

EcosizerEngine

Technical Documentation

Sizing and Simulation Methodology

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1 SIZING

This section describes the mathematical and physical principles behind the sizing of domestic hot water (DHW) systems in EcosizerEngine. Sizing determines the minimum heating capacity (kBTU/hr) and minimum primary storage volume (gallons) that a heat pump water heater (HPWH) system must have to meet the building's peak daily hot water demand. Two sizing paths exist: normal sizing (no load shifting) and load-shift sizing (the heater is prohibited from running during a user-defined shed window).

1.1 NORMAL SIZING OVERVIEW

Normal sizing assumes the HPWH can run during any hour of the day and must deliver the full daily DHW load within a designer-specified maximum runtime per day, H (default 16 hours). The procedure follows three steps.

- 1) **Step 1 – Required heating capacity.** The HPWH must heat enough water to meet the entire day's demand within the allotted run time. Let V_d be the total daily DHW demand at supply temperature (gal), H the maximum daily run time (hr), T_s the supply temperature (°F), T_i the design cold-water inlet temperature (°F), and f_d the defrost derate factor (default 1.0, dimensionless). The required heating capacity is:

$$Q = \frac{V_d}{H} \times \rho c_p \times \frac{(T_s - T_i)}{f_d \times 1000} \frac{BTU}{kBTU}$$

where $\rho c_p = 8.354 \text{ BTU}/(\text{gal} \cdot ^\circ\text{F})$ is the volumetric heat capacity of water.

- 2) **Step 2 – Running volume (supply temperature).** The running volume is the amount of usable hot water that must be held in storage at the start of a peak demand period so that supply never runs out before the HPWH can replenish it. The 24-hour load shape $L(h)$ (a normalised vector summing to 1.0) is compared hour-by-hour against the uniform generation rate:

$$G = \frac{V_d}{H}$$

The hourly difference is $d(h) = G - V_d * L(h)$. Positive values are surplus (heater catching up); negative values are deficit (demand exceeding current generation). To handle demand periods that straddle midnight, the algorithm tiles $d(h)$ over two consecutive days and, for each hour h^* where d transitions from positive to negative (a surplus→deficit transition), computes the cumulative deficit:

$$V_{run} = \max_{h^*} \left\{ -\min_{k \geq 0} \left(\sum_{j_0}^k d(h^* + j) \right) \right\}$$

If no such deficit exists (generation rate exceeds peak hourly demand every hour) then $V_{run} = 0$ and no storage is needed — this is the physical minimum of the sizing curve.

- 3) **Step 3 – Physical storage volume (storage temperature).** The running volume is expressed at supply temperature, meaning the storage tank needs to be able to store enough water to produce V_{run} gallons of supply temperature water while the tank is recharging. The physical tank stores water at the higher storage temperature, T_{st} , and is not perfectly stratified; there is a warm transition zone between the cold inlet layer at the bottom and the fully-hot zone at the top. Only a fraction of the physical tank volume is usable. To account for this, a conversions is applied. The stratification factor S (described in Section 1.2) captures this:

$$V_{storage} = \frac{V_{run}}{S}$$

1.2 STRATIFICATION FACTOR

The stratification factor S is the ratio of the supply-temperature gallons that a real (imperfectly stratified) 100-gallon tank can deliver to what a perfectly stratified 100-gallon tank would deliver. It accounts for the fact that the ON aquastat fires when the water at a certain height in the tank drops to the trigger temperature — at that moment the tank below the sensor is cold and unusable.

The tank temperature profile is modelled as a linear gradient in the transition zone. Let f_{on} be the fractional height of the ON sensor (0 = bottom, 1 = top), T_{on} the trigger temperature at that sensor, and m the stratification slope (°F per 1% of tank height, default 2.8). The temperature at fractional height f (expressed as percent $f_{pct} = f * 100$) above the sensor is:

$$T(f) = T_{on} + (f_{pct} - f_{on} \times 100) \times m$$

The heights at which T equals supply temperature T_s (lower boundary of usable zone) and storage temperature T_{st} (upper boundary) are:

$$f_s = f_{on} \times 100 + \frac{(T_s - T_{on})}{m}$$

$$f_{st} = \min \left(f_{on} \times 100 + \frac{(T_{st} - T_{on})}{m}, 100 \right)$$

Supply-temperature gallons producible from the 100-gallon tank are found by integrating over the two usable zones — the transition zone $[f_s, f_{st}]$ and the fully-hot zone $[f_{st}, 100\%]$:

$$X = \int_{f_s}^{f_{st}} \frac{(T(u) - T_i)}{(T_s - T_i)} du + (100 - h_{st}) \times \frac{(T_{st} - T_i)}{(T_s - T_i)}$$

The stratification factor is then $S = X / 100$.

