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Domestic Hot Water Preparation With Heat Pumps in MFH: Single-Pass vs. Multi-Pass Charging

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Abstract. An investigation was conducted to examine various charging strategies for domestic hot water (DHW) storage tanks in multi-family homes (MFH) with DHW circulation, using heat pumps. A system consisting of a brine-to-water heat pump, a stainless-steel storage tank, and all hydraulic components was installed and measured on a test bench under dynamic operation. The charging strategies tested included different variants of single-pass charging where the storage tank is charged in a single-pass from top to bottom and multi-pass charging with a stepwise temperature increase introduced at the middle of the storage tank. The results show that multi-pass charging requires a significantly lower heat pump temperature time-averaged over return and supply as well as a lower time-average supply temperature compared to single-pass charging to achieve the same level of comfort. This lower temperature is accompanied by a clear efficiency advantage: while the system's performance factor (PF) for the various single-pass charging variants was around 2.0, multi-pass charging achieved a PF of 2.4. For all charging variants, DHW circulation with return temperatures of at least 55°C as required by national standards led to a loss of system efficiency, as it initiated an early recharge of the entire storage tank volume to over 60°C.

Keywords: Domestic Hot Water Heat Pump Systems, Thermal Stratification, Single-Pass Charging, Multi-Pass Charging

1. Background

Due to the need to decarbonize heat supply systems, heat pumps (HP) are playing an increasingly important role in domestic hot water (DHW) production. As buildings become better thermally insulated, DHW accounts for a growing share of the buildings overall heat demand. However, the relatively high temperature requirements for DHW production and distribution, primarily driven by hygiene regulations aimed at preventing Legionella growth [1], [2], are difficult to meet with current heat pump concepts. Both field studies [3], [4] and laboratory experiments [5] indicate that the efficiency of DHW heating using heat pumps often falls significantly short of the technical potential.

There are a variety of possible charging concepts, such as charging by internal or external heat exchangers, the latter with single pass or multi pass respectively, as well as internal or external heat exchanger for DHW in combination with buffer storage tanks. Moreover, the potential for efficiency gains through improved thermal stratification and better management of the circulation return flow remains insufficiently understood and underutilized. A profound evaluation of different system concepts, which takes into account both efficiency and hygiene (temperatures reached, avoidance of temperatures in the critical range), does not exist.

As part of the EffPlusWW project funded by the Swiss Federal Office of Energy (SFOE) (SFOE contract number: SI/502673-01 and SI/502677-01), various standard concepts of water heating systems for multi-family houses with domestic hot water circulation are being tested and compared under identical boundary conditions. In this article, the focus is on hot water storage tanks for charging by means of an external heat exchanger. For charging strategies, a distinction is made between single-pass and multi-pass charging.

1.1 Charging process of single-pass and multi-pass charging

Figure 1 illustrates the ideal processes of single-pass and multi-pass charging in terms of heat pump flow rate, supply and return temperature, and storage tank temperature. With ideal single-pass charging (Figure 1, left), the set temperature at the heat pump supply is reached already at the start of the process. Thus, the storage tank is charged to the desired temperature in a single pass over the heat exchanger. Consequently, the heat pump must perform a high temperature rise at the beginning of the charging process, which requires a low flow rate. Only towards the end of the charging process, when the return temperature rises, does the flow rate increase. In contrast, with an ideal multi-pass charging strategy (Figure 1, right), the heat pump operates with a fixed temperature difference between the supply and return flow, and the temperature increases in multiple steps. This results in a high flow rate and multiple overturns of the storage tank volume over the heat exchanger. To sustain a high temperature in the peak coverage volume, the supply flow enters the storage tank in control volume (below the peak coverage). Only when the supply temperature exceeds the local tank temperature does the water rise to higher levels due to density differences, allowing it to settle at the correct stratification height.

Regardless of whether single-pass or multi-pass charging is used: With an ideal system design and control, and with any mixing processes being neglected, identical mean heat pump sink temperatures can be achieved.

