A COMBI STORAGE FOR COMBINATION WITH HEAT PUMPS – FROM SIMULATIONS TO THE TEST BENCH RESULTS

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Abstract

In this work the development and testing of a combi storage tank for the combination with a heat pump is described. The appropriate size and segmentation of the storage in different zones was determined with simulations in TRNSYS. Installations in the storage tank for efficient handling of the high volume flow rates of a heat pump were designed and selected using CFD simulations. Finally, the finished storage tank was tested to determine its stratification efficiency, demonstrating its good stratification properties. The storage tank performs very well with a stratification efficiency of 84 % at system level. The separation of the temperature ranges for hot water preparation in the storage tank above and the space-heating zone remains intact even when charged with the high mass flow rate of 2570 kg/h. As a result, the heat pump can be operated with a low supply temperature (the power weighted average supply temperature of the heat pump was 33 °C) and thus at a favorable operating point with high efficiency.

Keywords: Combistore, heat pump, stratification efficiency, CFD simulations, measurement, hardware-in-the-Loop

1. Introduction

The thermal refurbishment of existing buildings together with the replacement of inefficient, fossil fuel based heating systems provides a large potential for energy savings. Heat pumps are an attractive alternative heating system. Thermal energy storages (TES) are used widely for the storage of heat for domestic hot water (DHW) and space heating. Increased storage volumes are installed when fluctuating renewable energies are introduced into the system, such as heat from solar thermal installations or from the combination of photovoltaics (PV) and heat pumps with special control for the increase of PV self-consumption.

However, when this kind of storage is used in combination with a heat pump, the temperature stratification of the storage is a decisive factor for the overall efficiency and thus for the consumed final energy of the system. This paper presents the development of a combi storage tank, which was part of a larger project called "HybridHeat4San". In this project a hybrid heating system for space heating and domestic hot water was designed, which enables an energy-efficient supply of renovated residential buildings with an existing radiator heating system.

2. Zoning of the storage tank and simulation of the diffusors at the inlet

Basis for the system development within the project is a hydraulic layout with a combined storage tank (combistore) for domestic hot water (DHW) preparation and space heating. An air-source heat pump is connected to the combistore. It uses three-way-valves to charge either the DHW zone of the tank via the two connections on the top or the space heating zone via the two lower connections. The space heating system is supplied from the heat pump connections to the space heating zone of the storage via two T-pieces. This arrangement reduces the mass flow rate over the storage tank during space heating operation. DHW is provided by a DHW heat exchanger (external plate heat exchanger) with a temperature of 45 °C at its secondary outlet. Fig. 1 shows the hydraulic scheme, including the system boundaries for the subsequent measurement of the storage system.

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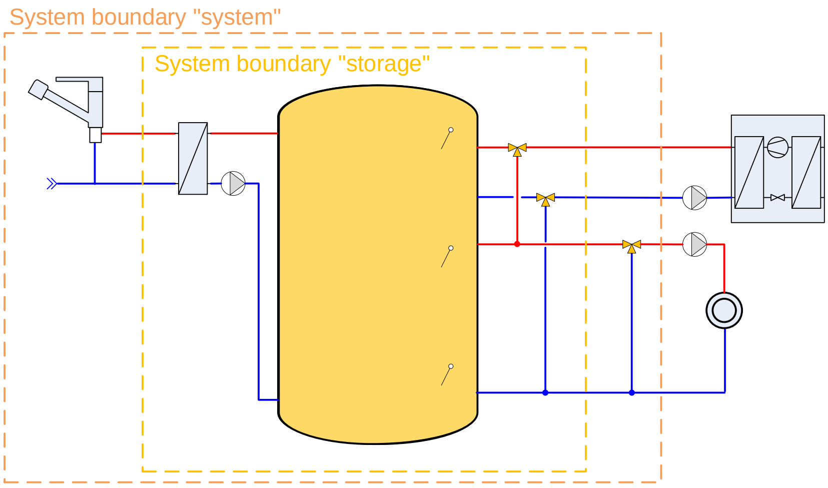

Fig. 1: Hydraulic scheme of the storage system, including the system boundaries for the subsequent measurement.

For a storage tank used in combination with a heat pump, the thermal stratification is of particular importance, since the efficiency of the heat pump depends on the temperature at which it has to provide heat. Three main processes deteriorate stratification and therefore increase the electricity consumption of the heat pump:

- Heat conduction and thermal diffusion processes in the storage medium and in the material of the containment and internal objects such as heat exchangers,
- plume entrainment caused by buoyant fluid movements, and
- inlet jet mixing caused by the kinetic energy and turbulences from direct charging.

