SIMULATION AND EVALUATION OF STRATIFIED DISCHARGING AND CHARGING DEVICES IN COMBINED SOLAR THERMAL SYSTEMS

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1. Introduction

Combined solar thermal systems for domestic hot water preparation and space heating are usually equipped with water storage tanks. The stratification behavior of the tank including its external connections is significant for the collector yield and the saving of conventional backup energy. The charging and discharging units take a decisive role for the development of the stratification. While many studies analyzed the stratified charging process in detail, investigations about stratified discharging units are rare. Stratified discharging means, that the fluid is leaving the tank from at least two different heights, which are nearest to the demand temperature, using a mixing device, in order to consume the smallest possible amount of the hottest water. It could more clearly be called “layer related discharging”.

This simulation study analyzes the effects of different discharging and charging strategies on the performance of a combined solar thermal system in a single-family house. Based on the system according to Task 32 of the Solar heating and Cooling Program of the International Energy Agency (IEA SHC) the system layout and in specific the storage connections are modified to investigate different stratified charging and discharging concepts realized by external valves or devices within the storage tank.

2. System configuration and variants

The simulation study presented in this paper evaluates different charging and discharging devices in a solar thermal combisystem. All simulations were carried out using the TRNSYS simulation environment, Klein et al. (2005). The starting point is the system design according to IEA Task 26 and Task 32 described in Weiss et al. (2003). The basis system covers the heat load of a single-family house (SFH100) with an area of 140 m² and a space heating demand of 100 kWh/m²a (design temperatures 60°C/50°C) at the location Zürich, Switzerland. The hot water consumption and its load profile correspond to the requirements according to Task 32 (200 l/day at 45°C, i.e. 3 MWh/a). In total, the useful energy demand amounts to 17 MWh/a. The system is simulated in two sizes of the solar thermal system – a small (15 m² and 0.75 m³) and a large collector storage combination (30 m² and 5 m³). Fig. 1 shows the system configuration and the relative heights of all storage connections for storage volumes of 0.75 m³ and 5 m³.

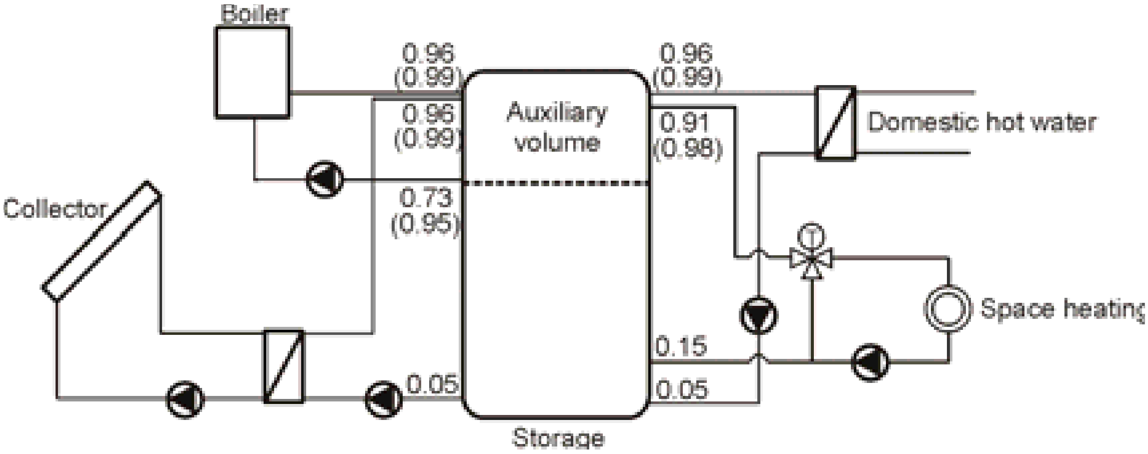

Fig. 1: System configuration according to IEA Task 32 with the relative connection heights at storage volumes of 0.75 m³ and 5 m³ (latter in brackets if deviating)

The positions for the in- and outlet connections displayed in Fig. 1 are calculated according to Heimrath and Haller (2007) as a function of the storage volume. The resulting heights might not be the optimum layer positions with the highest fractional energy savings. Therefore, in a first step, pre-simulations are carried out to find the optimum positions for solar inlet and space heating in- and outlet. In the following, these heights are used as the reference case.