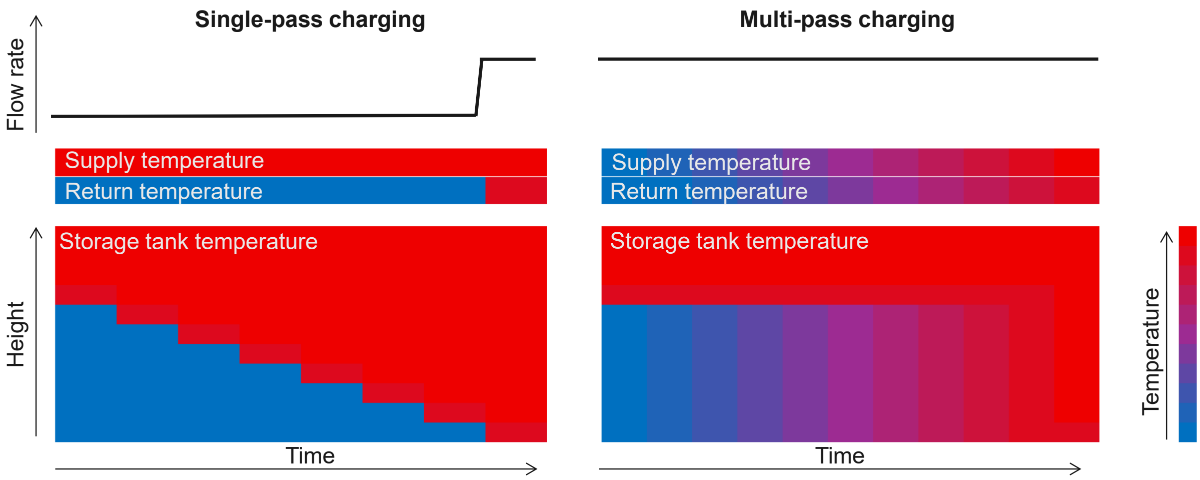

Figure 1. *Temperatures and flow rates during ideal single-pass charging (left) and ideal multi-pass charging (right).*

As shown, there are different strategies for charging the DHW storage tank, which differ in terms of supply inlet positions, supply flow rates and, consequently, supply and return temperatures. Different control strategies for the heat pump and corresponding hydraulics can be used to achieve either of the two charging strategies. The heat pump control strategies are shown in Figure 2. For single-pass charging, the water, already heated to the desired set point, enters the peak coverage volume directly. To achieve the high temperature rise two different heat pump control strategies are outlined:

- In **single-pass charging with return flow mixing (SCM)**, the return flow temperature is increased using an electronically controlled mixing valve between the supply and return of the storage tank. This allows the volume flow over the heat exchanger to be relatively high. On the primary side, regulation is achieved through controlling the pump speed (Figure 2, left).
- In **single-pass charging with throttle control (SCT)**, the volume flow over the heat exchanger must be regulated on the primary and secondary side to always achieve the correct set temperature, depending on the return flow. On the primary side, regulation is done with controlling the pump speed. On the secondary side, it is additionally controlled by a throttle valve (Figure 2, center).

With **multi-pass charging (MC)**, the charging occurs with a constant temperature difference between the supply and return flow of the storage tank and a high flow rate over the heat exchanger. The supply flow enters the storage tank below the peak coverage volume into the control volume, gradually heating the lower part of the tank step by step. Therefore, multiple passes over the heat exchanger are needed to charge the storage tank to the desired temperature (Figure 2, right).

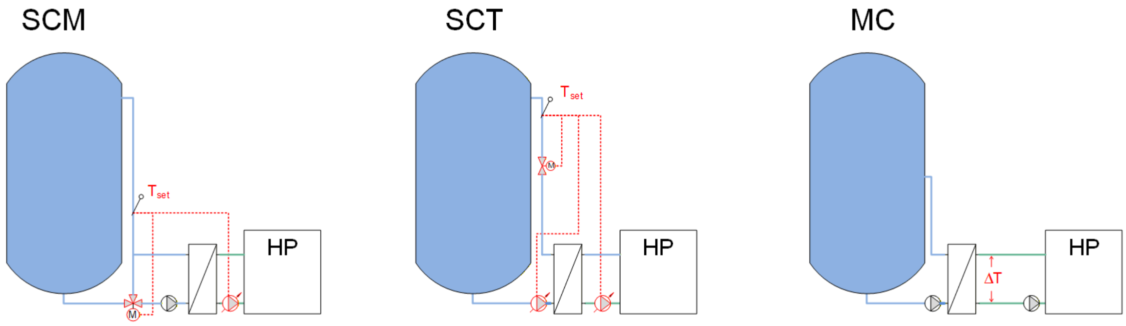

Figure 2. *Concept of different charging strategies, left: single-pass with return flow mixing, center: single-pass with throttle control, right: multi-pass charging. In single-pass charging, the HP is controlled to a fixed set point temperature, in multi-pass charging, the HP is operated with a fixed delta-T, meaning a constant mass flow rate*

2. Methods

2.1 Test method and tested system

The measurements were carried out in dynamic operation. For this purpose, a system consisting of a stainless steel storage tank, a brine-to-water heat pump, an external heat exchanger for charging and all the fittings required for hydraulic integration were set up on a hardware-in-the-loop (HiL) test bench. The set up is shown in Figure 3. The test unit has interfaces to the test bench, the so-called emulators. An emulator provides heating or cooling on demand. When hot water is tapped, the emulator conditions the cold water to the set temperature and regulates the tapping volume flow according to the specification of a predefined tapping profile. Losses in the circulation pipe were emulated to a given heat lose rate. In addition, the volume of a riser pipe is set up to represent its thermal mass. A third emulator acted as the source of the heat pump. Hence it conditions the brine temperature.