In the basic configuration, a combistore with a volume of 1000 l was assumed, whose data was provided by the industrial partner. As a first step, the position of the inlets and outlets and the temperature sensors on the storage tank were optimized using system simulations. For this purpose, the individual connection heights and sensor positions were varied within a certain range in a large number of annual simulations, thus finding an optimum in terms of energy consumption of the overall system. These simulations were carried out with the program TRNSYS. In the simulation, the multiport store model from Drück & Pauschinger (2006) with a vertical node count of 100 was used. The mixing processes caused by inlet jet mixing in the storage tank were not represented by the model. Plume entrainment (which is only represented in the model in an idealized way) is avoided by the appropriate selection of the inlet positions.

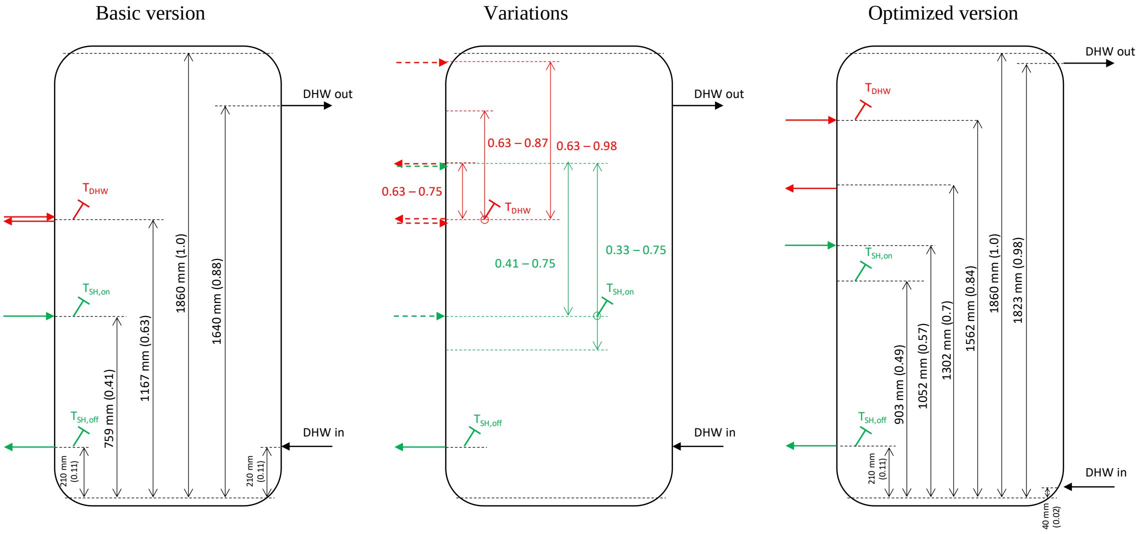

Fig. 2: Optimization of storage tank connections and sensor positions (left: original configuration or basic version, middle: variation ranges, right: optimized variant).

In the simulations of the overall system, the optimized connection configuration leads to a reduction of the system electric energy consumption by 4 % compared to the initial situation (Fig. 2 left). A detailed description of the simulation model and the boundary conditions can be found in a second contribution to the EuroSun 2020 conference in Heinz et al. (2020), entitled "Photovoltaic Heat Pump System for Renovated Buildings – Measures for Increased Efficiency". As already shown in the work of Gwerder et al. (2016), the geometry of the storage tank inlets has a very large effect on the stratification efficiency and the conservation of exergy in the storage tank, especially at high charging volume flow rates, as they occur with heat pumps. This is particularly important for operation with a heat pump, because a loss of exergy (or production of entropy) in the storage tank inevitably leads to a lower COP of the heat pump during charging and thus to higher electricity consumption of the system (compare Haller et al. 2019).

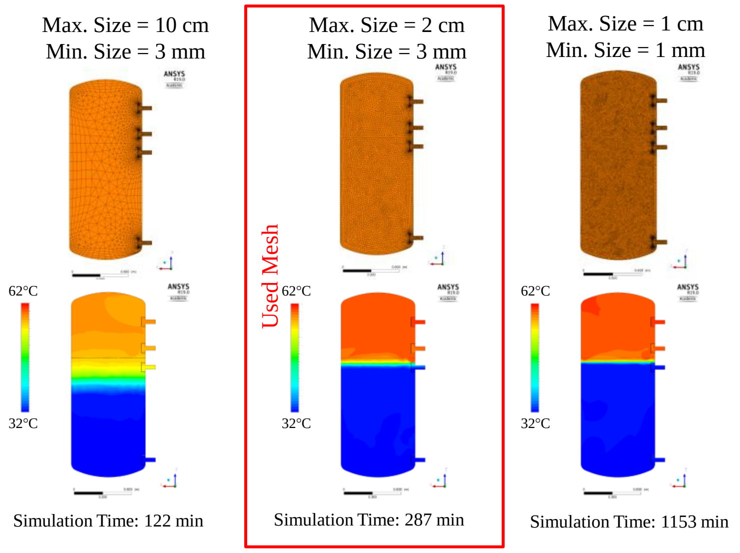

Fig. 3: Overview mesh study. Simulation type: DHW charging.