1.3 SIZING CURVE

The sizing curve is a design tool showing the capacity–storage trade-off for a given building. It is generated by sweeping H from 24 hours down to the physical minimum (where G is peak hourly demand, so $V_{\text{run}} \rightarrow 0$) in 0.25-hour steps, computing Q and V_{storage} at each step. The recommended design point corresponds to the default value of H for the system type being sized for (16 hours for most system types). Moving left on the curve (smaller storage) requires higher capacity; moving right (more storage) permits lower capacity.

1.4 LOAD-SHIFT SIZING

When demand response is required, the heater is prohibited from running during a shed window (e.g. 4 PM – 9 PM). The system must pre-heat enough water during the preceding load-up period to serve demand through the shed. Load-shift sizing runs alongside normal sizing; the final result is the component-wise maximum of both paths.

The load-shift sizing procedure introduces several additional quantities:

- **Shed hours:** the hours during which the heater is off.
- **Load-up hours:** the hours immediately before the shed window during which the heater pre-heats to a higher setpoint.
- **V_{shift} :** total demand volume during the first shed block, scaled by the demand fraction corresponding to the percentile of days with successful shed the system is being sized for.
- **V_{lu} :** demand volume during the load-up period.

LOAD-SHIFT GENERATION RATE

The load-shift sizing computation uses the aquastat setpoints to express storage bands as fractions of the total tank volume. Define the stratification percent of tank as:

$$P(f, T) = S(f, T) \times (1 - f)$$

where S is the stratification factor computed with the given sensor position, f , and trigger temperature, T . P is the fraction of the whole tank that is usable at supply temperature when the sensor fires at (f, T) . With separate setpoints for normal on sensor at the time heating turns ON (P_n), load-up off sensor at the time heating turns OFF (P_{lu}), and shed on sensor at the time heating turns ON (P_{sh}), the load-shift band width is:

$$\Delta P_{ls} = P_{lu} - P_{sh}$$

The volume of hot water that must be pre-loaded during load-up (V_{load}) is the share of V_{shift} that lies within the load-up zone:

$$V_{\text{load}} = V_{\text{shift}} \times \frac{(P_{lu} - P_n)}{\Delta P_{ls}}$$

The required load-up generation rate is then:

$$G_{lu} = \frac{(V_{\text{load}} + V_{lu})}{N_{lu}}$$

where N_{lu} is the number of load-up hours. The actual LS generation rate used for sizing is $G_{ls} = \max(G, G_{lu})$ where $G = V_d / H$ is the normal rate.

LOAD-SHIFT RUNNING VOLUME

Starting at the moment the shed ends (the tank holds only V_{shift} above the shed aquastat), the deficit algorithm accumulates from that point:

$$V_{ls,run} = V_{shift} + \max\left(0, -\min_{k \geq 0} \left(\sum_{j_0}^k d_{ls}(h_{shed\ end} + j)\right)\right)$$

Where $h_{shed\ end}$ is the end of the last shed hour and $d_{ls}(h) = G_{ls} - V_d \cdot CDF(p) \cdot L(h)$ and generation is zero during shed hours. CDF is the cumulative density function of the user defined percent of load shift covered, p . At 1.0 the system is sized for the maximum (design-day) load. At 0.89, for example, it accepts that the shed will be violated on the most demanding $\approx 11\%$ of days in exchange for a smaller tank. The load-shift storage volume is then:

$$V_{ls,storage} = \frac{V_{ls,run}}{S_{ls}}$$

where $S_{ls} = (\Delta P_{ls}) / 100$ is the effective stratification denominator for the load-shift band (the supply-temperature capacity difference between the load-up and shed aquastat positions in a 100-gal tank).