Components of the tested system are shown in Table 1. During multi-pass charging (MC), the storage tank is charged with a high mass flow rate. To avoid mixing in the storage tank, the flow is directed through internal components that increase the flow cross-section and provide a flow calming section to reduce flow velocity and turbulences.

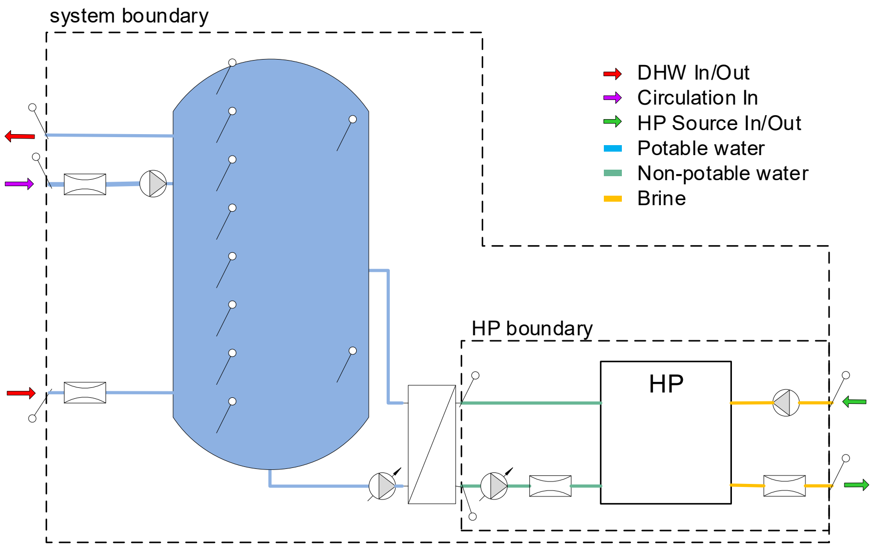

Figure 3. *Measurement concept and hydraulic integration of the storage tank. The multi-pass charging concept is shown as an example. Measurements are taken using immersed Pt100 temperature sensors and Coriolis flow meters at the system boundaries.*

Table 1. *Components of the tested system*

Components	**Specifications**
Stainless steel hot water storage tank	Nominal volume 1'300 l
Brine-water HP	Refrigerant: R290 Inverter-controlled Nominal output: 18 kW
Plate heat exchanger	Output 20 kW
Hydraulic components	Speed-controlled pumps for HP charging circuit; Throttle valve + mixing valve
Circulation pump + balancing valves	

2.2 Boundary conditions

A reference building was used to define the DHW demand as well as the circulation and riser pipes. The building is an apartment building with 6 flats [6]. The heat requirement was designed in accordance with the Swiss standard SIA 385-2:2025 [7]. Heat demand includes not only the demand for hot water, but also storage losses, circulation losses, and discharge losses due to the cooling of the discharge pipe. According to the design, this results in a total heat requirement of 70 kWh/d (see Figure 4). The proportion of "DHW demand" and "discharge losses" was used as the target value to define the test profile.

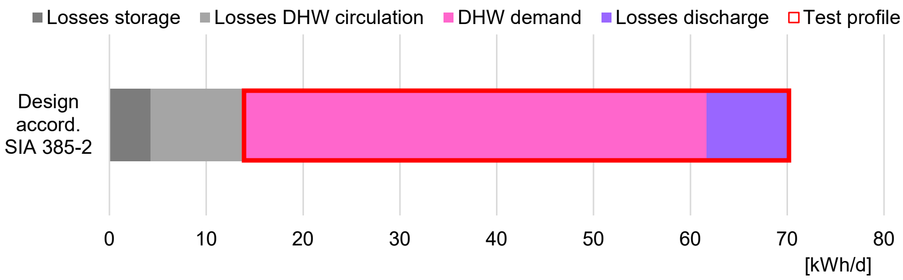

Figure 4. *Heat demand for domestic hot water preparation in the reference building in accordance with the design outlined in SIA 385-2:2025*

The 24-hour tapping profile was generated using the dhwCalc software [8] and prepared for implementation on the test bench. Figure 5 shows the cumulative energy demand without discharge losses and the volume flows of the individual tappings. The discharge losses were added proportionally to each tapping. Appropriate to the tapping profile, the boundary conditions of the DHW circulation were also defined, taking into account standards for discharge times, etc., and utilizing field data on standby losses [9]. The losses for DHW circulation emulated by the test bench were 500 W or 12 kWh/d and therefore higher than the design described above. The temperature of the ground source heat was set to a mean temperature between supply and return flow of 5 °C.

