated heating plants

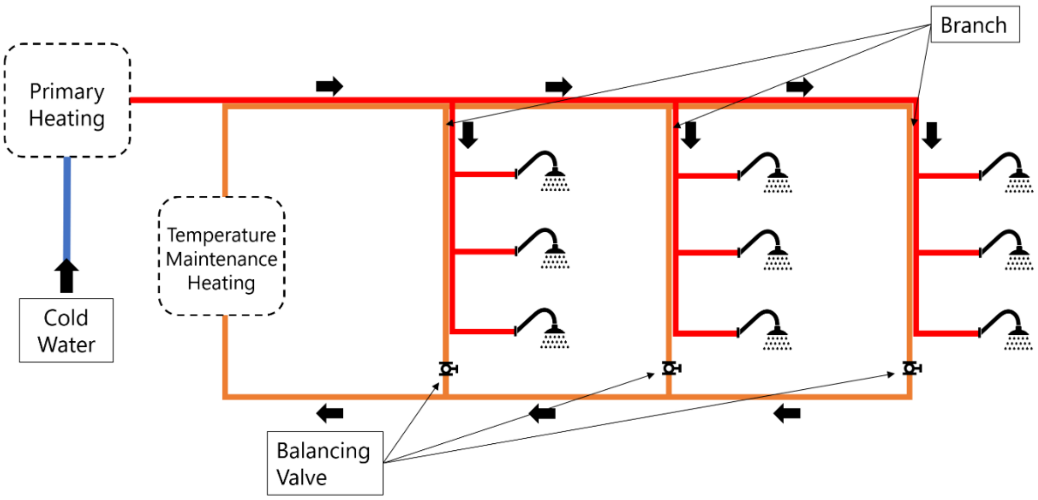


Figure 5. Circulated branches

The temperature-maintenance flow and delivery flow still travel through a supply pipe, but then split into separate branches throughout the building. Though there are additional flow considerations, the general principles are the same.

Balanced Branch Flow

The DHW distribution loop must maintain a minimum water temperature that's served to each fixture. Since some fixtures are much farther away from the primary heating source than others, the DHW must travel more quickly to get to them before it has cooled too much. That means there is a unique minimum flow rate required to serve water to each branch. To achieve this unique minimum flow, a balancing valve should be placed at the end of each branch to regulate the temperature-maintenance flow.

DHW Considerations Outside the DHW Distribution Loop

While this study focuses on heat loss in the distribution loop, there are additional aspects that must be considered to analyze and minimize the overall energy usage of the DHW system.

Heating for DHW Usage

DHW heating is largest and most apparent task of the DHW heating plant. This is the heating of cold city water up to the supply temperature that is delivered to the DHW distribution loop.

Heating Plant Heat Loss

Since there are often large hot water storage tanks in the DHW heating plant, as well as DHW pipe circulating water between heaters and storage tanks, there is quantifiable heat loss in the DHW heating plant that should not be ignored.

Uncirculated Pipe Heat Loss

The uncirculated pipe that delivers DHW from the distribution loop to the fixture will experience variable heat loss and is often not insulated. The water in this pipe cools to ambient temperature when the fixture is not in use, and all the cool water is flushed down the drain when an occupant requires hot water. When the fixture is in use, there is more constant heat loss from DHW flow that is being delivered. The only way to accurately measure this is to measure the flow and temperature of every fixture, which was not feasible for this study.

DHW Heater Efficiency

The energy required to heat water is widely variable and depends on the technology used as well as the environmental conditions. While the water heater efficiency does not directly affect the distribution heat loss, it can drastically affect the amount of energy required to make up for it.

Minimizing Energy Usage with Heat Pump Water Heaters

As the global community looks for technological solutions to minimize carbon emissions that are fueling the climate crisis, transitioning residential and commercial DHW from fossil fuel to heat pump water heater technology will be a likely focus. HPWH systems are a stable solution to minimize greenhouse gas emissions because they use electricity to harvest heat from the air, which circumvents the need to burn fossil fuels directly for DHW heating and minimizes electricity usage that may result in burning fossil fuels for electricity generation.

HPWH systems heat water two to four times more efficiently than an electric or gas water heater, and they run most efficiently when tasked with heating cold water to a high temperature in a single pass. This makes them great candidates for efficient primary heating because primary heating is tasked with heating DCW up to a specific supply temperature. Temperature-maintenance heating heats the temperature-maintenance flow from a warm return temperature (T_{Return}) back up to supply temperature, so a HPWH system must be designed very specifically to provide temperature-maintenance heating efficiently and reliably. A temperature maintenance heat pump is still more efficient than a conventional gas or electric resistance heater, but its efficiency can be further maximized if the distribution loop is designed to minimize temperature maintenance loss. Ecotope has worked with the Northwest Energy Efficiency Alliance (NEEA) to inform the Advanced Water Heating Specification, which illustrates proven HPWH system configurations that can efficiently and reliably provide primary and temperature-maintenance heating. Further discussion on these configurations can be found in Appendix A.

Quantifying Distribution Heat Loss

The DHW distribution heat loss, in its simplest form, is the transfer of heat out of the DHW in the distribution loop through the distribution pipe walls and out to the surrounding environment. You can calculate two things: heat transfer through the pipe walls or heat loss from the water flow via DHW temperature change.

Calculating DHW Distribution Heat Loss in Existing Systems

Each form of DHW distribution heat loss in existing systems can be calculated using DHW temperature and flow measurements.

Delivery Heat Loss

The delivery flow enters the DHW distribution loop at supply temperature, loses heat as it travels through the supply pipe, and leaves the DHW distribution loop at usage temperature. The rate of heat loss from the delivery flow can be measured using the following equation, derived in Appendix B:

$$\dot{Q}_{Delivery} = Flow_{Cold} * \rho * C_p * \left(\frac{T\ Supply - T\ Return}{2}\right)$$

Temperature Maintenance Heat Loss

The temperature-maintenance flow enters the DHW distribution loop at temperature T_{Supply}, loses heat as it travels through the distribution loop, and returns to the heating plant at temperature T_{Return}. The rate of heat loss from the delivery flow can be measured using the following equation:

$$\dot{Q}_{TM} = Flow_{TM} * \rho * C_{P} * (T_{Supply} - T_{Return})$$

Total Heat Loss

The total heat loss in the DHW distribution loop is the sum of temperature maintenance and delivery heat losses:

$$\dot{Q}_{Total} = \dot{Q}_{Delivery} + \dot{Q}_{TM}$$

Points of Measurement

The proper locations of flows and temperatures that drive heat loss calculations are illustrated in Figure 6 below.

This is the first figure that has included a thermostatic mixing valve (TMV). The TMV is a negligible source of heat loss and does not add heat to the system. Even so, the DCW flow to the mixing valve must be included in the flow measurement to ensure the DCW flow accurately represents the DHW usage.

Calculating DHW Distribution Heat Loss in Plumbing Designs

Calculating distribution heat loss will help a designer gauge the wasted energy in a DHW distribution system, which can drive more targeted efforts to minimize it.