1A SIZING FOR SWING TANK SYSTEMS

A swing tank system has two storage volumes: a primary tank (HPWH + stratified hot water storage) and a smaller temperature maintenance (TM) tank, typically heated through electric resistance, that sits on the recirculation loop. The TM tank absorbs recirculation loop losses, so the primary HPWH does not need to run during recirc-only periods.

TM TANK SIZING

The TM tank is sized from the recirculation loss rate alone. The required TM volume is the smallest entry in the TM sizing table [40, 50, 80, 100, 120, 160, 175, 240, 350, 400, 500, 600, 800, 1000, 1250 gal] that satisfies:

$$V_{TM} \geq \frac{Q_{recirc}}{100\ W/gal \times 3.412\ BTU/hr/W}$$

The TM element capacity is:

$$Q_{TM} = k_{TM} \times Q_{recirc}$$

where k_{TM} is the user defined safety factor (default 1.2) and Q_{recirc} is the recirculation heat loss:

$$Q_{recirc} = F_{recirc} \times 60 \times \rho c_p \times \frac{(T_s - T_{ret})}{1000}$$

with F_{recirc} the loop flow rate (GPM) and T_{ret} the return water temperature.

PRIMARY TANK SIZING — RUNNING VOLUME

The swing tank's thermal mass absorbs part of the demand peak, so the primary tank sees a reduced effective demand. The running volume is computed by simulating the swing tank at each peak transition in the load shape. The simulation tracks two temperatures — the swing tank temperature (T_{swing}) and the primary feed temperature (T_{st} , storage temperature) — and determines how much of each hour's demand can be supplied by the swing tank's stored heat vs. how much must come from the primary.

For each surplus to deficit transition h^* in the peak load shape, a 24-hour simulation of the swing tank is run starting from h^* . Let $hw_{swing}(t)$ and $T_{swing}(t)$ be respectively the volume and temperature of water leaving the swing tank at minute t to cover DHW usage, replacing that water with T_{st} temperature water from the primary. The primary sees a demand profile $hw_{primary}(t) = hw_{swing}(t)$. The running volume at peak h^* is:

$$V_{run}(h^*) = -\min_{k \geq 0} \left(\sum_{t_0}^k [G_{min}(t) \times f_{mix} - hw_{primary}(t)] \right)$$

where $G_{min}(t)$ is the effective per-minute generation rate and f_{mix} (the effective mix fraction) is:

$$f_{mix} = \frac{\sum_t hw_{swing}(t)}{V_d}$$

The overall running volume is the maximum over all peak transitions. It is then converted from storage-temperature to supply-temperature frame:

$$V_{run, st \rightarrow s} = V_{run} \times \frac{(T_{st} - T_i)}{(T_s - T_i)}$$

The primary storage volume is then derived using the same stratification derate as normal sizing:

$$V_{storage} = V_{run, st \rightarrow s} / S.$$

PRIMARY TANK CAPACITY — SWING OVERRIDE

The capacity formula for a swing tank system uses storage temperature (not supply temperature) in the ΔT term, and incorporates the effective mix fraction f_{mix} :

$$Q = \frac{V_d \times f_{mix}}{H} \times \rho c_p \times \frac{(T_{st} - T_i)}{f_d \times 1000 \frac{BTU}{kBTU}}$$

This is physically consistent because the primary heats water to storage temperature T_{st} (not supply temperature), and the mix fraction accounts for the fraction of demand satisfied by the primary rather than the swing tank.

1B SIZING FOR PARALLEL LOOP SYSTEMS

A parallel loop system has the recirculation loop running in parallel with the primary HPWH storage. The loop continuously returns water to the primary tank, and the primary heater must offset loop heat losses as well as the DHW load. A small TM tank on the recirc loop provides mixing and temperature maintenance.

The capacity formula is identical to the base formula (Section 1.1, Step 1) because the recirc losses appear as part of the daily BTU demand that the HPWH must supply. No separate recirc capacity term is added — unlike Single Pass Return to Primary (SPRTP) systems, the TM element handles the recirc loop independently.

The running volume algorithm is also the same as the base case (Section 1.1, Step 2). The load shape used is the peak daily load shape for the building type.