The reference case layout and in specific the storage connections are modified to investigate different stratified charging and discharging concepts. One stratified charging concept is realized with an external three way valve and two storage connections (similar to Zass et al. (2007), see Fig. 2a, points A), this concept is considered for the solar (from collector) or the space heating (return flow) inlet. Beside this external connection, the storage tank model by Drück (2006) allows to adjust an ideal charging, which means that the fluid enters the layer with the same or nearest temperature. The ideal charging is considered for all four inlets (auxiliary heating, solar circuit, domestic hot water and space heating circuit).

The stratified discharging is realized for the space heating flow with a four-way mixing valve (see Fig. 2a, on the right hand side of the storage tank, point B). Such a four-way valve represents in principle two three-way valves in serial connection with three inlets and one outlet. Two inlets are mixed to reach the required set temperature; a mixing of all three inlets is not possible (and not useful). In addition, an idealized mixing device of the storage and the return pipe is approached with seven connections to the storage tank (Fig. 2b).

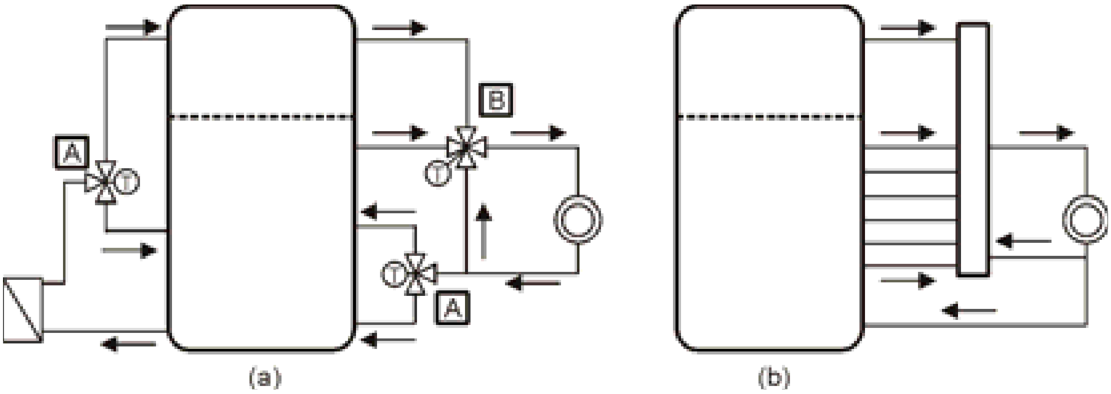

Fig. 2: Variants of stratified charging and discharging, on the left hand side: Three-way distributing valves (points A) for stratified charging of solar flow and space heating return and four-way mixing valve with thermostat (point B) for stratified discharging of space heating flow (a), on the right hand side: idealized stratified discharging of space heating flow with seven tapping outlets (b)

Beside the basic system the study investigates six system variants including an “optimum system” with an ideal stratified charging of all inlets and an idealized discharging of the space heating outlet.

Each variant is evaluated by the yearly collector yield and the yearly final energy demand of the boiler (Q_{Fin}, related to the net calorific value of the auxiliary energy source natural gas). Furthermore, the fractional energy savings are calculated according to Weiss (2003), see equation (1).

$$f_{Sav} = 1 - \frac{Q_{Fin} + \frac{W_{el}}{\eta_{el}}}{Q_{Fin,without\ Solar} + \frac{W_{el,without\ Solar}}{\eta_{el}}} \qquad \text{(eq. 1)}$$

The fractional energy savings f_{Sav} compare the final energy demand of the boiler and the electricity demand W_{el} of the system with solar thermal collectors with a conventional system without solar thermal support. The electricity demand is weighted with the electrical production efficiency η_{el}. Within this study a constant value of 0.4 is used. The consumption of natural gas and thus the final energy demand of the boiler are determined directly with Type 869 according to Haller (2009).

3. Annual simulation results of reference cases and variants

Within IEA Task 32 and Heimrath and Haller (2007) the positions are calculated depending on the storage volume. It is not guaranteed that these heights are the optimum positions with the highest fractional energy savings. However, since the stratified charging and discharging concepts should be compared to the best possible system without such devices, pre-simulations were necessary to determine the optimum positions for solar inlet and space heating in- and outlet. An optimization procedure is adopted to reduce the amount of simulations. First, the solar inlet is optimized while all other connections are kept at the values according to Task 32. With the optimal position of the solar inlet the procedure continues with the space heating inlet and afterwards with the space heating outlet. It cannot be excluded that there might be a combination of connecting heights, which still lead to a higher f_{Sav}, but the difference would be small if compared to the results of the procedure described above.