DHW Pipe Size and Temperature

Each section of pipe in the DHW distribution loop is sized to accommodate the maximum probable flow rate of all fixtures downstream, so the pipe size will change throughout the distribution loop. Since each pipe section is a unique size and carries a unique flow rate, each pipe section has a unique temperature and heat loss rate. The figure below illustrates the division of the DHW distribution loop required to calculate total DHW distribution loop heat loss most accurately. Each node, shown as a black oval in the Figure 7. Separated pipe sections (next page), connects the end of

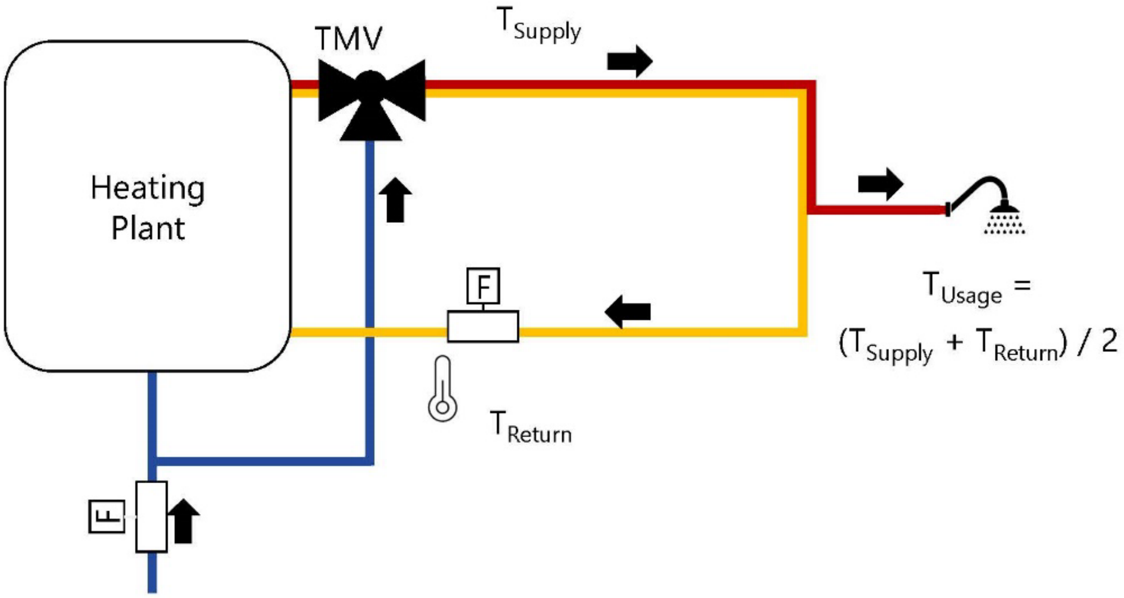


Figure 6. Measurement locations

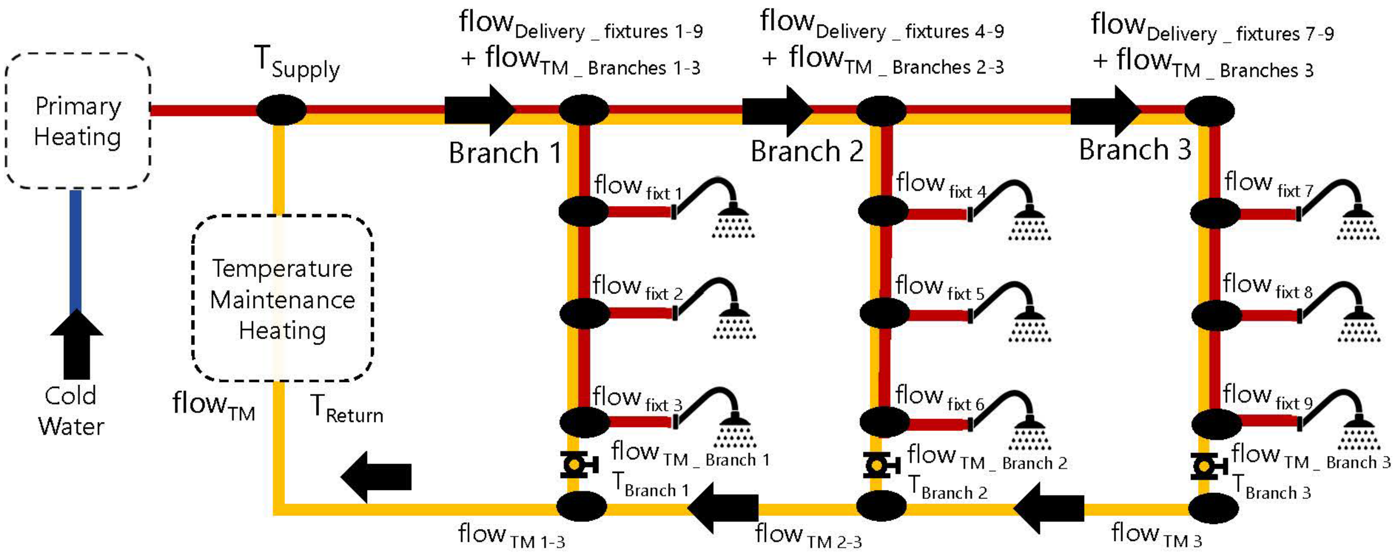


Figure 7. Separated pipe sections

one pipe section to the beginning of the next.

DHW Distribution Loop Simulation

A program was created that simulates the DHW distribution loop and captures the interaction between flow, temperature, and heat loss in each section of DHW distribution pipe. This program was inspired by the tool created for a research study conducted for the California Energy Commission, “Multifamily Central Domestic Hot Water Distribution Systems[ii].” The program performs a nodal analysis to calculate the heat loss of each pipe section and simulates branch balancing by iteratively adjusting the temperature-maintenance flow through each branch until a target DHW temperature is achieved at each balancing valve. This emulates a process a technician would have to perform with manual balancing valves, or a process thermostatic balancing valves would go through automatically. The program calculates the temperature and total flow at each node, which can be used to calculate the heat loss in each pipe section and further calculate the delivery heat loss, temperature maintenance heat loss, and total heat loss. A further explanation of the simulation tool’s calculation methodology can be found in Appendix C.

This program methodology has great potential if included as part of a simulation package that calculates pipe sizes and pressure drops in a DHW system. When considering the work required to input all the necessary data, as well as the special considerations and experience required for proper implementation, this tool may not be feasible for widespread adoption as a stand-alone calculator to find DHW distribution heat loss. It has been extremely valuable, however, in gaining a better understanding of the effects of branch balancing and interactions between temperature-maintenance flow, delivery flow, and return temperature. It also played a very important role in validating assumptions made for a much simpler heat loss calculation.

Simplified DHW Distribution Heat Loss Calculator

A simplified, user-friendly DHW distribution heat loss calculator was created and provided to Bonneville Power Administration to publish alongside this report. This calculator requires the user to input just three pieces of information: the total length of each pipe size; the supply temperature; and the target branch temperature. The calculator assumes the entire DHW distribution loop is equal to the average pipe temperature. This allows a single heat loss calculation for the total length of each size of pipe. The actual temperature throughout the distribution loop will vary between T_{Supply} and T_{Return}, but if the user follows proper design guidelines described later in this paper, the simplified heat loss calculator yields a distribution heat loss within a 5% error of the simulation program.

The simplified calculator also calculates total UA per apartment (UA/Apt). UA characterizes how much heat a section of pipe will lose, which is based off rate of heat transfer through the insulation (U) and pipe surface area (A). A high UA value associated with a section of pipe equates to a high rate of heat loss when that pipe carries hot water. UA calculation is outlined in Appendix D. UA/Apt can serve as a valuable tool to evaluate the efficiency of DHW distribution system designs by providing a simple number that compares the total surface area and insulation value of pipe required to serve each apartment.

Comparing Calculations to Real Buildings

The previously described heat loss calculations will simulate the heat loss of perfectly insulated DHW pipe, but in practice it is not possible to maintain perfectly insulated pipes throughout the entire DHW distribution system. Several steps were taken to better inform the difference between calculated heat loss and actual heat loss in buildings.

Unquantified Heat Loss

Several designers and installers were interviewed to help inform a better understanding of instances where pipes cannot be installed with continuous insulation. Installation photos of several buildings were also examined to find additional breaks in insulation that installers may not have mentioned in interviews. Non-continuous insulation has been observed in the following instances:

- Uninsulated pipe hangers and riser supports
- Pipe penetration through floor joists and headers between floors
- Branches from insulated, circulated pipes to uninsulated, uncirculated pipes – this causes natural convective heat loss between hot, circulated water and cool, uncirculated water.

There are additional scenarios that prevent an accurate calculation based on design drawings:

- Pipe routing deviates from plumbing drawings to avoid physical obstacles

- Pipe installed in ventilated space with temperatures and air flows unknown by the plumbing designer
- DHW temperature fluctuates due to improperly commissioned or ill-maintained pumps and mixing valves
- Imperfect branch balancing that drives unpredictable DHW temperature.