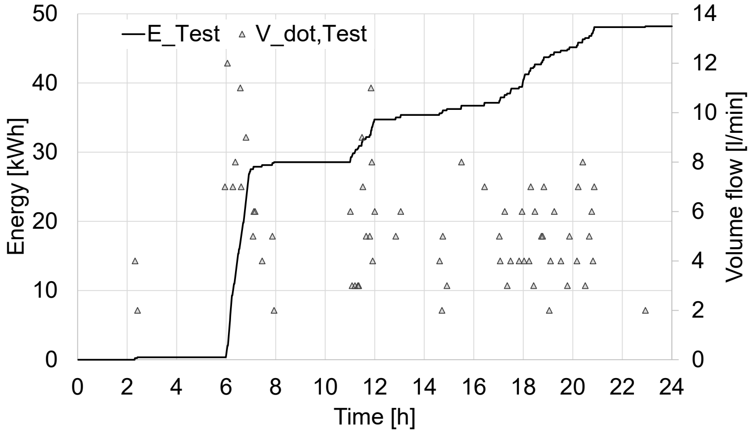

Figure 5. *DHW-tapping profile as prepared for test bench*

2.3 Measurement and characteristic parameters

As can be seen in Figure 3, the system was equipped with various measuring points for a comprehensive qualitative and quantitative assessment.

The thermal parameters important for determining the useful heat were measured using immersed temperature sensors in the supply and return line as well as a mass flow meter. The data was used to calculate thermal power $\dot{Q}$ every second, which was accumulated to energies Q:

$$\dot{Q} = \dot{m} \cdot \left[h(\vartheta_{in,i}) - h(\vartheta_{out,i})\right] \quad (1)$$

$$Q = \sum \dot{Q} \cdot \Delta t \quad (2)$$

The storage tank temperature was measured using a sensor tape with contact sensors, which was glued to the outer wall of the storage tank.

The electrical power was measured galvanically via integrated measuring devices, whereby the pumps were recorded separately.

The system's performance factor provides an indication of the efficiency of the DHW system. It is calculated from the ratio of the useful energy Q_{DHW} and the electrical energy required by the heat pump $W_{el,HP}$. Where $W_{el,HP}$ is the electrical energy including energy demand for elements of the refrigeration circuit, the primary and secondary sink pumps, the source pump and the control system.

$$PF_{system} = \frac{Q_{DHW}}{W_{el,HP}} \quad (3)$$

The performance factor of the heat pump is calculated by dividing the heat delivered by the heat pump Q_{HP} by the electrical energy required by the heat pump.

$$PF_{HP} = \frac{Q_{HP}}{W_{el,HP}} \quad (4)$$

Therefore, PF_{HP} only indicates heat pump performance, whereas PF_{System} also accounts for heat losses in the system.

2.4 Test procedure

Each test cycle was conducted over a 24-hour period. The tapping profile described above was emulated on the hot water storage tank using the test bench. As the system requires a certain amount of time to settle, the cycle was repeated until the change in storage tank temperature between the start and end of a 24-hour cycle became negligible. To evaluate this temperature change, the average tank temperature was calculated at the beginning and end of each cycle based on readings from contact sensors installed on the storage tank

Furthermore, compliance with the hygienic requirements, as defined in SIA 385/1, for domestic hot water production was mandatory for passing a test. According to the standard, the temperature in domestic hot water circulation pipe return must be at least 55 °C and may only fall below this for short periods of time (e.g. during charging or when large quantities of hot water are drawn). If a system did not reach the target temperature, the test was repeated and the set temperature in the storage tank was increased until the condition was met.

3. Results

The measurement results are summarized in Table 2. The data for single-pass charging with return flow mixing (SCM) and with throttle control (SCT) are shown. Further the data for multi-pass charging (MC) is shown.

With a value of 2.4, the system's performance factor for multi-pass charging was significantly higher than in the single-pass charging variants with 2.0 to 2.1. Similar, the heat pump performance factor for multi-pass charging was significantly higher than for single-pass charging variants.