TM volume is sized so the tank has enough thermal mass to absorb steady-state recirc losses during a full off-cycle without the TM element firing. Specifically, the volume is calculated as:

$$(k_{TM} \times Q_{recirc} / \rho c_p) \times (H_{off} / (T_{TM,off} - T_{TM,on}))$$

Where H_{off} is the user-configured maximum allowed off-cycle duration for the TM heater, $T_{TM,off}$ is the temperature off setpoint for the parallel loop heater, and $T_{TM,on}$ is the temperature on setpoint for the parallel loop heater

TM capacity is sized purely as a user-configured safety-factor multiple of the steady-state recirc loss rate: $safety_factor \times Q_{recirc}$ (default safety factor 1.75). The safety factor ensures the element can outpace the loss and actually recover temperature rather than just keeping pace with it.

1C SIZING FOR SINGLE PASS RETURN TO PRIMARY (SPRTP) SYSTEMS

In a single pass return to primary (SPRTP) system, recirculation return water flows back directly into the primary storage tank rather than through a separate TM vessel. This means the primary HPWH must heat both the DHW load and the continuous recirculation heat loss. There is no separate TM element.

CAPACITY

The HPWH must offset the full 24-hour recirc loss during its H -hour daily runtime. The recirc contribution is:

$$Q_{recirc,cap} = k_{TM} \times Q_{recirc} \times \frac{24}{H}$$

Total required capacity:

$$Q_{total} = Q_{DHW} + Q_{recirc,cap}$$

where Q_{DHW} is the base DHW capacity from Section 1.1 Step 1. The $(24/H)$ factor arises because the HPWH offsets 24 hours of continuous recirc loss during its H -hour runtime.

LOAD-SHIFT RUNNING VOLUME

During heater-off periods the recirc loop drains heat from storage continuously, beyond what the DHW load shape captures. The load-shift running volume algorithm is extended by adding the 24-hour recirc loss expressed as an equivalent daily gallon demand at supply temperature:

$$V_{recirc,daily} = k_{TM} \times Q_{recirc} \times \frac{1000}{\rho c_p \times (T_s - T_i)} \times 24$$

This volume is added to V_d before the deficit algorithm runs, so the generation rate and demand profiles both include the continuous recirc drain. The result is a larger running volume (and thus a larger primary tank) compared to an equivalent parallel-loop system.

The stratification slope used for SPRTP sizing defaults to 1.7 °F per %-height (vs. 2.8 for other system types), reflecting the different tank stratification characteristics of SPRTP configurations.

1D SIZING FOR MULTI PASS RETURN TO PRIMARY SYSTEMS

A multi pass return to primary (MPRTP) system routes recirculation return water through the primary heat pump water heater rather than a dedicated swing tank. Each pass of return water is heated before it continues back to the recirc loop. This topology requires a different tank-sizing approach: instead of a deficit integral over a load-shape profile, the minimum tank volume is found by simulating a “growing slug” of cold water that accumulates during peak demand periods.

CAPACITY

MPRTP capacity is sized identically to the SPRTP formula (Section 1c), with one difference: the default maximum daily run hours is $H = 14$ hr (versus 16 hr for SPRTP), reflecting the higher effective heating demand per run hour imposed by the multi-pass topology.

$$Q_{DHW} = \frac{V_d}{H} \times \rho c_p \times \frac{(T_s - T_i)}{f_d \times 1000}$$

$$Q_{recirc,cap} = k_{TM} \times Q_{recirc} \times \frac{24}{f_d}$$

$$Q_{total} = Q_{DHW} + Q_{recirc,cap}$$

where V_d is the daily DHW demand (gal at T_s), H is the maximum daily run hours, $\rho c_p = 8.354$ BTU/(gal·°F), T_s is the supply temperature (°F), T_i is the design cold-water inlet temperature (°F), f_d is the defrost factor (1.0 for no defrost), and Q_{recirc} is the steady-state recirculation heat loss (kBTU/hr). The (24/H) factor accounts for the recirc loop running continuously while the heater runs only H hours per day.

RUNNING VOLUME — GROWING-SLUG METHOD

The minimum physical tank volume is found by a 2-day, 1-minute-timestep simulation in which the heater is assumed to run continuously at the just-computed capacity Q_{total} . The “slug” is a fully-mixed virtual accumulator representing cold water at the bottom of the primary tank that still needs to be reheated.

