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Thermal storage concept for solar thermal power plants with direct steam generation

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Abstract

One possibility to increase the efficiency and thus economic viability of solar thermal power plants is to increase their operating temperature. This approach demands the substitution of the state-of-the-art heat transfer fluid (HTF) that limits the operating temperature to roughly 400°C. Promising heat transfer fluids for future applications are molten salts or water/steam. If water/steam is used as HTF, the feed-water from the power block is fed to the solar field (SF) and directly evaporated and superheated. This process is called direct steam generation (DSG). A recent study [1] has pointed out that the economic potential of the DSG process is utilized only, if the SF design is simplified and a competitive thermal storage is available. Thus, an R&D project was launched in Germany to develop a complete storage system covering the energy of the evaporation as well as of the pre- and superheating section. It consists of a phase change material (PCM) storage for evaporation and a molten salt storage for pre- and superheating. One specific feature of superheated steam is its changing specific heat capacity with temperature. Using molten salt as storage medium with a nearly constant specific heat and the application of an obvious simple heat exchange would lead to an inefficient process. A significantly reduced live steam temperature and thus power block efficiency during discharge would be the results. Furthermore, the specific storage density of the molten salt system would be reduced too. In this paper this effect will be discussed in more detail. The consequences for the storage system will be discussed and solutions of the developed processes for the integration of such storage into a DSG power plant will be presented that reduce or overcome the mentioned restrictions.

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Keywords: Thermal energy storage; Phase change material; Molten salt; Concentrated solar power; Direct steam generation; System analysis

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Nomenclature

CSP	concentrated solar power	PB	power block
DSG	direct steam generation	PCM	phase change material
HTF	heat transfer fluid	SF	solar field

1. Introduction

The direct steam generation (DSG) in solar thermal power plants is an interesting option to increase the efficiency further than the current one of state-of-the-art parabolic trough power plants using synthetic oil as primary heat transfer fluid (HTF). The live steam temperature of the turbine hereby is increased up to 550 °C. According to [1], DSG plants can only become economical competitive if a cost effective storage systems is available for DSG systems.

State-of-the-art parabolic trough power plants use a sensible HTF (synthetic oil) and a sensible storage medium (molten salt). Thus, the energy during charging and discharging can be transferred by a standard heat exchanger. If water/steam is also used as the primary HTF, the situation becomes more complex. Potential storage configurations are shown in schematic temperature-enthalpy diagrams in figure 1. During charging, the superheated steam from the solar field (SF) enters the storage system and is cooled down to the according saturation temperature by transferring its heat to the storage medium. During condensation the heat from the HTF is transferred at a constant temperature level. Finally, the condensate is sub-cooled in the storage system. If a sensible storage medium would be used (see figure 1 (a)), the occurring pinch-point problem causes a significant reduction of the live steam temperature and pressure during discharging and thus a significant reduction of the power block efficiency during discharging.