In order to identify the optimized second inlet position when using a three-way valve for stratified charging and the second outlet position for the four-way valve at stratified discharging according to Fig. 2a, a corresponding procedure as for reference cases has been applied. The optimum second in- or outlet positions were determined while the respective first position was taken from the reference cases.

The reference cases and all variants are simulated over one year with a time step of 3 minutes. The energy demand for the system without any solar collectors, the final energy demand for the boiler is 21.5 MWh/a and for the electricity (all pumps and boiler) 1.8 MWh/a. The yearly simulations of the two reference cases result in a final energy demand of the boiler of 17.0 MWh/a (small system) and 14.4 MWh/a (large system) with fractional energy savings of 18.1% and 29.3%, respectively. The collector yields are 307 kWh/m²a (small) and 290 kWh/m²a (large). Fig. 3 shows the increase in collector yield and the reduction in gas consumption and final energy demand of the boiler for the six alternative system variants. In addition, the figure lists the fractional energy savings for all systems.

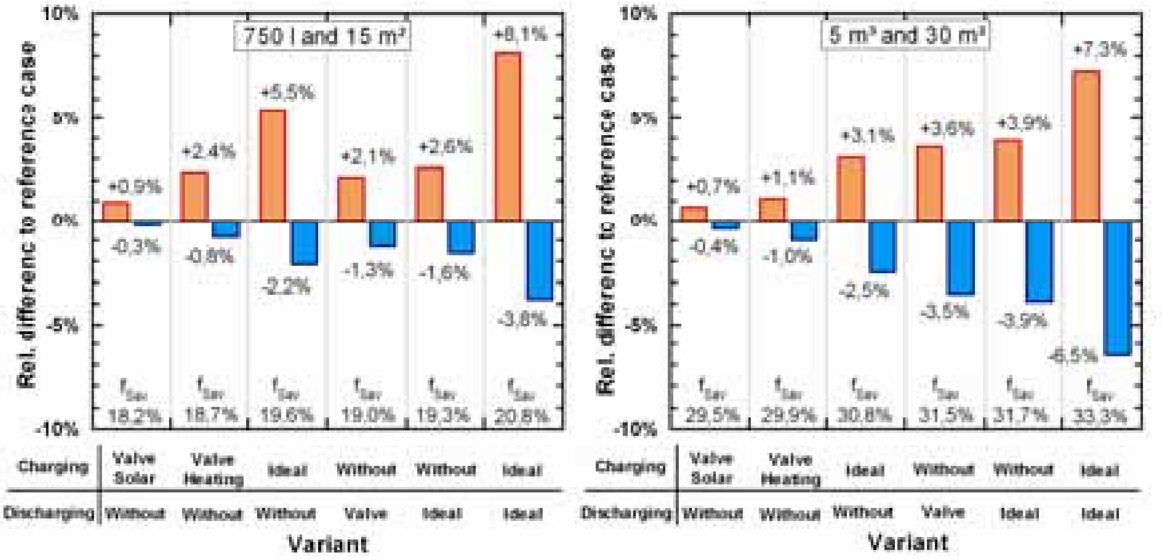

Fig. 3: Relative differences and fractional energy savings f_{sav} of the variants to the related reference cases, small system (left) and large system (right); the solar yield increase is marked by positive orange bars, the final energy demand reduction is marked by negative blue bars. Results for simulations with single family house with heat load of 100 kWh/m²a (SFH100), reference case f_{sav}-values: 18.1% for small (left) and 29.3% for large system (right))

The results show that the relevance of a stratified discharging is at least as high as for the stratified charging; thereby significant differences can be detected depending on the size of the system. In the small system a stratified discharging with a four-way valve leads to a solar yield increase of 2.1%. This is more than double the value of 0.9%, which is achieved with a three-way valve for the stratified charging of the solar inlet. For that variant the reduction in final energy demand is only marginal at 0.3%. With a three-way valve in the space heating inlet the collector yield increases by 2.4%, which is more than that for the space heating discharging option with a four-way valve. However, the final energy demand reduction and the fractional energy savings are higher (19% to 18.7%) in case for the discharging variant.

The energy savings with the idealized discharging device with seven outlets is only marginal higher than the variant with one four-way mixing valve. A higher collector yield increase and energy demand reduction is reached with an ideal stratified charging of all inlets, whereby the stratified charging of the space heating return contributes the highest share of the additional energy savings. In combination with the idealized discharging the final energy demand can be reduced by 3.8% and the fractional energy savings are at 20.8%, these are 2.7%-points more than in the reference case.