UA Multiplier

We will discuss prevention measures that can minimize some unquantified heat loss through design best practice, but even so, the insulation and installation of DHW distribution pipes will never be perfectly consistent with plumbing design drawings. Therefore, a factor must be applied that aligns the calculation of perfectly insulated pipe in a design drawing with the reality of what is installed in a building. Since imperfections in pipe insulation vary from building to building, a multiplier can be applied to the UA calculation that will effectively assign an insulation quality to the entire DHW distribution system and proportionally increase the calculated distribution heat loss, so it aligns with the actual heat loss.

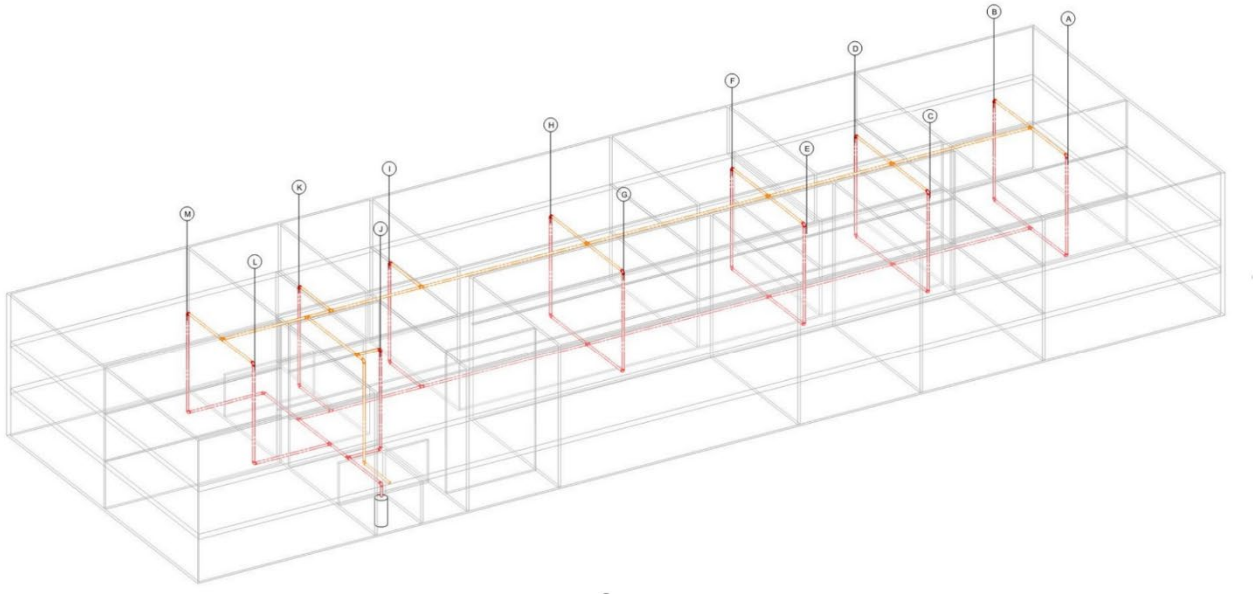


Figure 8. Representative distribution loop layout

Building Heat Loss Comparison

Monitoring equipment was installed on two multi-family buildings to calculate their observed DHW distribution heat loss and each building's design drawings were analyzed to inform a theoretical heat loss calculation. The comparison of the calculated and observed heat loss informed a unique UA multiplier that would be applied to each building to align the calculated and observed heat loss.

Building Overview

Two separate buildings, referred to as buildings A and B, were monitored for several weeks. Both are multi-family buildings with circulated DHW distribution loops and a central heating plant. A supply pipe on the bottom floor of each building serves several DHW branches, or risers, that connect to a return pipe that sends temperature-maintenance flow back to the DHW plant for heating. The temperature-maintenance flow is driven by a constant speed circulation pump and the branches are balanced by manual balancing valves. A simple version of the DHW distribution loop design is illustrated in Figure 8 below.

Building A

Building A is a relatively large building with 384 apartment units located in Seattle, WA. Monitoring equipment was installed in the locations recommended in figure 6.

Building A uses a digital mixing valve that provides a relatively stable supply temperature to the building. Supply temperature ranged from 120-127°F and usage temperature ranged from 117-122°F.

A UA multiplier of 1.35 was applied to Building A to align the actual temperature maintenance loss to the calculated temperature maintenance loss, with a 0.7% error. This resulted in an error in total calculated heat loss of 0.1% and an error in delivery heat loss of less than 9%. The delivery heat loss makes up less than 10% of the total DHW distribution heat loss, so the higher error in delivery heat loss did not contribute significantly to the error in total heat loss.

Building B

Building B is a much smaller building with 71 apartments, also located in Seattle, WA. Supply and return sensors and a temperature flow meter were installed to measure temperature maintenance heat loss, but there was not proper clearance in the existing plumbing to measure DCW flow. The ratio of average delivery flow to apartment count at Building B was assumed to be equal to Building A, which resulted in an average assumed delivery flow of 1 gpm.

The mixing valve at Building B was much too large for the size of the building and was not installed per the manufacturer’s recommendation, which resulted in extremely variable supply temperatures.

A UA multiplier of 1.95 was applied to align the actual temperature maintenance loss of Building B to the calculated temperature maintenance loss, with a 0.1% error. This resulted in an error in total calculated heat loss of 0.02% and an error in delivery heat loss of 0.3%. This multiplier is much higher than the Building A’s UA multiplier. Despite a lower average DHW temperature, Building B’s observed average temperature maintenance loss as a ratio of total pipe area (UA) is much higher than in Building A. This instills greater confidence in the higher UA multiplier applied to Building B.

The assumed delivery flow does impact calculation of delivery heat loss, which would contribute to a worst-case calculation error in total heat loss if the actual average delivery flow of Building B was 0 gpm. This flow would lower the required UA multiplier to 1.53. Since the building was occupied at the time of monitoring, it is safe to assume the average delivery flow was not this low.

Driving Factors of Different UA Multipliers

Differences between Building A and Building B that likely contributed to the higher UA multiplier include the following:

- A DHW pipe ran the entire length of the garage at Building B, outside of conditioned space. This contributed to a higher ΔT between the pipe and surrounding environment, and likely increased convective heat loss.
- Uninsulated pipe hangers were used at Building B that cause thermal bridging from the DHW pipe to the mounting surface.
- State of insulation inside the walls was unknown, but poorly insulated DHW pipes inside the walls would contribute to a higher required UA multiplier.

Extreme Observed Heat Loss Fluctuations

Instances of extremely high heat loss were observed over some short time periods due to the transient nature of the DHW system. Whenever there was a rapid increase in delivery flow, there was a rapid increase in supply temperature before the mixing valve was able to re-adjust its mixing ratio to achieve setpoint temperature. There was also a rapid increase in temperature-maintenance flow that accompanied the increase in delivery flow. Intuitively, the increased supply temperature and temperature-maintenance flow should cause a sudden increase in return temperature. It takes time for the temperature-maintenance flow to work its way around the building and register as a higher return temperature, so there is a short period of time where the supply temperature and temperature-maintenance flow are disproportionately higher than the return temperature, which drives up the observed temperature maintenance heat loss for a short period. Shortly after the spike in the observed temperature maintenance heat loss, the supply temperature settled back down, abnormally warm temperature-maintenance flow from the previous supply temperature spike reached the return temperature sensor and drove the observed temperature maintenance heat loss down below average. These fluctuations offset each other to some extent. The transient nature of this calculation means it is essential to measure the average temperature maintenance heat loss over a longer time period instead of relying on a single measurement that is potentially inside a large short-term calculation spike.

DHW Distribution Design Best Practice

There are several ways to minimize heat loss in the DHW distribution loop, but it is important to remember that minimizing heat loss is not the only goal of an ideal DHW distribution design. The top priority of the designers and installers interviewed is the ability to consistently deliver DHW to occupants without fail. Designers want to ensure hot water is delivered warm enough and at a sufficient pressure, while installers are interested in using reliable components that minimize cold water complaints.

Thirty-nine percent of the water heating required in building A, just under 70 Watts per apartment, accounted for temperature maintenance and delivery flow heating. This is still lower than the median heat loss of a typical DHW loop shown in recent research, 93 Watts per apartment[iii]. This is a significant amount of wasted energy that should be addressed in the design process.