Table 2. *Measurement results. SCM = Single-pass charging with return flow mixing; SCT = Single pass charging with throttle valve; MC = Multi-pass charging;*

Test		SCM	SCT	MC
DHW set temperature	[°C]	60	62	62
Hysteresis	[K]	4	6	6
DHW demand	[kWh]	59.4	57.0	57.3
Heat circulation losses	[kWh]	12.0	12.2	12.0
Losses storage tank + hydraulics	[kWh]	14.3	15.7	13.5
Heat supply	[kWh]	85.7	85.3	83.0
El. energy HP	[kWh]	26.8	26.3	21.4
El. energy hydr. pumps	[kWh]	2.1	2.0	2.6
Operating time HP	[hh:mm]	6:43	5:28	4:16
Mean storage temperature	[°C]	55.4	53.6	56.2
Mean circulation temperature	[°C]	56.6	58.1	56.7
Mean supply flow temp. HP (weighted)	[°C]	59.3	63.1	48.1
Mean temp. HP (weighted)	[°C]	57.2	54.9	45.9
PF HP	[-]	3.0	3.0	3.5
PF system	[-]	2.1	2.0	2.4

Figure 6 shows the temperature profile of the storage tank during the 24-hour test cycle for the SCM, SCT, and MC measurements. It is shown that for all tested configurations the tank is charged twice within the 24-hour test cycle.

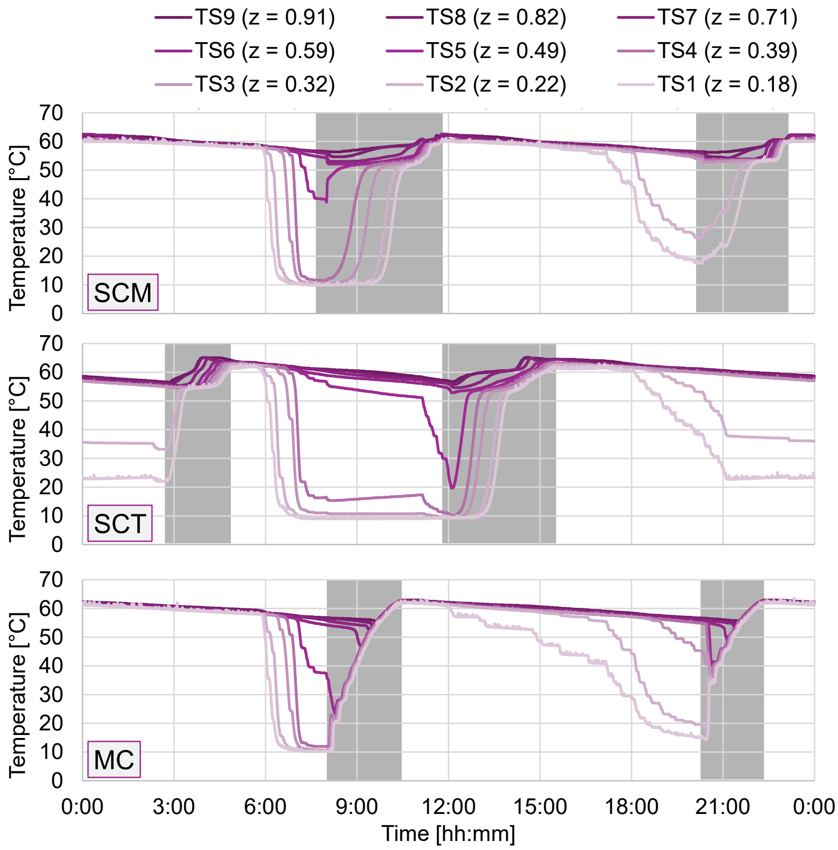

Figure 6. *DHW storage tank temperature over 24 h test cycle, measured with contact sensors along the storage tank wall (z = relative storage height), charging periods indicated by grey background*

4. Discussion

4.1 Temperature set points

Charging of the DHW storage tank was controlled by two sensors. The upper sensor that determines the switch-on condition for the heat pump was positioned below the hourly peak or the peak coverage volume. The switch-off sensor was positioned close to the bottom (z = 0.23) of the storage tank. Charging was terminated when the temperature at the switch-off sensor reached the given set point. For all tests the temperature set points were adjusted to meet the hygiene criteria. Hence, the switch-on condition was set to 56 °C for all tests. The temperature set point for the storage was either 60 °C or 62 °C (see Table 2). With these set points only a brief drop of the circulation return temperature below 55 °C was observed, while achieving a high heat pump efficiency. It was observed that the heat pump supply temperature rises above the temperature set point at the end of the charging process to fully charge the storage tank. This occurs because the return temperature increases towards the end of the charging process, as the volume flow rate cannot be infinite, the heat pump increases the supply temperature.