CFD simulations with ANSYS CFX 19.1 were carried out to determine a suitable inlet geometry, respectively a diffuser. The Scale-Adaptive Shear-Stress-Transport-Model was used as turbulence model. The influence of the mesh was first determined by a mesh study and a meaningful grid size for the simulation was determined. Fig. 3 shows an overview of the mesh study: The thermocline in the storage tank during the process of DHW charging was examined after 20 minutes of time with an inlet mass flow rate of 2750 kg/h for a diffusor design that ensures a velocity into the bulk storage volume of < 0.1 m/s. Different tetrahedron meshes were used. The figure shows good correspondence between the results of the simulations shown in the middle (max./min. size of 20/3 mm) and on the right (max./min. size of 10/1 mm), and the meshing shown in the middle was chosen. Subsequently, charging and discharging processes of both the DHW zone and the space heating zone of the storage tank were simulated with different diffuser geometries. The diffusor design was intended to keep the mixing inside the storage tank as low as possible despite the high volume flow rates. Nine different diffuser geometries were simulated and their stratification behavior examined: Five different variants of a baffle plate and/or a division into flow channels, three different geometries that can be folded from one sheet metal and fixed to the storage wall by spot welding and one variant with a perforated plate at the inlet to the storage volume. Special attention was paid to the charging of the space heating zone, as the upper part of the storage tank is reserved for the storage of heat for DHW at much higher temperatures and should not be influenced negatively (i.e. the temperature in this region should not decrease) during this process. Fig. 4 shows exemplary the temperature distribution in the storage tank after 7 min. of space heat charging, for various diffusor geometries. Each of the shown simulations started with the same temperature of 50 °C in the upper part of the storage tank above the separating plate.

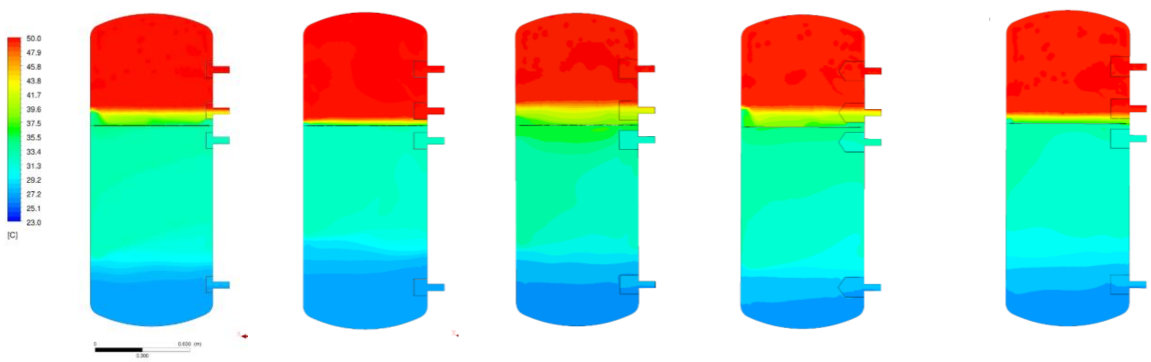

Fig. 4: Temperature distribution in the storage tank after 7 min. space heat charging simulated by CFD, for various inlet diffusors; each simulation started with the same temperature of 50 °C in the upper part of the storage tank.

The inlet geometry that was finally chosen meets the recommendations defined in Gwerder et al. (2016):

- The Reynolds number of the flow at the entrance should be below a certain value, i.e. less than 3000–7000, velocities should be below 0.1 m/s as suggested by Jenni (2000), and possibly even lower for larger inlet diameters and larger mass flow rates.
- The flow has to be sufficiently developed, requiring a minimal entrance length of 3 - 4 times the hydraulic diameter after a change of cross section or flow direction.

According to the geometries and dimensions determined with the help of various simulations, a storage tank was produced by the company Solarfocus and sent to the Institute for Solar Technology SPF for testing.

3. Measurement of stratification efficiency

3.1 Test method

A test method to measure the stratification efficiency as key performance indicator was used. The Concise Cycle Test (CCT) method follows the hardware-in-the-loop concept: The storage, including the hydraulics for charging and discharging (compare Fig. 1), is installed on the test bench. The test bench emulates the thermal load as well as a heat pump to provide heat according to the actual temperature in the storage tank. A predefined 24 h load profile for DHW and space heat demand is used and repeated several times in succession (compare Haller et al. 2018).

The space heating load of the test day is 42.5 kWh at a constant outside temperature of 2.5 °C. Fig. 5 shows the continuous target value for space heating. The test bench emulates both the heating circuit pump and the heating circuit mixer. The return temperature is determined and emulated based on the supply temperature, which is derived from the temperature delivered by the storage and the hydraulics, in combination with the current target heating power and heat transfer rate to the heated room. The target supply temperature for the space heating system remains constant at 30 °C during the test. To successfully complete a test, the supply temperature must be high enough for delivery of heat to a room with 20 °C temperature and a given floor heating system with its heat transfer capacity, and the average supply temperature during the test must be higher than 30 °C. The daily DHW demand is 9.45 kWh, corresponding to a consumption of 232 l at a cold water temperature of 10 °C and a hot water temperature of 45 °C.