Below are several best practices a designer should implement when designing a DHW distribution system to minimize heat loss and maximize occupant satisfaction. Several of these best practices are accompanied by potential energy savings based off their estimated UA reduction in a prototype mid-rise mixed-use multi-family building[iv].

Heat loss calculations for perfectly insulated pipe in the prototype building that includes Appendix M sizing, modest insulation increase, and optimized plumbing loop design, showed only 17 Watts per apartment heat loss. When accounting for less-than-perfect installation of insulation, offset by heating efficiency more than 200% utilizing heat pump water heaters, these design guidelines should yield DHW distribution design that consistently draws less than 25 watts per apartment, only ¼ of a typical building today.

Heat Pump Water Heaters

HPWH's do not technically minimize DHW distribution heat loss, but they significantly minimize the energy used to make up for the DHW distribution heat loss. The DHW heating plant's primary design consideration, aside from (and including) providing hot water to the occupants, should be to provide proper conditions for reliable and efficient HPWH operation.

Because of the HPWH's high efficiency, a properly designed HPWH system can reduce the energy required to make up for DHW distribution heat loss by over 60%.

Thermostatic Balancing Valves

Thermostatic balancing valves in each branch allow a consistent temperature to each branch, regardless of delivery flow. They will decrease temperature-maintenance flow when there is an increase in delivery flow, which will maintain a more consistent flow rate that results in a more consistent DHW temperature served to the branch. They also minimize temperature maintenance losses because temperature-maintenance flow is only circulating as needed. Minimizing return temperature and temperature maintenance heat loss will also maximize the efficiency of DHW systems using HPWHs or condensing gas boilers because it minimizes the water temperature entering the heating equipment.

Thermostatic balancing valves have the potential to decrease temperature maintenance heat loss by over 30% during moderate- to high-flow events. Research should be conducted on real buildings that implement thermostatic balancing valves to better quantify the real-world reduction in temperature maintenance heat loss and ensure the reliability of this technology. Researchers can compare existing data of buildings with manual balancing valves and acquired data of installations that employ thermostatic balancing valves, in addition to interviewing the installers to gauge the difference in difficulty and cost of installation. This will help inform appropriate measures to drive their adoption.

Thermostatic Mixing Valve

It is important to properly size the thermostatic mixing valve according to the manufacturer's recommendations and include a mixing valve detail in the drawings that is specific to the scheduled manufacturer. Additionally, it is recommended to detail a hose bibb and temperature gauge on the mixing valve outlet so supply temperature can be tested, as well as detailing ball valves on the inlets and outlets so the mixing valve can be isolated for maintenance.

Temperature creep of over 20°F has been observed in the field, which could increase distribution heat loss by over 40%. Unreliable supply temperature could not only increase distribution heat loss, but it could also pose a safety hazard for the occupants.

Mixing valves sized for the max building flow rate calculated per Appendix M of the Universal Plumbing Code are far less likely to be oversized, which would drive more ideal mixing operation. A study should be conducted that compares mixing valve sizing using both Hunter's Curve and Appendix M, followed by flow monitoring that tracks delivery temperature and actual building flow. This would help build designer confidence that sizing mixing valves per Appendix M will result in correctly sized mixing valves.

DHW Temperature

A small temperature differential between the supply temperature and balancing valve temperature will ensure steady delivery flow temperature to all fixtures. If the supply temperature is set to 120°F with a target temperature at the thermostatic balancing valve set to 115°F, the average DHW temperature in the DHW distribution loop will be relatively low.

Decreasing the DHW temperature by 5°F can decrease distribution heat loss by 5-10%. This will also drive a return temperature below 115°F, which is easier and more efficient to heat with a heat pump water heater.

Size DHW pipes with UPC Appendix M

Appendix M of the uniform plumbing code has been proven as a reliable method to size DHW distribution pipes that results in smaller pipe diameter and lower UA. Sizing with Appendix M minimizes the wait times for hot water as well because there is less cooled water in uncirculated pipes that must be flushed out when a DHW fixture is used. Appendix M has not been adopted by a lot of jurisdictions, but data is accumulating, and education is spreading that is making way for its adoption at a larger scale.

When Appendix M is applied to the prototype mixed-use building, the UA value, and resulting heat loss, decreases by 3%. The reason this decrease in heat loss is so insignificant is because several hundred feet of pipe decrease in diameter from 1.5" to 1". Current plumbing code requires 1.5" thick insulation on 1.5″ pipes, but only requires 1″ insulation on 1″ pipes. Therefore, the concurrent decrease in pipe surface area and insulation thickness offset each other.

If the required insulation thickness of pipes under 1.5″ diameter is set equal to that of pipes greater than 1.5″ diameter, a modeled shift to Appendix M results in a 19% heat loss reduction. A cost analysis should be performed that evaluates the lesser cost of smaller pipes and higher cost of thicker insulation to determine the predicted change in cost for an installer to implement this change, which could easily be driven by an energy efficiency measure.

Riser and Fixture Location

If risers are located on shared walls and fixtures are located on the same shared walls, a single riser can serve two apartments per floor. This will greatly reduce the pipe length required to distribute DHW, which will minimize heat loss, material cost, and labor cost. Early coordination with the architect is necessary to facilitate fixture location.

Serving two stacks of apartments with a single riser in the mixed-use prototype building yielded a decrease in heat loss by over 30%. A measure should be implemented and accompanied by design guidelines that encourages an optimized floor layout to minimize circulated pipe length without increasing uncirculated pipe length. Experienced designers should work with Architects to create guidelines that appease modern architecture practices and efficient plumbing design.

Intermittent Circulation Pump Operation

While turning off the DHW circulation pump during periods of no flow can decrease TM heat loss, it poses other problems regarding occupant comfort. If the flow sensor is not sensitive enough to sense the flow of a single faucet, an occupant will run a fixture for several minutes without getting warm water, and the minimum flow required for proper mixing through the mixing valve will not be satisfied.

Intermittently cycling a circulation pump in large multi-family buildings shows little benefit because there aren’t any extended periods of time without DHW usage, but commercial buildings with extended periods of vacancy will see DHW distribution heat loss savings that are proportional to the amount of time per day the building is vacant. An office building, for example, that operates 10 hours per day, can see an average decrease in distribution heat loss of over 55% if the circulation pump is scheduled off during the 14 hours of building vacancy. A measure should be implemented for pump scheduling in commercial applications with consistent occupancy schedules but should be avoided in applications like multi-family where there are always occupants present and in need of DHW.

Insulated Pipe Hangers

Insulated pipe hangers allow for mounting of insulated pipes without the interruption of insulation. They also prevent thermal bridging between the insulated pipe and the surface it is being mounted to. Uninterrupted insulation means less heat loss to the surrounding air, while preventing thermal bridging will prevent unnecessary conductive heat loss to the supporting structure.

Lab testing should be conducted to help quantify the difference in heat loss between insulated pipe hangers and "typical" pipe hangers that allow conductive heat transfer between the DHW pipe and mounting surface. Since there are pipe hangers every 3 to 10 ft depending on pipe size and material, a well-informed measure that encourages insulated pipe hangers could have a significant effect on overall heat loss.

Heat Traps on Uncirculated Pipes

Heat traps placed between the circulated distribution loop and uncirculated supply pipes will minimize convective heat loss. There is often an uncirculated pipe that delivers DHW water from a branch (or riser) to the ceiling of each apartment. When there is no DHW usage in the apartment, the water in the uncirculated pipe cools and allows more buoyant, hot water from the circulated loop to float up to the ceiling and replace it. This creates a natural convection of hot water rising into the ceiling of the apartment, and cool water falling into the distribution loop. The heat trap will prevent this unwanted convection, as shown in Figure 9 and Figure 10.

Heat loss from natural convection has not been well documented in DHW systems but is potentially a very high fraction of the difference between calculated and observed heat loss. If every dwelling unit creates an interface between circulated and uncirculated hot water, there are potentially hundreds of occurrences of heat loss that can be easily prevented. Lab testing should be carried out to better quantify this heat loss, which can drive installation measures accompanied by easily deployable design guidelines.