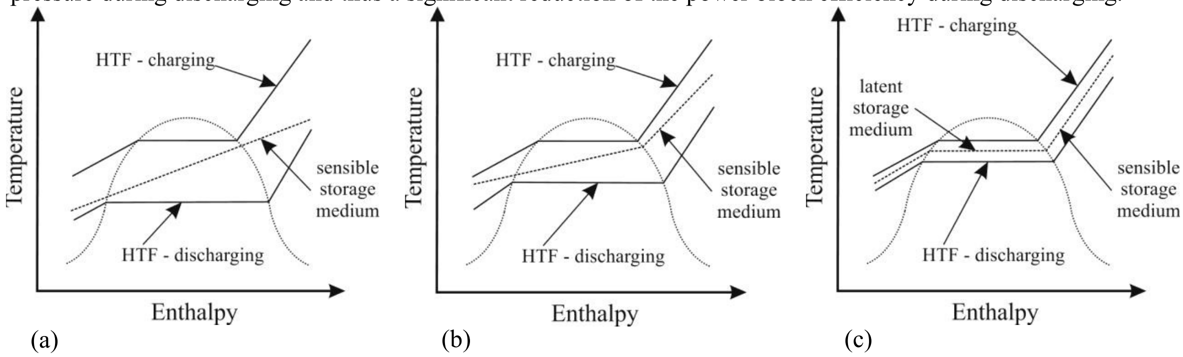

Fig. 1. Schematic temperature-enthalpy diagrams for the charging and discharging processes with water/steam as heat transfer fluid – (a) using a sensible storage medium, (b) using a sensible storage medium with different mass flows and (c) using a sensible storage medium for pre- and superheating and a latent storage medium for evaporation.

One possibility to reduce this problem would be to use a three-part storage system for preheating, evaporation and superheating like proposed in [2]. To store the sensible heat, a molten salt storage system with a cold tank, a hot tank and an intermediate tank is used. This approach would allow two different mass flows. A higher mass flow in the lower temperature range and a smaller mass flow in the higher temperature range. According to figure 1 (b), the live steam temperature and pressure reduction is not as large as in the previous case leading to a more moderate reduction of the power block efficiency during discharging.

If a latent heat storage system is used to store the evaporation enthalpy of water/steam, the temperature profile in the storage system is matched to the temperature profile of the heat transfer fluid during charging and discharging. This approach leads to the highest live steam parameters and thus power block efficiency during discharging at the expenses of an increased system complexity. Since the specific heat capacity of water is much higher than that the one of steam, the gradient of the steam curves is steeper when compared to the water curves in figure 1. To compensate the different slopes, different molten salt mass flows are utilized in the preheating and in the superheating section of the storage system. This demands the use of a three tank molten salt system for the sensible heat. The schematic diagram of a conceivable set-up is shown in figure 2.

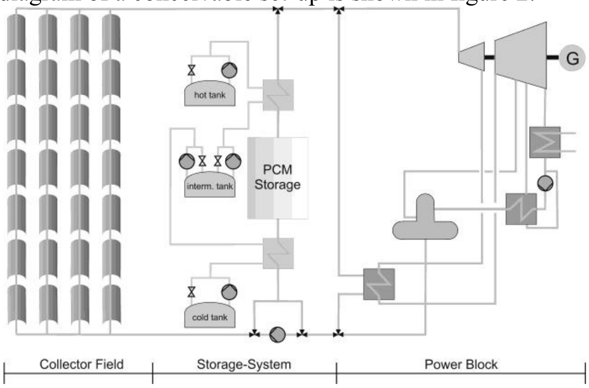

Fig. 2. Schematic diagram of a DSG plant with a thermal storage consisting of a PCM-storage for evaporation and a 3-tank molten salt storage for the pre- and superheating.

In figure 2, feed-water from the power block is fed directly to the SF, where it is preheated, evaporated and superheated. The live steam produced in the SF is passed back to the power block where it feeds the turbine. If the live steam mass flow from the SF exceeds the capacity of the turbine, the surplus of steam is fed to the storage system for charging. During periods with no or reduced solar irradiation, the accordingly reduced live steam mass flow can be supplemented by steam from storage discharging. As any other solar thermal power plant a DSG plant can be equipped by a fossil fired back-up burner (not displayed in figure 2). In this paper the plant set-up from figure 2 serves as the reference system in this paper.

In the schematic temperature-enthalpy diagrams of figure 1 it was assumed that superheating of steam is represented by a straight line. In reality, the specific heat capacity of superheated steam changes over the temperature (see figure 3) in particular close to the saturation temperature. Accordingly, the superheated steam lines in the temperature-enthalpy diagram are no longer straight lines, but exhibit a distinct curvature (see figure 4).