To emulate the heat pump, a model of a non-power-controlled air-to-water heat pump with a nominal power of 15 kW at A7/W35 was used. The mass flow rate in the heat pump emulation is set to 2570 kg/h, which corresponds to a temperature spread of 5 K for the nominal heating capacity.

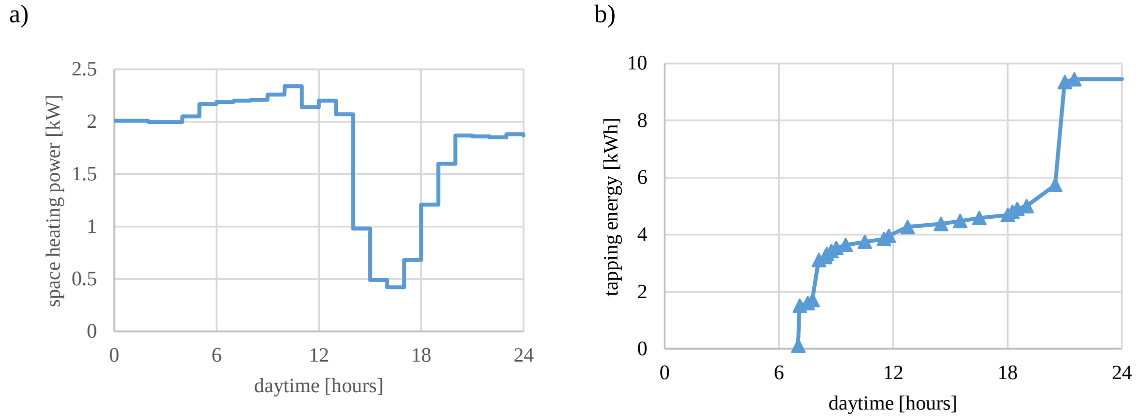

Fig. 5: Space heating load (a) and DHW profile (b) of the test cycle.

The test method is based on the fact, that mixing of fluids with different temperatures results in (measurable) entropy production. The method thus uses the second law of thermodynamics by measuring the irreversible entropy production of storage systems ($\Delta S_{irr,exp}$) during realistic operation. From the entropy production measured during the test cycle, the stratification efficiency (ζ_{str}) is determined as a dimensionless quantity. For this purpose, the measured entropy production is set in relation to the entropy production of a completely mixed storage unit ($\Delta S_{irr,mix}$)[1]:

$$\zeta_{str} = 1 - \frac{\Delta S_{irr,exp}}{\Delta S_{irr,mix}} \qquad \textbf{(eq. 1)}$$

The stratification efficiency thus describes how well the storage tank "does its job" compared to a completely mixed storage tank (worst case). A perfectly stratified system[2] would achieve a stratification efficiency of 100 %. A completely mixed storage 0 %. The method is described in detail in Haller et al. (2018, 2019).

Not only stratification processes in the storage tank are relevant for the stratification efficiency, but also mixing processes and heat transfer in the hydraulic system for charging and discharging the storage tank. Therefore, external heat exchangers, such as for DHW preparation, the additional pumps provided for this purpose and the corresponding hydraulics are also included in the system boundary. In Fig. 1, different boundaries for the balancing are drawn, whereby the boundary "system" describes the decisive variable.

3.2 Test results

During the stratification efficiency test, the heat pump is switched on and off according to the temperature in the storage tank. Fig. 6 shows the positions of the sensors used for this. The selected set-point temperatures are shown in Table 1, whereby it should be noted that hot water production was limited to two time windows per day (from 2:00 to 4:00 and from 16:00 to 18:00). The target temperature set in the DHW heat exchanger was 47 °C. This allowed a DHW temperature of 45 °C to be guaranteed at all times.