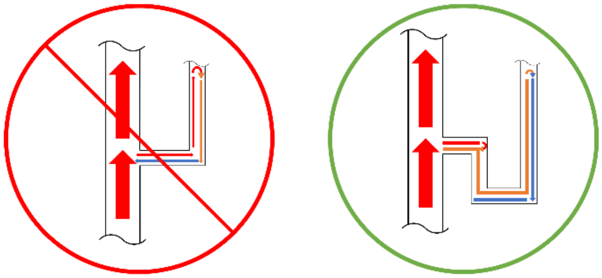


Figure 9. Natural convection in a heat trap

Figure 10. Heat trap installed in a building

Increased Insulation Thickness

Perhaps the most intuitive solution to decreasing distribution heat loss is to increase insulation thickness. 2018 Seattle Energy code now requires an increase in insulation thickness by 1″ on circulated DHW pipe.

This new requirement decreases the estimated heat loss in our modelled mixed-use building by 29%. This can serve as a valuable case study if buildings are properly monitored. Contractors should also be interviewed to address the challenges of fitting pipes with thicker insulation in building walls. This could help create a well-informed measure that could be implemented by jurisdictions across the country.

Commissioning Criteria

Creating a DHW distribution system commissioning checklist and including it in the design documentation will ensure the designer's intent is carried out by the installer. Commissioning criteria should be discussed with the installer early on so the installer can better align with the goals of the designer. A checklist should be created that contains the following criteria to be reviewed by the installer before installation of plumbing and insulation, and reviewed by the commissioning agent after installation of plumbing and insulation:

- Inspect all DHW distribution pipe and take a picture of any sections that do not contain continuous insulation
- Spot check insulation thickness to ensure it complies with the insulation schedule provided on the plumbing drawings
- Check for heat traps on all branches to uncirculated pipe
- Check temperature setting on thermostatic balancing valves
- Measure supply and return temperature and confirm it complies with design drawings
- Test the control functionality of any variable speed or intermittently operating circulation pumps under various building flow conditions
- Measure the time it takes the last water fixture on each branch to receive hot water and note the water temperature.
- Targeted commissioning criteria would not only inform designers and installers of potential improvements, but if well-documented, it could help refine inspection practices to ensure energy-efficient installation in every building. Steps should be taken in a series of pilot buildings that illustrate a clear dialogue between the designer and installer while effectively implementing the energy-efficient practices mentioned above. This will help inform measures that are carefully created with more than energy efficiency in mind. If measures are created that are reviewed and easily implemented by the designer, installer, and inspector, they are much more likely to have a significant impact on the energy efficiency of the building sector.

Communication

Designers should clearly communicate their goal of minimizing the DHW distribution heat loss with the installation and insulation teams because they will be the first to notice any shortcomings of conventionally insulated DHW systems. Installers know the nuts and bolts of the DHW distribution system best. They may also be able to offer creative solutions using reliable products they are familiar with.

Conclusion

Domestic hot water distribution heat loss is a large contributor of energy usage in a DHW system and should not be overlooked by plumbing designers. Not only is it important to consider the heat loss in the DHW distribution loop, but it is important to consider the reliability of DHW delivery at a consistent temperature. If a measure is implemented that minimizes heat loss but does not provide reliable and consistent DHW, that measure will fail. This study devised mechanisms to help designers better predict heat loss in DHW systems, as well as practices they can employ to minimize it while simultaneously improving the reliability and consistency of hot water delivery to the occupant.

DHW distribution heat loss is quantifiable, but several factors of the plumbing design and installation process that vary from building to building contribute to a significant difference between the calculated heat loss of perfectly insulated pipes in design drawings and real-world installations. Employing design and installation best practices outlined in this study will minimize the difference between calculated and actual heat loss, but further research can highlight which of these variables contribute more prominently to the difference between calculation and reality. This research can inform targeted measures to significantly decrease unnecessary heat loss in DHW systems.

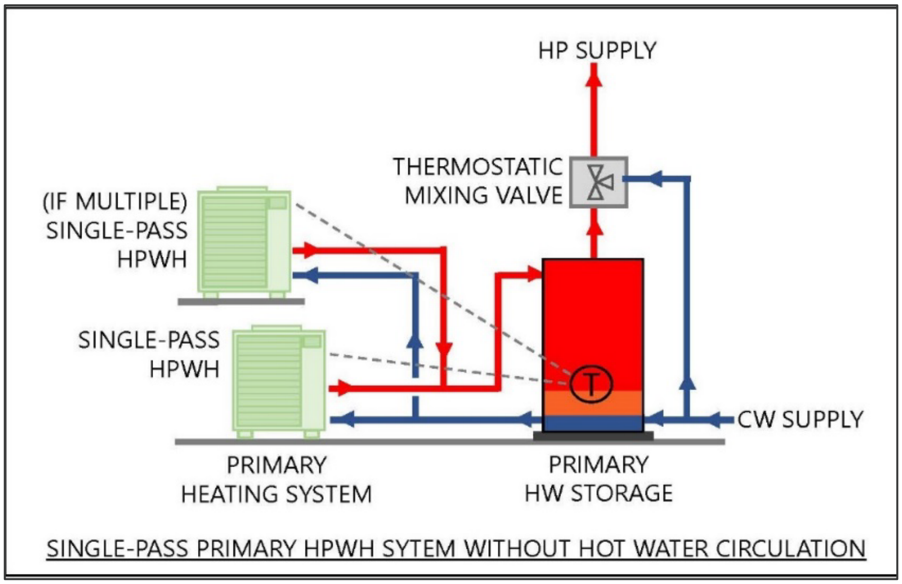
Path to 25

Almost 100 Watts of power is consumed to make up for heat wasted while delivering hot water to each apartment in the typical multi-family building[v]. A thoughtful combination of research, designer/installer collaboration, and implementation of energy-efficiency measures could drive future buildings to consistently use less than 25 Watts of power per apartment to reliably deliver hot water to happy occupants. The technology is here, and with proper guidance and verification, this could be a reality for typical multi-family buildings before 2025.

Appendix A: Effect of Temperature Maintenance Heat Loss on Heat Pump Water Heating Systems

Well-designed heat pump water heating (HPWH) systems are a reliable and efficient way to heat DHW without burning fossil fuels. Special considerations must be made when designing these systems to ensure reliable and efficient operation. HPWH's operate most efficiently when heating cold water up to DHW temperature in a single pass. Since warm temperature-maintenance flow requires consistent reheating, a HPWH design should aim to re-heat the warm temperature-maintenance flow while minimizing the temperature of the water received by the HPWHs.

The following HPWH system configurations have been field-proven and posted in the Advanced Water Heating Specification (AWHS) 8.0 to provide guidelines for designers to implement successful HPWH systems. They are shown side-by-side with diagrams that will illustrate the importance of efficient distribution system design.



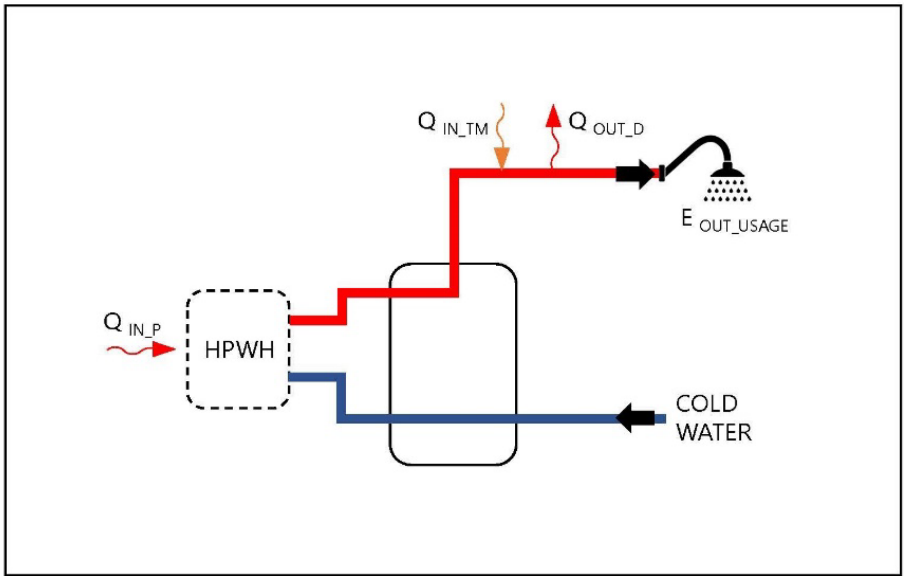


Figure 11. No recirculation

No Recirculation

System Flow and Energy Balance

See Figure 11. Cold water is heated up to temperature and delivered to the fixtures. Hot water delivery is sent to the DHW fixtures without temperature-maintenance flow, so the only heat loss is delivery heat loss. Water in the hot water delivery pipe will cool between uses. The occupant must then flush all the cooled water down the drain and wait for hot water to replace it. A way to combat this is to use heat tape to maintain the temperature of the hot water delivery pipe. The heating provided from the heat tape must directly offset the delivery heat loss.