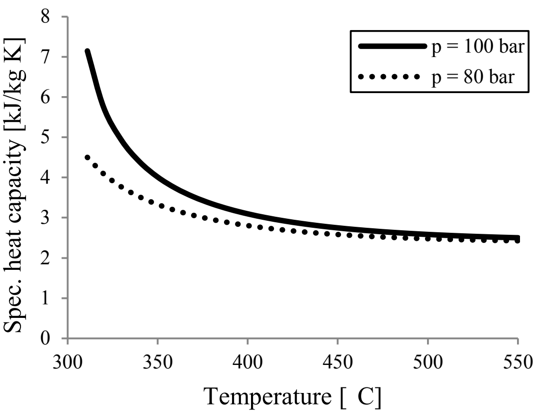

Fig. 3. Specific heat capacity of superheated steam at 100 and 80 bar.

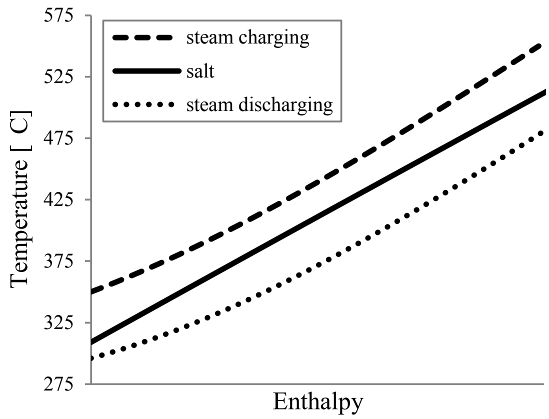

Fig. 4. Temperature-enthalpy diagram for the charging and discharging processes with superheated steam as heat transfer fluid.

Figure 4 shows the charging and discharging process, using superheated steam as HTF and molten salt as storage medium. Since the specific heat capacity of molten salt is nearly constant, the salt line is still a straight line. Due to this different behavior, the steam line and the salt line do not match as perfect as assumed in figure 1 (c). Especially during charging, the minimum temperature difference of the heat transfer between the steam and the salt has to be considered. If it is located at the left side of the diagram, significantly reduced salt temperature in the hot tank would be the result. If it is located on the right side, the salt temperature in the hot tank would be as high as possible, but the temperature at the cold end would be reduced accordingly. This would necessarily lead to an according reduction of the live steam pressure during discharging. As a compromise, the minimum temperature difference between the steam and the molten salt can be located in the middle of the diagram of figure 4, whereas design parameters and efficiency losses have to be weighed up against each other. In any case the effect of the curved steam line will cause some reduction of the live steam temperature in between charging and discharging of the storage. This has to be considered appropriately during storage design and system analysis. In this paper, storage concepts are identified and assessed that consider the mentioned effect. The concepts aimed at the highest possible steam parameters during the discharging process of the system.

2. System analysis

Within this section three approach cases are presented and analyzed that consider the effect of the non-linear course of the specific heat capacity of superheated steam. The systems are compared to a reference system using a PCM-storage and a 3-tank molten salt storage that comprises a simple process without optimization. The systems are assessed with respect to their effect on the power blocks efficiency during charging and discharging, the sizes of the storages and their complexity. In this paper, the assessment is limited to the design point. For all systems sodium nitrate ($NaNO_3$) is considered as PCM-material and a 60/40 wt-% mixture of sodium nitrate / potassium nitrate ($NaNO_3/KNO_3$) as molten salt, further referred to as “Solar Salt”.

The discussed processes are named

- Case 1: Reference system (three tanks),
- Case 2: Adapted salt system (three tanks),
- Case 3: Adapted steam system (two tanks) and
- Case 4: Pressure adapted system (two tanks).

The main parameters of the reference storage system are listed in table 1. The size of the power block was chosen with an electric gross power of 50 MW for comparability reasons with state-of-the-art in parabolic trough plants with synthetic oil as heat transfer fluid. The storage capacity of 1,000 MWh represents approx. 8 h of full load nameplate electricity production of the power block (PB).

Table 1. Main parameters of the reference system.