At each 1-minute timestep the following sequence executes:

1. **Mixing-valve draw.** The mixing valve determines how much water is drawn from primary storage, accounting for cold city water, recirculation return flow, and the average hot-water temperature at the heater on-trigger setpoint.

2. **Slug accumulation.** The drawn volume, V_{draw} , at temperature T_{draw} is blended into the slug via a weighted-average energy balance, updating the slug temperature from $T_{slug,current}$ to T_{slug} and the volume from $V_{slug,current}$ to V_{slug} :

$$T_{slug,mixed} = \frac{(V_{slug,current} \times T_{slug,current} + V_{draw} \times T_{draw})}{V_{slug,current} + V_{draw}}$$

$$V_{slug} = V_{slug,current} + V_{draw}$$

3. **Heater input.** The heater adds heat to the slug each minute:

$$\Delta T_{slug} = Q_{total} \times \frac{1}{60} \times \frac{1000}{V_{slug} \times \rho c_p}$$

$$T_{slug} = T_{slug,mixed} + \Delta T_{slug}$$

4. **Slug reset.** If $T_{slug} \geq T_{st}$ the slug is considered fully reheated and resets to zero volume at the cold-water inlet temperature. The reset threshold is the storage temperature T_{st} (not T_s) to ensure the tank can always serve mixed-down demand.
5. **Peak tracking.** The maximum slug volume observed across the entire 2-day simulation is the minimum required physical tank volume (gal). Unlike other sizing methods, no stratification-factor conversion is applied; the slug volume is already expressed as physical gallons.

The recirculation return flow passes through the mixing valve calculation at every timestep regardless of DHW demand. Recirculation losses are captured in Q_{total} via the capacity formula; the slug simulation adds only the storage volume needed for the demand-induced cold-water accumulation.

CAPACITY BOOST

The analytic capacity formula may underestimate the true requirement because it does not account for transient slug behaviour during sustained peak demand. After the initial sizing and tank construction, an iterative correction loop runs up 3 times:

6. **Trial simulation.** Run a 3-day simulation with the current capacity. The tank is initialized at the heater on-trigger fraction.
7. **Outage detection.** If the usable tank volume ever reaches zero, record the minimum tank outlet temperature $T_{min,outlet}$ reached during the outage and the number of elapsed minutes $t_{deficit}$ since the heater last turned on.
8. **Capacity correction.** Compute the energy needed to raise the tank contents from $T_{min,outlet}$ to T_s and spread it over the deficit period:

$$\Delta E = V_{tank} \times p_{useable} \times \rho c_p \times \frac{(T_s - T_{min,outlet})}{1000}$$

$$\Delta Q = \frac{\Delta E}{\frac{t_{deficit}}{60}}$$

where V_{tank} is the total physical tank volume (gal), $p_{useable}$ is the usable fraction of the tank (the region above the heater on-sensor height), T_s is the supply temperature, $T_{min,outlet}$ is the minimum observed tank outlet temperature during the outage, and $t_{deficit}$ is the number of minutes the heater has been on since the outage began.

9. **Heater update.** Set $Q_{cap} = Q_{total} + \Delta Q$. Rebuild the water heater with the new capacity and repeat. If no outage is detected the loop exits early.

SIZING CURVE

The MPRTTP sizing curve shows the trade-off between heating capacity and tank volume as the daily run hours vary. Unlike other system types, the curve sweeps only downward from the configured 14 hour daily run time; there is no over-designed region above the default run hours because higher run hours are already the least-demanding operating point.

Each point on the curve is produced by a full sizing run (including the capacity boost loop) at the target run hours. The effective run hours plotted for each point are back-calculated from the final capacity, Q_{cap} , to account for any boost that was applied:

$$h_{back} = \frac{\left(\frac{V_d \times \rho c_p \times (T_s - T_i)}{1000} + Q_{recirc} \times 24 \right)}{(Q_{cap} \times f_d)}$$

Points with non-strictly-decreasing back-calculated run hours are discarded (the capacity boost has stalled and further points are not meaningful), and the sweep stops when the target run hours fall below 9 hr. The recommended design point is always the highest run hours, lowest required capacity, and largest tank volume.