In the large system the advantages of the stratified discharging are more pronounced. The values for stratified charging are in the same magnitude like in the small system. In contrast to this, the benefit of the discharging variants increases significantly: The reduction in final energy demand with four-way valve is -3.5% compared to -1.3% in the small system. With only one four-way valve the collector yield increase and the final energy reduction are higher than with an ideal stratified charging of all inlets. As in the small system the additional benefit by an almost ideal discharging device is only small. In the best system, having idealized charging and discharging devices, the collector yield increases by 7.3% and the final energy demand decreases by 6.5%.

4. Annual simulations with a low-energy house

Until now, all simulations were carried out with a single-family house having a heat demand of 100 kWh/m²/a (SFH100 with overall 17.5 MWh/a). This section presents simulation results with a single-family house having a lower heat demand of 60 kWh/m²a (SFH60 with overall 8.4 MWh/a for heating) and reduced design temperatures in the space heating circuit (40°C/35°C). The optimization of the in- and outlet positions was repeated with the new heating load.

The reference cases with the optimized connection heights have a yearly final energy demand of the natural gas boiler of 10.7 MWh/a (small system) and 8.7 MWh/a (large system) with energy savings f_{Sav} of 21.9% and 34.6%, respectively, whereby the system without solar collectors would require 14.4 MWh/a final energy demand for the boiler and 1.6 MWh/a for the electricity. The collector yield is 298 kWh/m²a (small) and 270 kWh/m²a (large). Fig. 4 shows correspondingly to Fig. 3 the results for the different charging and discharging variants.

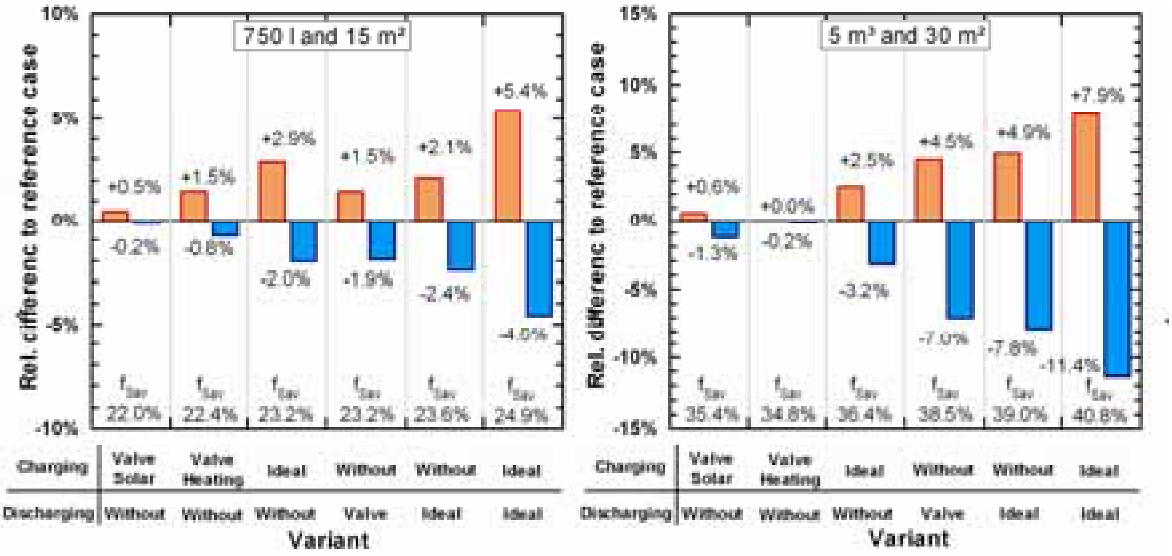

Fig. 4: Relative differences and fractional energy savings f_{sav} of the variants to the related reference cases, small system (left) and large system (right); the solar yield increase is marked by positive orange bars, the final energy demand reduction is marked by negative blue bars. Results for simulations with single family house with heat load of 60 kWh/m²a (SFH60), reference case f_{sav}-values: 21.9% for small (left) and 34.6% for large system (right))

In comparison with the SFH100 cases, the advantages of the stratified discharging variants increase, especially if compared to the stratified charging strategy based on three-way valves. In the small system even an ideally stratified charging at all inlets does not lead to higher energy savings than with one four-way valve (both 23.2%), although the increase in collector yield is far higher (2.9% compared to 1.5%). Within the large system the increase in energy savings are more than double as high for the stratified discharging if compared to the ideal charging (-7.0% to -3.2%).