Plant capacity	50	MW
Storage capacity	1,000	MWh
Design charging and discharging time of the storage	8	h
Live steam temperature (charging)	550	°C
Minimum temperature difference latent storage	10	K
Minimum temperature difference sensible storage	7	K
Melting temperature of the PCM ($NaNO_3$)	306	°C
Fusion heat of the PCM ($NaNO_3$)	175	kJ/kg
Specific heat capacity of the molten salt	1.5	kJ/kgK

For the design of the storage system further assumptions are made. The concentrated solar power (CSP) plant is designed for superheated steam with a temperature of 550 °C, representing a temperature that current DSG-system developments are aiming at. This steam is used to charge the storage. The pressure of the used steam in the charging process depends on the melting temperature of the chosen PCM and the assumed temperature difference during condensation and evaporation. For all the discussed storage systems in this paper, the melting temperature of sodium nitrate with 306 °C appears suitable. Considering a temperature difference of 10 K in the PCM-part correspond to condensing parameters of 316 °C and 107 bar and evaporation parameters of 296 °C and 81 bar. For the heat exchangers of the sensible molten salt part, a temperature difference of 7 K is assumed. In table 2 the main system parameters of the designed storage concepts are shown.

Table 2. Design conditions of the different storage approaches

		Reference system Case 1	Salt adaption Case 2	Steam adaption Case 3	Pressure adaptation Case 4
Number of sensible salt tanks	-	3	3	2	2
Steam temperature (charging)	°C	550	550	550	550
Steam mass flow (charging)	kg/s	56	57	60	58
Steam pressure PCM (charging)	bar	107	107	107	107
Water temperature (charging)	°C	285	294	315	297
Steam temperature (discharging)	°C	477	535	536	536
Steam mass flow (discharging)	kg/s	57	53	53	53
Steam pressure PCM (discharging)	bar	81	81	81	81
Water temperature (discharging)	°C	262	255	260	262
Hot tank temperature	°C	510	543	543	536
Intermediate tank temperature	°C	309	400	-	-
Cold tank temperature	°C	270	270	270	270
Cold salt mass flow (char./dischar.)	kg/s	170	139	104	112
Hot salt mass flow (char./dischar.)	kg/s	110	91		
Hot tank salt mass	t	3,200	2,600	3,000	3,200
Intermediate tank salt mass	t	1,700	1,400	-	-
Cold tank salt mass	t	4,900	4,000	3,000	3,200
PCM active salt mass	t	13,500	12,600	13,300	12,900
PB design efficiency	%	42.3	42.3	42.3	43.0
PB efficiency in storage mode	%	40.3	41.5	41.5	41.7
PB efficiency loss	%	2.0	0.8	0.8	1.3
PB design power	MW	50	50	50	50
PB power in storage mode	MW	35.8	37.2	37.2	30.1
PB part load point	%	71.6	74.4	74.4	60.2
Heat ratio latent/sensible	-	1.9	1.7	1.9	1.8

2.1. Case 1: Reference system

The reference storage system for the DSG model plant is designed with three molten salt tanks for sensible pre- and superheating, and a PCM-storage for evaporation respectively condensing. Figure 5 (a) shows the charging process of the reference storage system. On the right side (stream 1) hot steam from the SF enters a heat exchanger with a temperature of 550 °C and a mass flow of 56 kg/s. Due to the changing heat capacity of superheated steam, the temperature of the de-superheated steam (stream 2) is limited to 350 °C. For technical reasons of the PCM-storage construction, it may be not possible to feed such overheated steam into its tubes directly. Therefore, a recirculation of condensed water is introduced. The recirculated mass flow can be used to control the temperature of the steam at the inlet of the PCM. The mixed steam flow at the PCM inlet has a temperature of 330 °C. The steam inside the PCM tubes is condensed during the charging mode with a heat transfer temperature difference of 10 K at a temperature of 316 °C and a pressure of approx. 107 bar. The saturated water at the outlet of the PCM module (stream 3) is then further subcooled by another heat exchanger. Finally, the water is returned back to the feed-water pump of the SF with a temperature of about 285 °C (stream 4).