LOAD-SHIFT SIZING

MPRTTP does not support load-shift sizing. The growing-slug volume algorithm is inherently time-sequential and cannot be analytically decomposed into shed and load-up periods. Passing a control map with a “shed” key to `size()` or `from_size()` raises a `ValueError`.

2 SIMULATION

The 3-day design-day simulation models system performance at 1-minute time steps over three consecutive peak-demand days. An annual simulation runs at 10-minute intervals for a full year. The simulation is driven by the Building object, which provides per-timestep demand, outdoor air temperature, and inlet water temperature. The storage tank state is updated each step via heating and draw operations.

2.1 STORAGE TANK MODEL

The primary storage is modelled as a stratified tank. The stratification is represented linearly, with an assumed slope of a change in 2.8 °F per percentage of change in height on the tank in most piping configurations (1.7 °F per percent height change in SPRTTP and 0.8 °F per percent height change in MPRTTP). Once the tank temperature on the linear stratification reaches T_{st} , all water above that point on the tank is also T_{st} . Conversely, when water

on the stratification line reaches T_i , all water below that point is also T_i . Two operations have the potential to update the tank state each timestep:

- **Heat:** the HPWH injects energy at the top of the tank. Hot water at T_{st} displaces cooler water downward. Nodes that exceed T_{st} are capped and excess energy is propagated downward.
- **Draw:** demand removes hot water from the top of the tank and introduces cold inlet water at the bottom. The algorithm tracks the physical displacement through the node stack. If any node reaches below supply temperature, the usable volume begins to drop.

The usable volume reported at each timestep is the number of supply-temperature gallons currently available in the tank, computed by integrating the node temperatures from top to bottom until the cumulative temperature-weighted volume equals the demanded volume or a node falls below supply temperature.

2.2 CONTROLS AND HEATER ON/OFF LOGIC

Each water heater carries a Controls object for each operating mode ('normal', 'loadUp', 'shed'). The Controls object specifies:

- **on_sensor_fract:** fractional tank height of the ON sensor (0 = bottom, 1 = top).
- **on_trigger_t_f:** temperature at which the heater turns ON.
- **off_sensor_fract:** fractional tank height of the OFF sensor.
- **off_trigger_t_f:** temperature at which the heater turns OFF.
- **outlet_temp_f:** maximum outlet water temperature for this mode.

At each timestep the heater's on/off state is updated based on the current tank temperature at the sensor heights:

- If OFF and $T(\text{on_sensor_fract}) \leq \text{on_trigger_t_f} \rightarrow$ turn ON.
- If ON and $T(\text{off_sensor_fract}) \geq \text{off_trigger_t_f} \rightarrow$ turn OFF.

The active mode is determined by the control schedule (a 24-element list mapping each hour to 'normal', 'loadUp', or 'shed'). During shed hours the heater is forced OFF regardless of tank temperature, so the tank temperature may fall below the normal ON setpoint during the shed window. During load-up hours the heater runs to a higher OFF setpoint, pre-heating the tank before the shed begins.

2.3 SIMULATION STEP SEQUENCE

Each 1-minute (or 10-minute) timestep executes in the following order:

1. Query the Building for DHW demand, outdoor air temperature (OAT), and inlet water temperature for the current interval.
2. Determine the active control mode for the current hour of day.
3. Update each water heater's on/off state by reading the tank temperature at its sensor positions for the current mode.

4. Sum heating output (kBtu/hr) and electrical power draw (kW) from all active heaters. Output is a function of OAT and top-of-tank temperature via the heater's PerformanceMap (if available) or its nominal capacity.
5. Apply heating to the storage tank (heat operation).
6. Draw DHW demand from the top of the storage tank, replacing with cold inlet water (draw operation).
7. Record per-step metrics: demand, usable volume, heater output, power, OAT, inlet temperature, and tank temperature profile.

2A SWING TANK SIMULATION

The swing tank simulation adds a second thermal mass — the swing tank — that interacts with the recirculation loop and partially buffers demand before the primary storage is tapped.