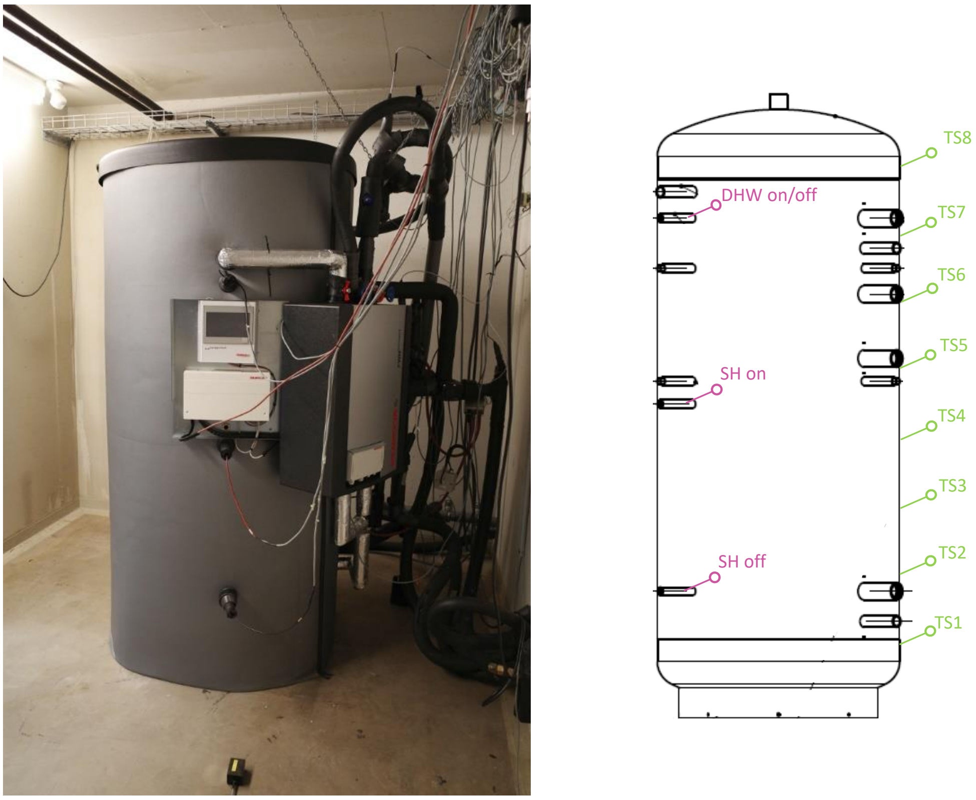

Fig. 6: Storage tank including the hydraulics on the test bench (left) and the positions of temperature sensors for the control of the heat pump (DHW on/off, SH on/off) as well as the positions of the temperature sensors, which were fixed equidistantly to the tank wall with a sensor tape for monitoring purposes (right).

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[1] The worst case is a completely mixed storage tank, which must always be charged with the maximum supply temperature of the heat pump of 55 °C.

[2] A perfectly stratified system is not physically possible, so the result of the measurement will always be less than 100 %.

Table 1: Set-point temperatures (for control of the heat pump).

DHW on	°C	47
DHW off	°C	51
SH on	°C	25
SH off	°C	27

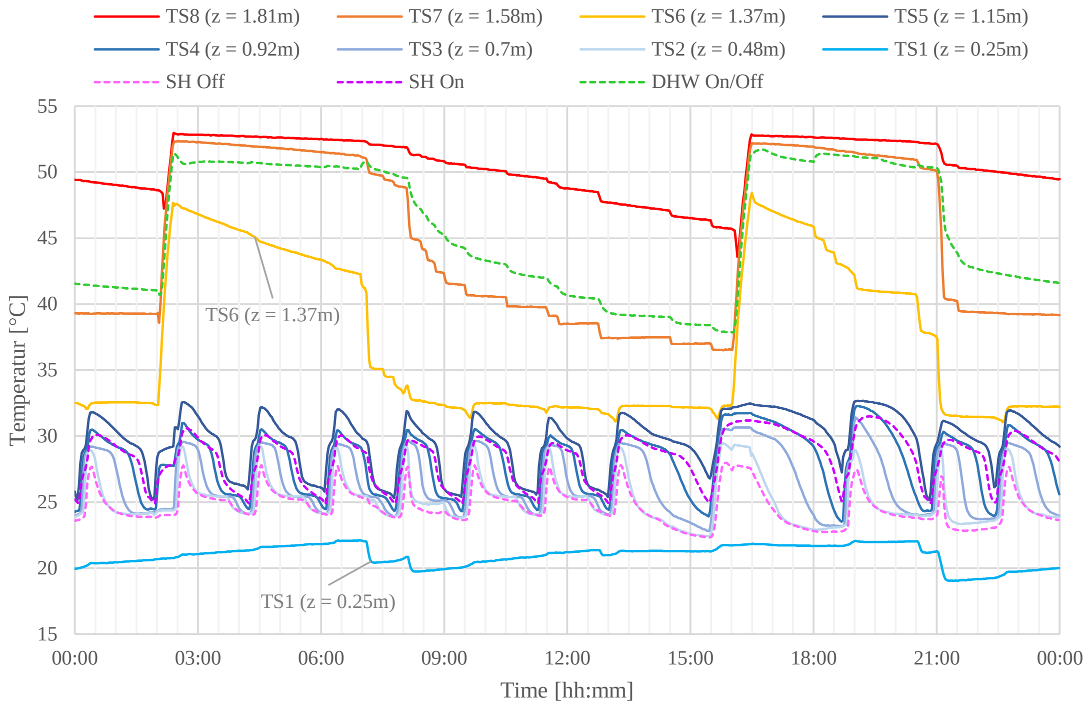

Fig. 7: Temperatures during the measurement. In addition to the contact sensors TS1 to TS8 on the storage tank wall that were used for monitoring only, the temperatures for controlling the heat pump for hot water (WW) and space heating (RH) are also shown.