The benefits from stratified charging strategies with three-way valves are smaller with the SFH60. Especially within the larger system the valve for return space heating line shows almost no improvement. This may be the result of the lower design temperatures, and thus the lower space heating return temperature.

The additional energy savings by stratified discharging are higher with the SFH60 than with the SFH100. However, the increase in the collector yield is slightly higher for the SFH100.

It may be derived both for the SFH60 and SFH100 (see figures 3 and 4), that stratified discharging often has a higher final energy saving effect than the stratified charging devices, which on the other hand in many cases lead to higher solar yields. As the reduction of the conventional energy consumption is in the focus of an efficient heating system, exclusively energy savings should be taken for the performance assessment of a stratified charging or discharging device, while the solar yield is only additional information of lower importance.

5. Discussion

Table 1 summarizes the results for the four reference cases and the benefits from the variants with ideal stratified charging of all inlets and stratified discharging with one four-way valve. The table lists the simulations made with both space heating loads as introduced above.

Tab. 1: Overview of the simulated results for the reference cases and increase in collector yield (percental values) and fractional energy savings (absolute percentage point values) for the variants ideal stratified charging of all inlets and stratified discharging with one four-way mixing valve

System	Collector yield			Fractional energy savings f_{Sav}		
	Reference	**Charging**	**Discharging**	**Reference**	**Charging**	**Discharging**
SFH100 750 l, 15 m²	**307 kWh/m²a**	+5.5%	+2.1%	**18.1%**	+1.5%	+0.9%
SFH100 5 m³, 30 m²	**290 kWh/m²a**	+3.1%	+3.6%	**29.3%**	+1.5%	+2.2%
SFH60 750 l, 15 m²	**298 kWh/m²a**	+2.9%	+1.5%	**21.9%**	+1.3%	+1.3%
SFH60 5 m³, 30 m²	**270 kWh/m²a**	+2.5%	+4.5%	**34.6%**	+1.8%	+3.9%

The overview points out that the benefits of the two listed stratification variants depend on the system size and the building heat load. The collector yield increases by ideal stratified charging varies between 2.5% to 5.5%, while with the stratified discharging the increase is a bit lower with values from 1.5% to 4.5%. With regard to the energetic advantages, the fractional energy savings of the ideal stratified charging show an almost system independent increase of 1.3 to 1.8%, while the stratified discharging has a significant higher dependency. The final energy savings increase by 0.9% in the small system and the high heat load (SFH100) to 3.9% in the large system and the low heat load (SFH60). Especially with the large storage tank the discharging device improves the system performance more significantly even than an ideal stratified charging at all inlets.

6. Conclusions

The results of the study show, that a good thermal stratification within the storage, and thus higher energy savings, can be achieved by applying stratified charging and discharging devices. Depending on the system size and the design of the charging and discharging connections the stratified discharging leads to the same or even higher energy savings than a stratified charging. Already one single four-way mixing valve in the space heating flow (i.e. two tapping points) leads to more than 80% of the advantage of an idealized discharging with seven tapping points. The relative energy savings increase with increasing solar fraction, e.g. with larger system dimensions and better insulated buildings. The advantage appears particularly during the transition period. In spring and autumn, the storage tank is better utilized with a stratified discharging. It can be assumed that in this case the storage tank can be dimensioned smaller when using a discharging valve.

The stratified discharging with a four-way mixing valve improves the stratification without any changes inside the storage tank (if there are enough outlets). In the case of retrofitting or improving a solar system the constructive effort is significantly lower than e.g. installations inside the tank, which would be necessary with an ideal charging device. Therefore, stratified discharging strategies should be considered as more important in solar thermal systems, especially in systems and buildings with a high solar fraction. In case of solar active buildings with fractional energy saving values of above 50%, it is thus recommended to take stratified discharging devices into consideration.

However, the best option with the highest benefit depends on the system design like storage in- and outlet positions, system size and load conditions. Therefore, simulations are in general necessary to decide, which stratification strategy leads to the best results.

7. References

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8. Nomenclature

f_{Sav}	Fractional energy savings (-)
η_{el}	Electrical production efficiency
Q_{Fin}	Yearly final energy demand (MWh/a)
W_{el}	Yearly electricity demand (MWh/a)
Subscripts	
IEA	International Energy Agency
SFH	Single Family House
SHC	Solar Heating and Cooling Program