The simulation loop proceeds as follows each timestep:

- The recirculation loop continuously draws heat from the swing tank at the loop's return temperature. The swing tank's electric resistance TM element fires to maintain temperature above the TM on-setpoint (`tm_on_temp_f`), turning off at `tm_off_temp_f`.
- Domestic hot water demand is drawn first from the swing tank (which replaces stored heat with primary feed water).
- The primary tank sees the thermal feed to the swing tank. The draw from the swing tank to meet building demand is the exact draw in physical gallons from primary storage

Because the swing tank absorbs part of the demand, the primary HPWH cycles less frequently. The usable volume reported at each step is the sum of supply-temperature or above gallons in the primary tank. However, if the swing tank temperature drops below T_s , the usable volume will be reported as zero since the swing tank must be kept at or above T_s in order to supply DHW to the building.

2B PARALLEL LOOP TANK SIMULATION

The parallel loop simulation follows the base simulation sequence (Section 2.3) with the addition of a TM tank on the recirculation loop. The TM tank is a small, fully-mixed tank whose electric resistance element maintains the recirc loop temperature.

At each timestep the recirculation heat loss is drawn from the TM tank. Cold return water entering the TM tank mixes with its stored volume. The TM element fires when the TM tank temperature drops below `tm_on_temp_f` and shuts off at `tm_off_temp_f`. TM tank state is tracked independently from the primary stratified tank.

The primary HPWH heats the primary storage and feeds hot water to the recirc loop via the TM tank. The demand drawn from the primary is the full DHW load plus any heat needed to maintain the TM tank temperature. Usable volume is reported for the primary tank only.

2C SINGLE PASS RTP (SPRTP) SIMULATION

The SPRTP simulation is similar to the normal simulation described in section 2.3, however, in addition to the storage tank losing heat to water being drawn, it also loses heat to recirculation loss at every time step. The method performs a two-step energy-to-thermocline conversion. First it computes the heat energy extracted from the tank by the recirc loop during the timestep:

$$Q_{recirc} = g_{recirc} \times \rho c_p \times \frac{(T_s - T_{ret})}{1000}$$

Where g_{recirc} is the gallons of T_{ret} temperature water that returns to the system during the time step. Then it converts that energy loss into an equivalent thermocline shift in gallons — asking "how many gallons of the current hot-to-cold temperature range carries this much energy?":

$$\Delta V = Q_{recirc} \times 1000 / (\rho c_p \times (T_{st} - T_i))$$

The stratification profile in the storage tank is then shifted down by ΔV as that is the equivalent amount of T_{st} temperature water being replaced with T_i temperature water as the shift in tank energy from recirculation loss.

2D MULTI PASS RTP (MPRTP) SIMULATION

In the MPRTP simulation the recirculation return enters the bottom of the primary tank directly, mixing with stored hot water. There is no separate TM tank. This has two consequences for the simulation:

- The inlet temperature seen by the storage tank is a blend of cold city water (from DHW demand) and warmer recirculation return water. The effective inlet temperature and amount of water entering the tank each minute is directed by the mixing valve (see Appendix A)
- The HPWH heats the primary tank to offset both DHW load and continuous recirc losses. Because return water enters at a higher temperature than cold city supply, the tank stratification is affected differently than in other systems: the warm return water displaces hot water at the bottom of the tank more slowly, potentially giving a slightly longer effective usable volume at supply temperature.

The usable volume is computed the same way as the base simulation — gallons at or above supply temperature in the stratified primary tank. There is no secondary TM volume contribution.