Fig. 7 shows the temperature curves during the 24-h test cycle. These show a good separation of the DHW zone from the space heating zone. During the charging of the DHW zone at 2:00 and 16:00, the temperatures in the lower part remain unaffected. Also during the charging of the space heating zone, only sensor TS6 close to the interface between the two zones is influenced slightly.

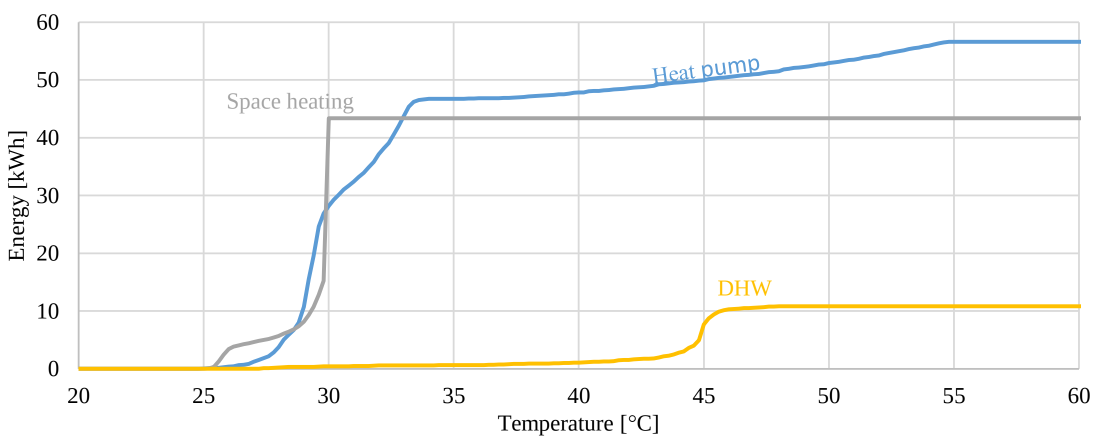

Fig. 8: Energy temperature diagram of the measurement.

Fig. 8 shows an energy-temperature diagram of the measurement. In this diagram, the energy supplied to the system from the heat pump as well as the energy supplied by the system for space heating and hot water are sorted according to their supply temperature. The sharp edge for the space heating curve results from the fact that the mixing to the target flow temperature of 30 °C was not done with a mixer installed in real life, but was calculated by the test bench software. It can be seen that approx. 47 kWh were delivered by the heat pump with a supply temperature below 34 °C, i.e. slightly more than was necessary to cover the space heating demand. The reason for this is the preheating of the hot water supply in the lower part of the storage tank. The shown line of the heat supply by the heat pump shows a bend in the area of the heat supply for the space heating. Up to a flow temperature of 30 °C the flow temperature remains constant over a longer period of time. During this time the thermocline in the storage tank is pushed down. Once the space heating zone has been completely charged, the return temperature rises and so does the flow temperature shown. Only with the second cycle the temperature is raised to the required temperature.

The energy balances and the entropy produced in the storage system are shown in Table 2 and Table 3. In each test, the 24-hour test cycle is repeated without interruption until the results of three consecutive test cycles are practically identical. This report shows the average values from the last three consecutive test cycles. The stratification efficiency is reflected in the measured entropy production in the system (Table 3). This should be as low as possible for a good stratification efficiency.

Table 2: Results of the stratification test – energy balance in kWh.

Heat pump (total heat)	55.32
Heat pump (heat in DHW-mode)	9.38
Space Heating	42.22
DHW (above 40 °C)	9.45
DHW (below 40 °C) [(a)]	1.37
Storage change [(b)]	0.26
Losses	2.05

(a) When tapping DHW, the heat is only defined as useful heat when 40 °C is reached.

(b) Difference in the energy content of the storage tank at the beginning and end of the 24 h test cycle (identical energy content is desired).

Table 3: Results of the stratification test - entropy production in the storage system in kJ/K. Low values mean good stratification and exergy conservation.

Within the storage tank	7.52
In the hydraulics	1.11
Total	8.64
Total Entropy production of a fully mixed storage tank	54.00

From the entropy balance, the stratification efficiency is calculated for the balance boundary already described (see Fig. 1):

- "Storage": For the storage tank with all internal and external heat exchangers and the hydraulics for charging and discharging. This key figure provides information about the stratification behavior of the storage tank including the loading hydraulics and heat exchangers.
- "System": For the storage system including discharge hydraulics. This figure also takes into account the entropy production in the mixing valves for space heating and hot water ("balance limit system").

The difference between the two figures provides information about the influence of the integration of the storage tank into the system and the control of the charging and discharging. The numbers are shown in Table 4 together with the repeatability of the results[1].

The DHW ratio is the ratio of the amount of heat supplied by the heat pump in DHW mode to the actual DHW drawn from the storage tank. This figure gives an important indication for the quality of the separation of the different zones for hot water and space heating in the storage tank and is therefore a good indicator for the storage concept and management. The aim should be to achieve the lowest possible value for the hot water ratio[2].