HPWH Performance

Since the HPWH receives cold water in this configuration, it heats very efficiently.

Best Application to Maximize Efficiency

From a heating perspective, this system is very efficient. However, this system wastes a lot of water if there are any periods with low/no DHW usage. This system should only be utilized in applications that require consistent hot water usage, or small systems with very short distances between primary heating and the DHW fixtures. Heat tape is a feasible solution for short runs of pipe because it eliminates water waste, but it heats very inefficiently compared to a HPWH. Minimizing delivery heat loss will result in a more efficient DHW system.

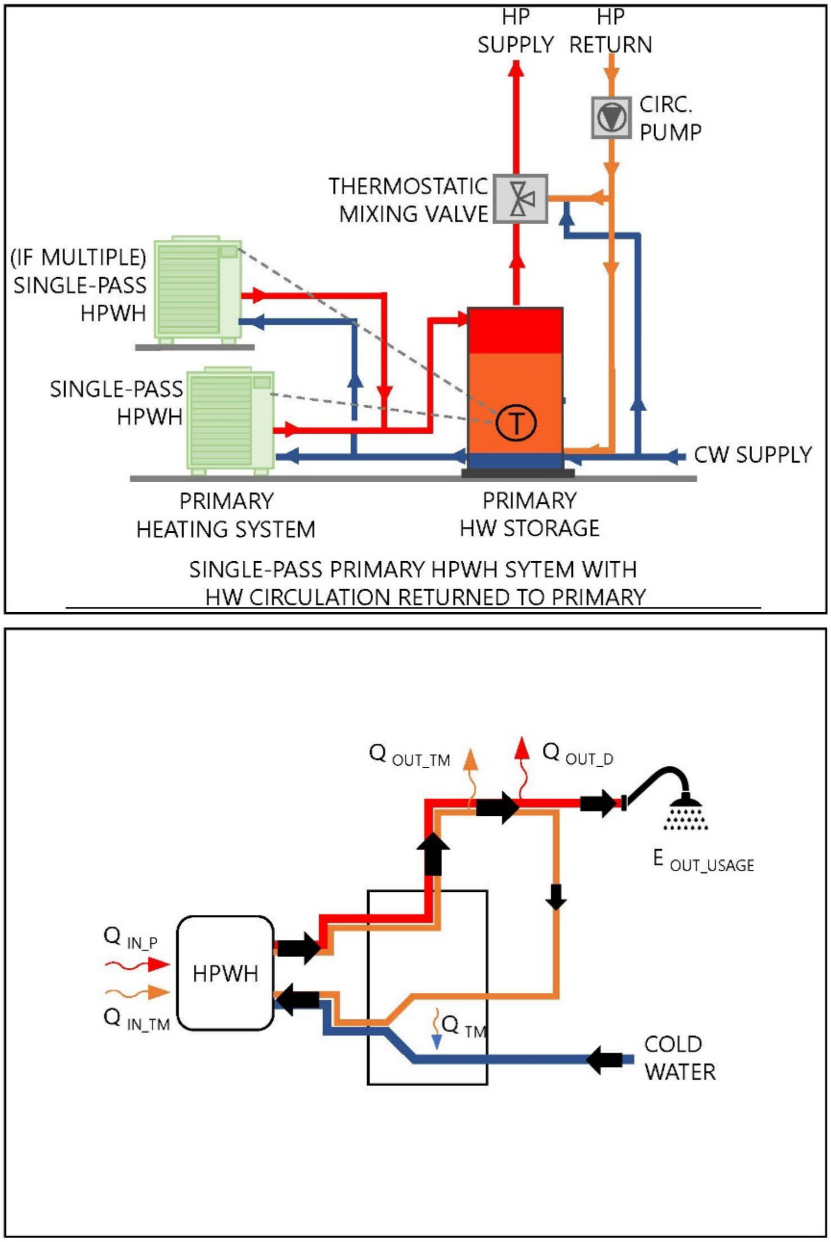


Figure 12. Return to primary

Return to Primary

System Flow and Energy Balance

See Figure 12. Hot water delivery is sent to the fixtures, while temperature-maintenance flow circulates to keep the hot water delivery pipe warm when there is little or no usage. The temperature-maintenance flow then returns to the primary storage, where it is mixed with cold water. Heat is lost from the hot water delivery flow, as well as the temperature-maintenance flow. The HPWH reheats the temperature-maintenance flow and delivery flow simultaneously, which offsets both losses.

HPWH Performance

The water temperature entering the HPWH, and resulting HPWH efficiency, depends on the rate of DHW usage. The rate of cold water entering the system is proportional to the rate of DHW leaving the system. If there is no DHW usage, there is no cold water entering the primary heating system. That means the HPWH is only reheating the temperature-maintenance flow, so the HPWH entering water temperature is high. This will result in less efficient HPWH operation at times of low DHW usage. A HPWH must be selected that is designed to accept high entering water temperatures. The designer must ensure the temperature-maintenance flow returns at a temperature that is lower than the maximum acceptable HPWH entering water temperature.