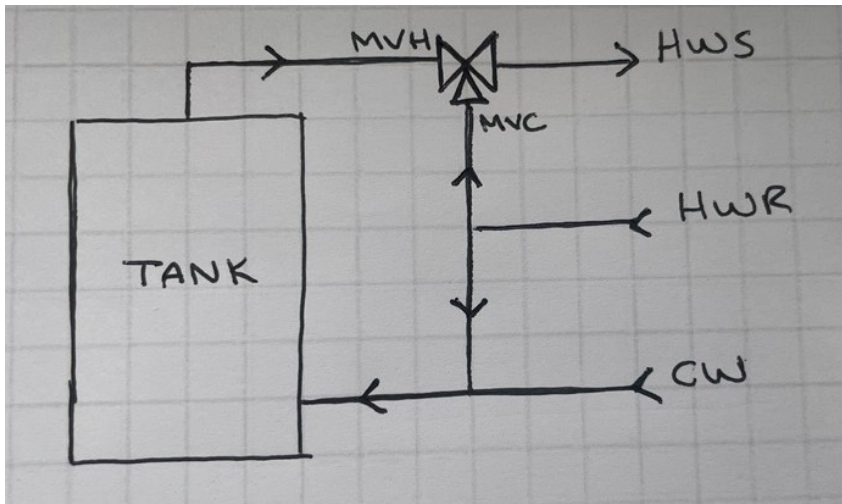
The heater's on/off state is updated via normal aquastat logic. When the heater turns on, the "growing slug" section of the tank is activated, which pulls the sub-supply-temp zone out of the base storage tank stratification profile into a fully-mixed slug overlay at the bottom of the usable volume. Each minute the heater is on, the water heater adds energy (kBtu) directly to that slug, and any drawn volume is removed from the main tank and added to the slug as water of the temperature determined by the mixing valve (see Appendix A). The slug's new size and temperature is determined in the exact same way as the "Growing Slug Method" (section 1d). The slug stays active until the heater turns off, at which point the storage tank merges all slug BTUs back into the stratification energy profile.

While the slug is active, the off-sensor sits inside the slug zone, meaning the heater turns off when the slug reaches the off-trigger setpoint.

APPENDIX A: SUPPORTING CALCULATIONS

MIXING VALVE INLET AND FLOW TO PRIMARY SYSTEM DURING PEAK DRAW

HPWH Inlet Temperature during peak draw is important because it dictates available HPWH capacity during a peak draw. The illustration and equations below define a system where warm return water from the building splits to either return to the mixing valve or the storage tank. These equations are only relevant when hot water usage is below a specific threshold (critical usage further defined below) so cold water does not supplement warm return water at the mixing valve's cold inlet to satisfy the mixing valve's supply water temperature setpoint.



1. Assessing the boundaries of the hot water plant, flow entering as cold city (CW) water, at temperature T_i , plus flow entering as hot water return (HWR), at temperature T_{ret} , is equal to flow leaving the mixing valve (hot water supply) at temperature T_s .

$$F_{HWS} = F_{HWR} + F_{CW}$$

2. Hot water return flow splits and either flows to the cold mixing valve inlet (F_{HWRMVC}), or the bottom of the tank (F_{HWRT}).

$$F_{HWR} = F_{HWRT} + F_{HWRMVC}$$

3. Flow into the hot side of the mixing valve equals flow into the bottom of the tank. This flow consists of all the cold water flow, plus some portion of the hot water return flow.

$$F_{MVH} = F_{CW} + F_{HWRT}$$

4. All the water flowing to the cold mixing valve inlet is hot water return.

$$F_{MVC} = F_{HWRMVC}$$

5. Mixing ratio equation relates mixing valve flows to temperatures.

$$\frac{F_{MVH}}{F_{MVH} + F_{MVC}} = \frac{T_s - T_{ret}}{T_{st} - T_{ret}}$$

6. Rate of cold water entering the system is equal to the rate of hot water usage.

$$F_{CW} = F_{USAGE}$$

7. Hot water return flow can be derived from total heat loss from the recirculation loop and the heat equation.

$$F_{HWR} = \frac{Q_{recirc}}{8.3(T_s - T_{ret})}$$

8. The seven equations above are combined to derive tank inlet temperature.

$$T_{TANKIN} = \frac{F_{USAGE} \cdot T_i(T_{st} - T_{ret}) + T_{ret} \left[\frac{Q_{recirc}}{8.3} - F_{USAGE}(T_{st} - T_s) \right]}{F_{USAGE} \left(T_s - T_{ret} + \frac{Q_{recirc}}{8.3} \right)}$$

CRITICAL HOT WATER USAGE

There is a critical point where there is just enough hot water usage (and associated cold make-up water) that 100% of the primary tank make-up water is cold water, and 100% of the cold mixing valve inlet is warm return water. Setting $F_{HWRT} = 0$ in the equations above defines this case, and results in the following equation:

$$CRITICAL\ USAGE = \frac{Q_{recirc}}{8.3 \cdot (T_{st} - T_s)}$$

If hot water usage is above the critical usage threshold, all warm return water flows through the mixing valve cold inlet and the water temperature entering the tank is equal to cold water temperature.