[1] Specified by twofold standard deviation of the mean value from three successive measurements.

[2] Assuming that the water in the lower part of the storage tank is preheated to the temperature of the space heating system, the amount of heat supplied by the heat pump for hot water should not exceed the amount of heat drawn from the storage tank.

Table 4: Stratification efficiency and DHW ratio.

Stratification efficiency storage (%)	**86.07**
Twofold standard deviation (%)	0.11
Stratification efficiency system (%)	**84.01**
Twofold standard deviation (%)	0.02
DHW ratio (-)	**0.87**
Twofold standard deviation (%)	1.34

Table 5 shows the power weighted average temperatures of heat input and heat output. The average supply temperature of the heat pump is determined according to eq. 2. The average temperatures for the heat output are determined in the same way.

$$\overline{T_{HP,flow}} = \frac{\sum(T_{HP,flow,i} \cdot \dot{Q}_{HP,i})}{\sum \dot{Q}_{HP,i}} \quad \textbf{(eq. 2)}$$

Table 5: Average flow temperatures of the heat input and heat output, weighted according to output.

Heat input	
Heat pump [°C]	33.1
Heat output	
Space heating [°C]	30.4
DHW [°C]	43.5

Fig. 9 shows the stratification efficiency (green) of the system. It also shows the loss of stratification efficiency, which is due to entropy production in the storage including discharging heat exchanger (dark grey) or in the hydraulic system, i.e. DHW and space heating mixing valve that reduce the supply to the temperatures that were actually needed (light grey).

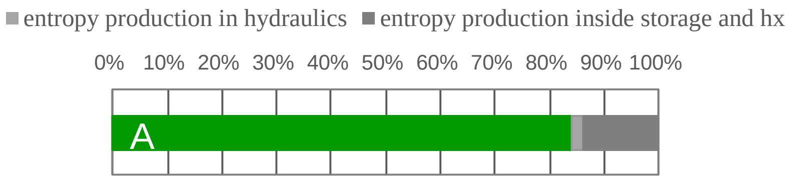

Fig. 9: Stratification efficiency and stratification losses of the storage system.

4. Comparison of simulations with measurement

After completion of the stratification test with the combined storage tank, the same test cycle was applied to the simulation model of the storage tank in TRNSYS. Fig. 10 shows the temperature curves obtained from measurements as well as from simulations. It can be seen that the storage temperatures during charging by the heat pump for hot water as well as for space heating match quite well between measurements and simulations. A difference can be seen especially in the discharging of the storage tank through the DHW heat exchanger: The temperatures in the upper part of the storage tank remain high for a longer time in the simulation than in the real measurement. The temperature in the lowest section of the storage tank is lower in the simulation than in the measurement.

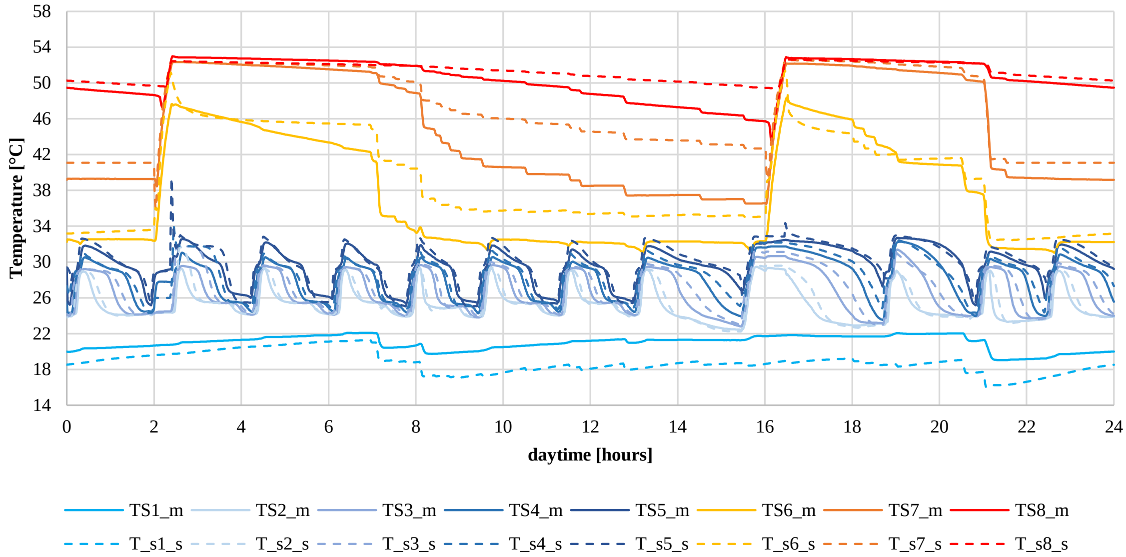

Fig. 10: Comparison of simulated (_s) and measured (_m) temperatures of the combistore, with the initial parameters of the simulation.