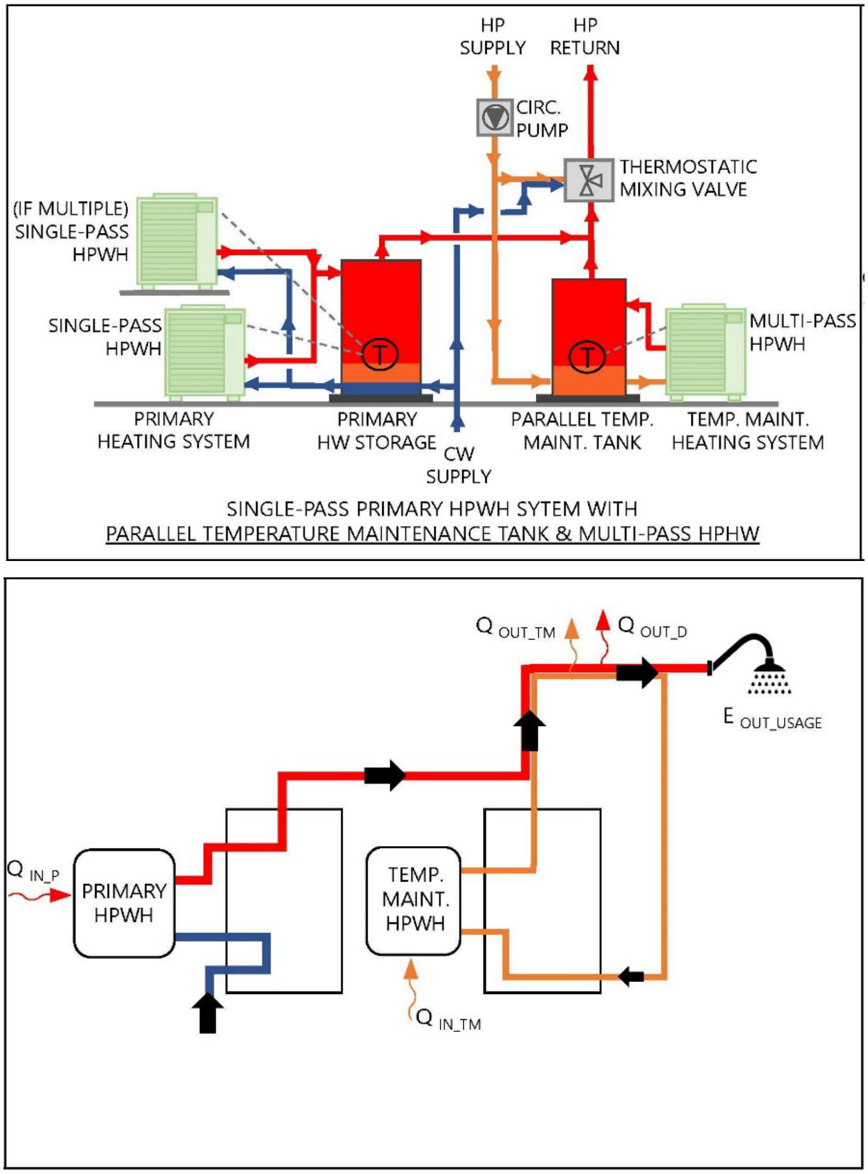


Figure 13. Parallel temperature maintenance

Best Application to Maximize Efficiency

Since all heat loss in this system is made up by a HPWH, the system will always be more efficient than gas or electric resistance heating. This system configuration is best suited for an application that has relatively moderate temperature maintenance losses accompanied by semi-consistent DHW usage. Minimizing DHW distribution losses will result in less work done by the primary heater, as well as increased heater efficiency due to lower entering water temperature. Minimizing the temperature maintenance return temperature will maximize the efficiency and reliability of the HPWH.

Parallel Temperature Maintenance

System Flow and Energy Balance

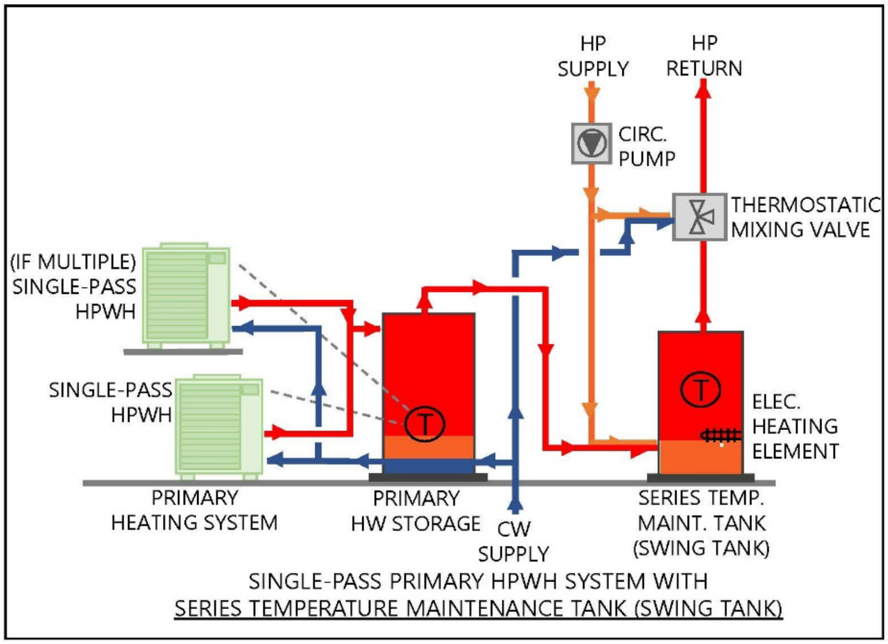
See Figure 13. Hot water delivery is sent to the fixtures, while temperature-maintenance flow circulates to keep the hot water delivery pipe warm when there is little or no usage. The temperature-maintenance flow is heated using a dedicated HPWH. Delivery heat loss and DHW usage are offset by the primary HPWH, while the temperature maintenance heat loss is offset by the temperature maintenance HPWH.

HPWH Performance

There is only cold water delivered to the primary HPWH, so it will operate very efficiently. The designer can select a primary HPWH that will not accept high entering water temperature. The temperature maintenance HPWH will always receive relatively warm water, so it must be designed to heat warm entering water efficiently and reliably.

Best Application to Maximize Efficiency

Since all heat loss in this system is made up by a HPWH, the system will always be more efficient than gas or electric resistance heating. This system is best suited for an application that has medium or high distribution loop losses and relatively long periods without DHW usage. Minimizing the distribution loop losses will minimize the work required by the temperature maintenance HPWH, while minimizing the temperature maintenance return temperature will maximize the efficiency of the temperature maintenance HPWH.



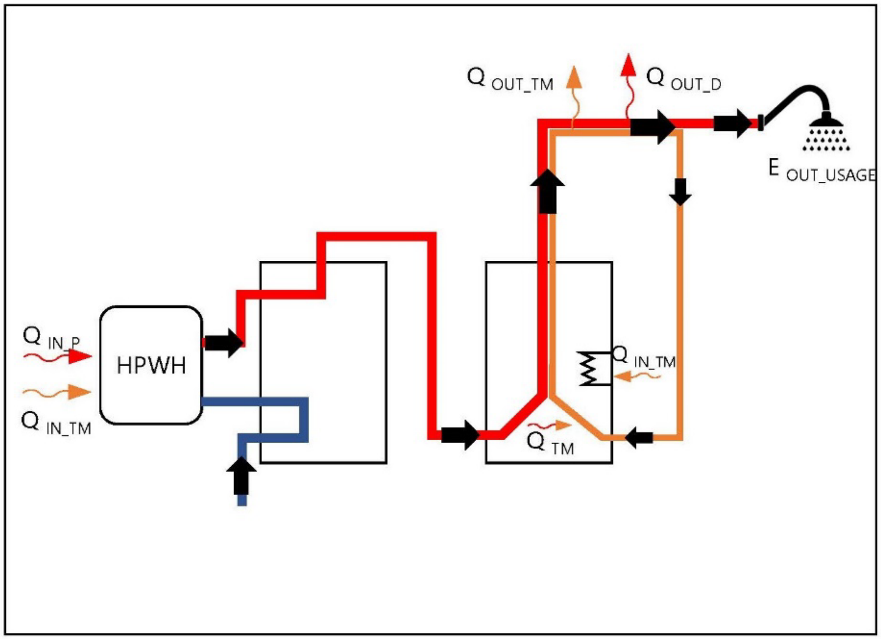


Figure 14. Swing tank

Series Temperature Maintenance (Swing Tank)

System Flow and Energy Balance

See Figure 14. Hot water delivery flow is heated by the primary HPWH. The temperature maintenance return flow and hot water delivery flow mix in a dedicated temperature maintenance tank before being sent to the building, which will result in a mixed water temperature somewhere between the primary heating temperature and temperature maintenance return temperature. If the resulting mixed water temperature is higher than what is required to deliver to the building, there is no additional heating required and the primary heater has passively heated the temperature-maintenance flow through the mixing of DHW delivery flow. If there is not enough DHW delivery flow to mix and sufficiently warm the temperature maintenance return flow, the mixed water temperature will not be warm enough to send to the building and will require additional heating. This is typically handled by an electric heating element. Since DHW delivery flow is proportional to DHW usage, the primary HPWH can offset all DHW system heat loss if there is sufficient DHW usage and low temperature maintenance heat loss.

HPWH Performance

There is only cold water delivered to the primary HPWH, so it will operate with high efficiency.

Best Application to Maximize Efficiency

The primary HPWH will offset all DHW system heat loss when there is high DHW usage and low temperature maintenance heat loss. Since we do not want to promote higher DHW usage, minimizing temperature maintenance heat loss would maximize the efficiency of this system by minimizing the usage of inefficient electric resistance heating.

Appendix B: Delivery Heat Loss Derivation

The rate of delivery heat loss can be measured and calculated using the following equation:

$\dot{Q}_{Delivery} = Flow_{Delivery} * \rho * C_P * (T_{Supply} - T_{Usage})$

Since it is not practical to measure the flow and temperature of every fixture in a large building, an average fixture temperature must be either be measured or calculated. If we assume that, on average, the temperature at each faucet is halfway between supply and return temperature,

$T_{Usage} = (T_{Supply} + T_{Return}) / 2$

This assumption will introduce error and the magnitude of that error will depend on two things:

1) Temperature variation of the DHW distribution loop: If a large proportion of fixtures is near the return end of the DHW loop, and the return end of the loop is 10°F cooler than the supply end of the loop, the assumed usage temperature will be higher than the actual usage temperature.
2) If there are long branches connecting the loop to each fixture, the delivery flow will cool while traveling through the branch pipe and result in a usage temperature that is cooler than the assumed usage temperature. In this study, the heat loss in the uncirculated pipes is ignored and the usage temperature represents the temperature served to uncirculated pipe.