4.2 Heat losses

The test rig controls the hot water demand according to the specified tapping profile and simulates circulation losses. However, the ambient temperature of the test chamber was not controlled. Therefore, the heat losses of the DHW storage tank resulting from losses to the environment and from the installed riser pipe, which was also placed in the test chamber, could not be controlled. This leads to variance in heat loss and hot water demand, as can be seen in Table 2. The hot water demand varies by less than 5 % between the different tests, and the heat loss by up to about 14 %. However, as can be seen, the energy delivered by the heat pump differs by only about 3 % between the different tests. Therefore, the results of the different charging strategies on heat pump efficiency are comparable.

4.3 Energy-temperature diagram

Figure 7 shows the energy-temperature diagrams of the SCM, SCT and MC variants. In energy-temperature diagrams the energy is plotted over temperature. The energy of the heat pump, circulation and domestic hot water is represented based on the return temperature (RF) and the supply temperature (SF), further mean temperature (Mean) is shown for heat pump and circulation. Here, mean temperature refers to the mean temperature between supply and return.

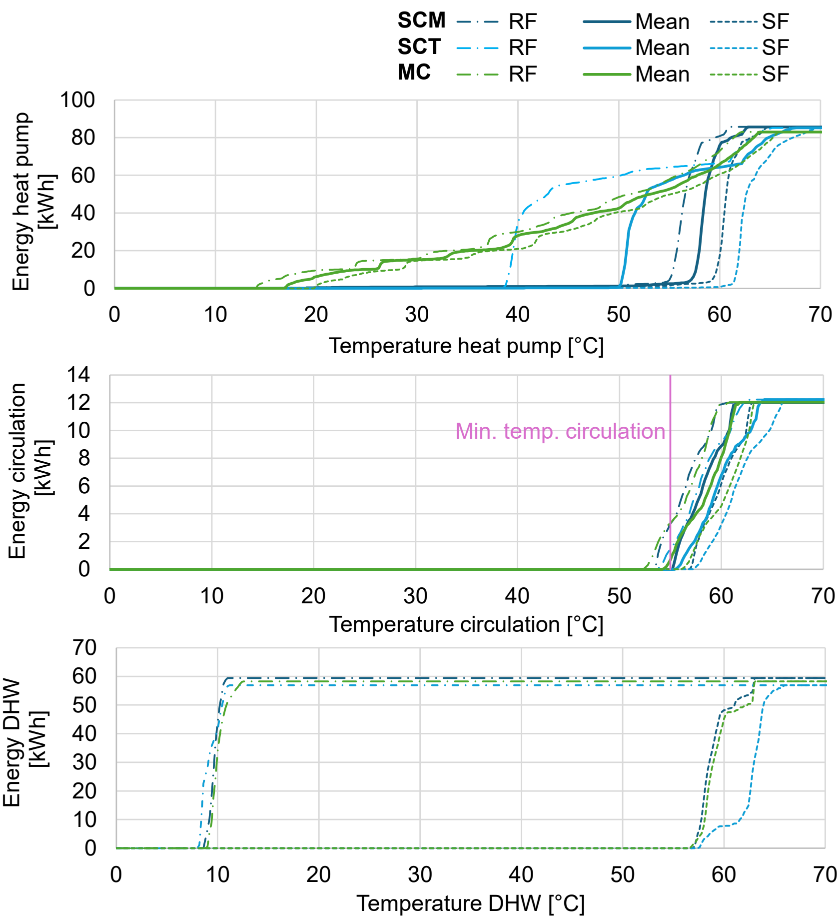

Figure 7. *Energy–temperature diagram of the measurements with single-pass and multi-pass charging. The energy is represented based on the return temperature (dash-dotted line), the supply temperature (dotted line) and mean temperature (solid line).*

The distinct difference in behavior of the energy-temperature diagrams for the heat pump (top figure) highlights the difference between the charging variants. The following points summarize the key observations:

- SCM: As a result of the return flow mixing on the secondary side of the heat exchanger, the temperature difference on the primary side of the heat pump was approximately 5 K. With a set temperature of 60 °C, this resulted in a mean temperature of around 58 °C over an extended period. Throughout the entire operating time, the load-weighted mean temperature remained above 57 °C (see Table 2).
- SCT: Using a throttle valve to control the volume flow over the secondary side of the heat exchanger, a lower return temperature of approximately 40 °C - and consequently a greater temperature difference - was achieved compared to SCM on the primary side. However, the supply temperature increased to nearly 70 °C by the end of the charging process. Over the entire charging period, the mean heat pump temperature weighted by load was 55 °C.
- MC: The temperature difference between return and supply is 5 K over the entire charging process. As a result of the charging control strategy the heat pump supply temperature is about 20 °C at the beginning and increases to about 5 K over the storage tank temperature set point during the charging process. Further, it can be seen that the heat pump rises its temperature in distinguished steps for the first 50 kWh delivered. With a mean heat pump temperature (weighted by load) of 46 °C over the entire operating time, a significantly lower mean heat pump temperature was achieved with MC compared to SCM and SCT.