In order to achieve a better agreement of the simulations with the measurements, a few parameters in the DHW heat exchanger and its hydraulic integration had to be adjusted. The target temperature of the DHW heat exchanger was adjusted to 47 °C according to the real measurement, the pipe length between the DHW heat exchanger and the storage tank was increased to 1.5 m instead of 0.5 m and the UA-Value of the DHW heat exchanger was reduced by 20 %. Due to these small adjustments a much better agreement of the simulation with the measured data was achieved, which is shown in Fig. 11.

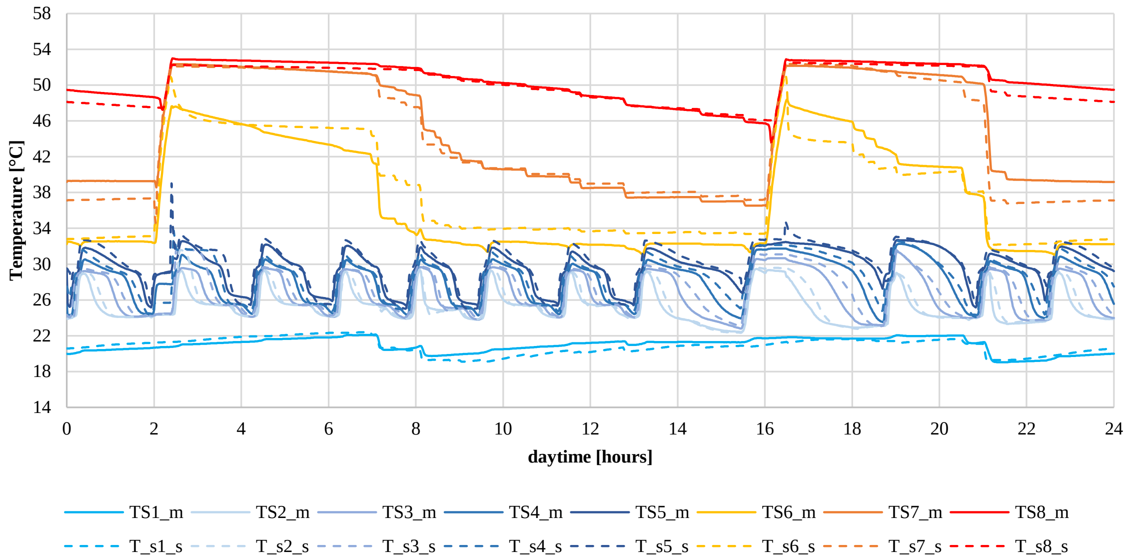

Fig. 11: Comparison of simulated (_s) and measured (_m) temperatures of the combistore after adaption of the simulation parameters of the DHW heat exchanger and its hydraulic connections.

6. Summary

In this work the development and testing of a combistore for the combination with a heat pump is described. The appropriate size and segmentation of the storage in different zones was determined with simulations in TRNSYS, using a storage model that cannot simulate mixing processes due to high flow velocities (inlet jet mixing) but takes into account the effects of incorrect positioning of the connections. An optimization of the connection heights led to a 4 % reduction in energy consumption in the simulations.

With the help of CFD simulations in ANSYS CFX, a diffuser design was developed which calms the incoming flow to such an extent that an existing thermocline in the storage tank is not destroyed even at mass flows of 2750 kg/h.

The stratification efficiency of the combistore developed in this way was then measured. For this purpose, the storage tank, including the hydraulics for charging and discharging and a DHW heat exchanger, was installed on the test rig. The test method follows the hardware-in-the-loop and concise cycle test concepts: The test bench emulates the charging and discharging processes according to a predefined 24-hour load profile and the actual temperature in the storage tank. During this dynamic and realistic operation, the entropy generated within the storage system is determined. By comparing the measured entropy with the entropy production of a fully mixed storage tank, the stratification efficiency can then be determined on a scale from 0 % (fully mixed) to 100 % (ideally stratified).

The storage tank performs very well with a stratification efficiency of 84 % at system level when charged by a 15 kW heat pump with a flow rate of 2570 kg/h. The separation of the temperature zones for hot water preparation above and the space heating zone below remains intact even when the storage is charged with the high mass flow rate mentioned above. As a result, the heat pump can be operated with a low supply temperature (the power weighted average supply temperature of the heat pump was 33 °C) and thus at a favorable operating point, with high efficiency. The ratio of the amount of heat supplied by the heat pump in hot water mode to the actual hot water drawn from the storage tank was 0.87 - a further indication of good separation of the different temperature zones in the storage tank.

A comparison of the measured data from the stratification test with the TRNSYS simulation model shows that the mixing in the storage tank (due to the incoming volume flow) is prevented so well that an exact image of the storage tank can be simulated even with a simulation model, which cannot represent inlet jet mixing processes. In order to closely match the measured temperatures of the storage tank with simulations, only adjustments of the integration of the DHW heat exchanger were necessary.

7. Acknowledgements

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