Since a DHW system is a constant volume, it is safe to assume cold water is entering the system at the same rate DHW is leaving the fixtures:

$Flow_{Delivery} = Flow_{Cold}$

Substituting for $Flow_{Delivery}$ and T_{Usage}:

$\dot{Q}_{Delivery} = Flow_{Cold} * \rho * C_P * (\frac{T_{Supply} - T_{Return}}{2})$

Appendix C: Simulation Program Calculations

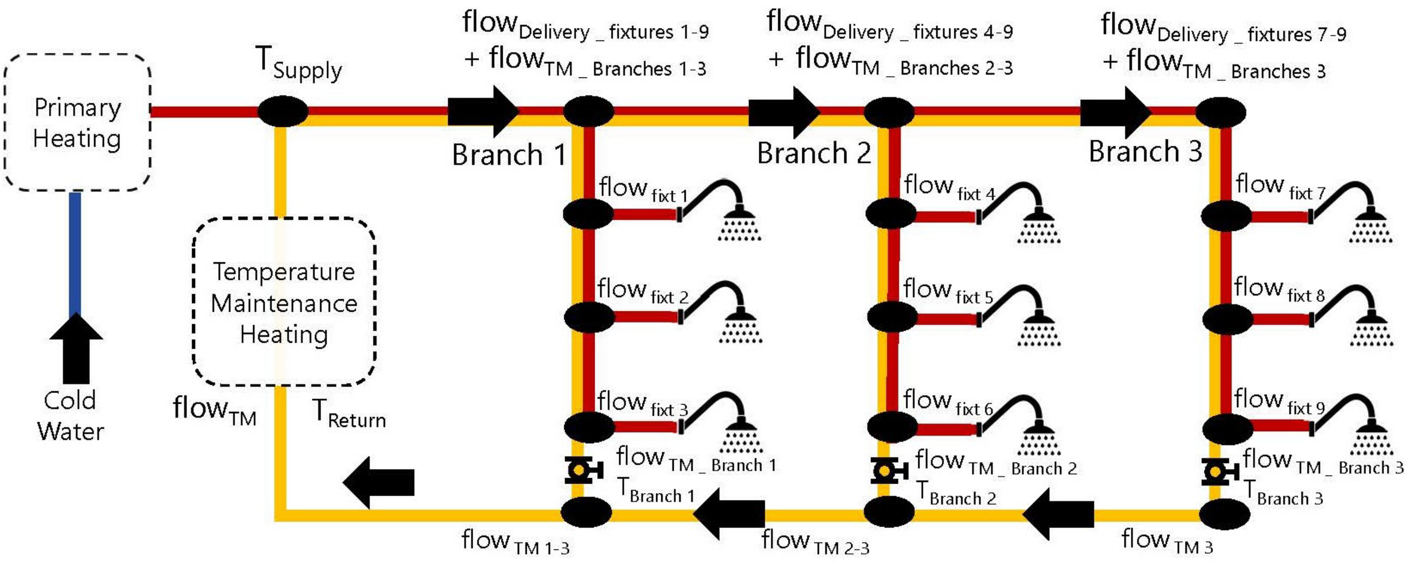


Figure 15. Nodal analysis

A program was created that simulates a DHW distribution loop with thermostatic balancing valves that balance the temperature-maintenance flow through each branch top achieve a target branch temperature. The simulation is excel based, with a block of inputs and outputs that represent each node in the DHW distribution loop. A node is the end of one pipe section, and the start of the next downstream pipe section, as shown in Figure 15.

Each pipe section has a specific heat loss characteristic based off pipe size, insulation thickness, and insulation quality:

$$UA_L = \frac{2 \cdot \pi \cdot k_{insulation}}{ln(\frac{r_{outside}}{r_{copper}})}$$

Where:

$k_{insulation}$ = insulation thermal conductivity
$r_{outside}$ = outside insulation radius
r_{copper} = outside pipe radius[vi]

The flow through a supply pipe section is the sum of all delivery and temperature-maintenance flows downstream of that pipe section, while the flow of a return pipe section is the sum of all temperature-maintenance flows upstream of that pipe section. The simulation assumes an initial flow through each balancing valve and requires a user to input the total delivery flow, as a percentage of maximum probable flow. The total delivery flow is distributed proportionally to each apartment based off the total fixture units assigned to that apartment. Given the first guess at temperature-maintenance flow through each branch, and the delivery flow to each fixture, the program can then calculate the total flow through each section of pipe. Once the flow through each pipe section is known, the temperature can be calculated at each node using the following equation:

$$T_{flow}(L) = (T_{in} - T_{amb}).e^{-\frac{UA_L}{\rho \cdot c_p \cdot Flow} \cdot L} + T_{amb}$$

Where:

$T_{flow}(L)$ = temperature of the node at the end of a pipe section

T_{in} = temperature of the node at the beginning of a pipe section / end of the upstream pipe section

T_{amb} = temperature of the air surrounding the pipe section[vii]

After the temperature at each node is calculated, the program compares each branch temperature to the user input target temperature. If the temperature at a branch is too low, the program incrementally increases the temperature-maintenance flow associated with that branch and re-calculates all flows and node temperatures. If the temperature is too low, the program incrementally decreases the branch flow and re-calculates. This process is performed iteratively until all the branch temperatures are within 0.1°F of the target branch temperature.

Once the node temperatures are determined, the heat loss can be calculated for each pipe section using the following equation:

$$\dot{Q}_{Section} = Flow_{Section} * \rho * C_P * (T_{Start\ Node} - T_{End\ Node})$$

The total heat loss is the sum of heat losses in all sections of the DHW distribution loop.

$$\dot{Q}_{Total} = \sum \dot{Q}_{Section}$$

Temperature maintenance heat loss is calculated using the temperature and flow of the last node (T_{Return}, $Flow_{Return}$), and the temperature of the first node (T_{Supply}) as if it were measured in an existing system.

Delivery heat loss is the difference between Q_{Total} and Q_{TM}

Appendix D: Simplified Calculator

The simplified heat loss calculator assumes a constant temperature for the entire DHW distribution loop, which allows a single calculation for UA per ft of pipe using the following equation:

$$UA_L = \frac{2 \cdot \pi \cdot k_{insulation}}{ln(\frac{r_{outside}}{r_{copper}})}$$

Where:
$K_{insulation}$ = insulation thermal conductivity
$r_{outside}$ = outside insulation radius
r_{copper} = outside pipe radius

Pipe insulation conductivity and dimensions were used that meet the 2015 Washington State Commercial Energy Code per Table C403.2.9, and an assumption was made that the outer diameter of each pipe was 1/8" greater than the nominal size, as is standard in copper pipes.

The calculator requires the user to input the total length of each size of pipe, then calculates total UA for each pipe size by multiplying the total length of each pipe size by its unique UA_L value:

$Q_{TM} = Flow_{Return} * \rho * C_P * (T_{Supply} – T_{Return})$

$UA = UA_L * L_{Pipe}$

Total UA of the entire DHW distribution loop is then the sum of UAs from each size of pipe.

An additional feature outputs the ratio between UA and number of apartments to give designers an idea of how efficiently they are laying out the pipe. This simply divides total UA by a user input number of apartments.

Total heat loss is calculated by using user inputs that include usage temperature, space temperature, and UA multiplier, and inputting them in the following equation:

$\dot{Q}_{Total} = UA_{Total} * Multiplier_{UA} * (T_{Usage} – T_{Space})$

Delivery heat loss is calculated using the following equation:

$\dot{Q}_{Delivery} = flow_{Delivery} * \rho * C_P * (T_{Supply} – T_{Usage})$

Temperature maintenance heat loss is the difference between total heat loss and delivery heat loss:

$Q_{TM} = Q_{Total} - Q_{Delivery}$

Works Cited

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