With the energy-temperature diagram for the circulation (Figure 7, middle) it is clear that the circulation return temperature is above 55 °C for about 9 kWh for SCM and MC configurations and 10 kWh for the SCT. Resulting in a mean circulation temperature of the 24 h test cycle of almost 57 °C for SCM and MC and above 58 °C for SCT. Therefor all three configurations meet the hygiene requirements.

For domestic hot water (Figure 7, bottom) it can be seen that cold water enters the tank at about 10 °C and water is tapped above 56 °C for the whole test cycle. The hot water temperature corresponds to temperature at storage tank top at the time of discharge.

4.4 Impact of DHW circulation

As shown in Figure 6, for each variant two charging events happen within 24 h. It appears that only one of the two charging events was triggered at a time when the lower part of the storage tank had cooled down. Like the plug flow during a single-pass charging process, a plug flow occurs from bottom to top while discharging. Cold water is layered at the bottom and hot water is drawn off at the top. Recharging starts when the forming thermocline reaches the position of the upper temperature sensor. Therefore, temperature at the top of the tank should remain high during discharge. Cooling of the upper volume occurs both through heat loss to the environment and through DHW circulation.

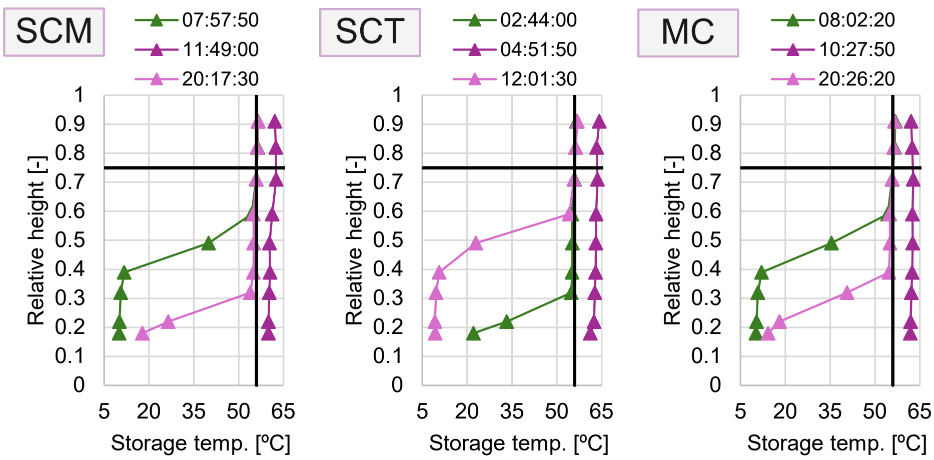

Figure 8. *Storage temperature at the two points in time when recharging was triggered (green and light purple), as well as at the end of the first charging cycle of each day (dark purple)*

Figure 8 shows the storage tank temperature at the points in time at which charging were triggered and at the end of the first charging cycle. At the end of charging, the temperature in the entire storage tank is in the range of 60 to 62 °C in all cases. With time, the upper storage tank volume cools down almost homogeneously in each case. A distinct thermocline formed by the circulation return flow cannot be observed due to the small temperature difference between the fluid entering the tank and the temperature in the tank. (The circulation was operated with a temperature difference of 3K). At least once a day, this cooling due to the circulation leads to premature charging of the storage tank when the lower part is not cold yet and thus to efficiency losses. Further charging takes place at a point in time at which the spatial distance between the “cold water thermocline” and the switch-on sensor is at least 15 % of the storage tank volume. The storage tank temperatures measured at the sensors with the relative height of 0.59 and of 0.71 are almost identical. Therefore, the pronounced cooling in the upper part of the storage tank caused an early recharging, that was not caused by the hot water tapping.

4.5 Comparison of ideal and real behavior

Under ideal single-pass charging conditions, a low return temperature is gradually increased to the desired domestic hot water temperature over a prolonged duration, characterized by a large temperature differential. As described for the ideal single-pass process, this requires a very low secondary mass flow. The measured data shows that this is not achieved. Even after optimization of the heat pump control, the primary-side return temperature of the single-pass charging with throttle control was above 40°C for most of the charging process (as shown in Figure 7). The average temperature of the heat pump, weighted by load, from the supply and return was 54.9 °C. For an ideal process, a temperature of 35.7 °C on the secondary side could be reached.

With multi-pass charging, the difference between the ideal and measured mean heat pump temperature is significantly smaller. The mean, load-weighted, temperature of the HP was 45.9 °C. The corresponding ideal secondary-side temperature would equally be 35.7 °C, just as for the single-pass process.

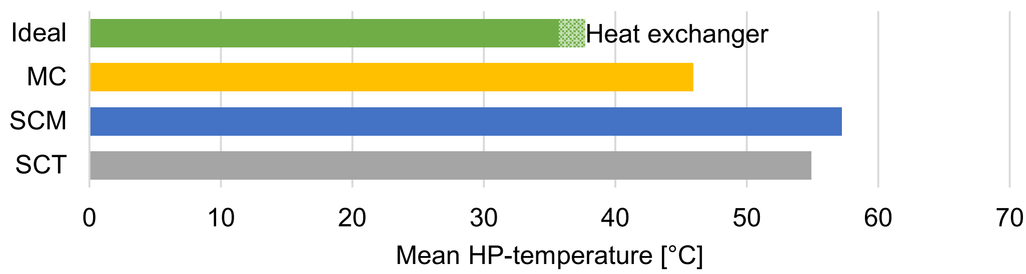

Figure 9. *Average heat pump temperatures based on the load-weighted supply and return temperatures over the entire 24-hour test cycle. For the ideal temperature, the secondary-side temperature plus the delta-T across the heat exchanger is shown (green and light-green).*

The challenge of multi-pass charging does not lie in the control of the refrigerant circuit or the inlet and outlet temperatures of the water to be heated using variable flow rates or mixing. Instead, it lies in preventing inlet jet mixing of water that has been heated with a small delta-T and therefore enters the storage tank with a high flow rate. In particular, the high momentum of the incoming flow must be considered and mitigated to a flow velocity of < 0.1 m/s by corresponding design of inlets. This task can be effectively managed by redirecting and expanding the flow cross-section at the entry point to the storage volume, with a sufficiently long stabilization section, as recommended by SPF (StorEx project [10] and BigStrat [11], [12], as well as the guideline on the SPF homepage), which has been implemented in the tested storage tank.

5. Summary

Various strategies for charging a domestic hot water storage tank via a HP using an external heat exchanger were tested. The strategies investigated include single-pass charging and multi-pass charging. With single-pass charging, the storage tank is charged with a high supply temperature directly into the peak coverage volume from the start. This approach was tested with the two variants: return flow mixing and throttle valve. Multi-pass charging, on the other hand, uses a constantly low temperature difference between the supply and return flow of the storage tank. It operates with a high flow rate and the inlet to the storage tank is located below the peak coverage volume. In this case, due to the very high flow rates, flow rate mitigation to prevent inlet jet mixing is of particular importance.

The differences in the sink temperatures of the heat pump during charging is reflected in the performance factor at system level (including all losses): This amounted to 2.0 or 2.1 for the single-pass charging variants (the latter with return flow mixing). Multi-pass charging on the other hand achieves a system's performance factor of 2.4 and thus the best result in the comparative test.

The theoretical analysis of the two charging strategies shows that the load-weighted mean charging temperature (heating power weighted time-average of mean supply and return temperatures) must be identical for both charging strategies: 35.7°C, but the heating-power weighted time-average of the supply temperature is lower for multi-pass charging than it is for single-pass charging. Single-pass charging requires a very low mass flow rate as long as the temperature in the bottom of the storage tank is low in order to reach the needed set temperature with a given capacity. With a cold water temperature of 10°C and a power output of 18 kW, this corresponds to 310 l/h. The multi-pass charging strategy achieves lower supply temperatures on average, but higher return temperatures and high flow rates. Further, for multi-pass charging, it must be assured that the incoming high mass flow is introduced into the storage tank with flow mitigation in order to prevent mixing of the storage water.

The practical implementation of the charging strategies in the laboratory was tested using a hardware-in-the-loop test bench under realistic conditions, including emulation of the circulation losses. This showed that the theoretically low heat pump return temperatures in the case of single-pass charging are not achieved. Moreover, in the author's opinion the performance of the installed inlet flow mitigation for the multi-pass charging could still be improved and an even better results could be achieved.

Data availability statement

The measurement data underlying the results are published under https://doi.org/10.5281/zenodo.15518939

Author contributions

Vera Gütle: Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft; **Robert Haberl:** Project administration, Conceptualization, Funding acquisition, Methodology, Investigation, Validation, Visualization, Writing – original draft; **Michel Haller:** Conceptualization, Funding acquisition, Validation, Writing – review & editing, Supervision

Competing interests

The authors declare that they have no competing interests.

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