To store the sensible heat, a molten salt tank system is used. Because of the solidification point of the used Solar Salt mixture at about 238 °C, the lower temperature of the cold tank was limited to 270 °C. This corresponds to a safety margin of about 32 K to the solidus point. The temperature of the intermediate tank was set to 309 °C. This temperature was deducted from the saturation temperature of the heating steam at 316 °C and an economic upper temperature difference in the heat exchanger of 7 K. The energy of the superheated steam heats the salt up to a temperature of approx. 510 °C. Due to the different heat capacity of water and steam, different molten salt mass flows inside both heat exchangers are necessary. This fact makes a third intermediate tank necessary. This tank collects the salt mass flow that is not further transferred into the hot tank.

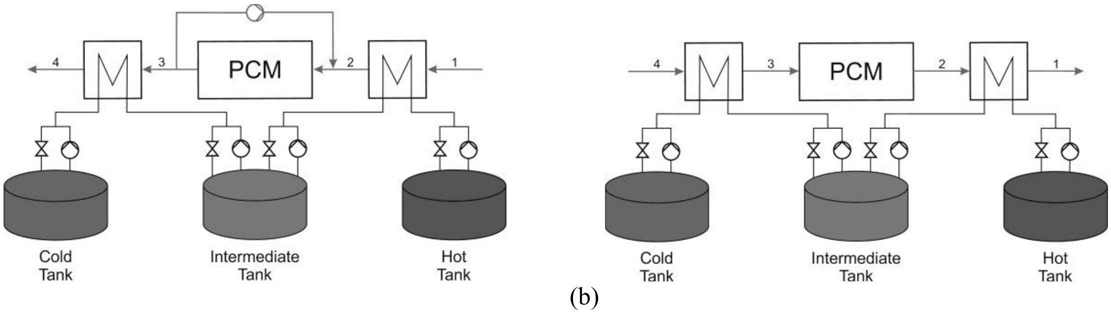

Fig. 5. Charging (a) and discharging (b) schematic of the reference system

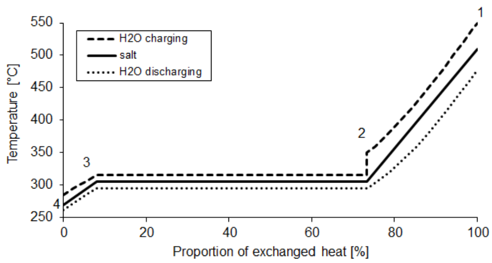

Fig. 6. Schematic temperature-heat diagram of the reference system

For the discharge process all flows reverse. Figure 5 (b) shows the schematic overview of the discharge process of the storage system. During discharging, water with a temperature of 262 °C returns from the PB and is preheated up to saturation temperature of 296 °C at a pressure of 81 bar. The evaporation inside the PCM-module is then performed at constant temperature. As last step the steam is superheated up to a temperature of about 477 °C.

The salt from the hot tank is transferred through the superheater and cooled down to 309°C before it enters the intermediate tank. From there, the entire salt mass in the intermediate tank is passed through the preheater to the cold tank. A schematic temperature-heat diagram of this system is shown in figure 6.

For the design of an 8 h storage system with 1,000 MWh thermal capacity there are about 4,900 t Solar Salt necessary. Due to the system layout, the size of the cold tank must be large enough to collect the total amount of sensible salt inventory of the storage system. The hot and the intermediate tank can be sized smaller and have to contain 1,700 t and 3,200 t of salt. The PCM module must be designed for approx. 13,500 t of sodium nitrate.

Very important aspects of the storage concept are the effects on the power block. A steam turbine is designed for a special mass flow under defined inlet pressure conditions. The inlet pressure and the absorbing capacity of a turbine stage in part load are correlated by Stodola`s law. This leads to problems in the use of PCM-storage systems. The discharging pressure resulting from the assumed 10 K heat exchange temperature difference is only about 75 % of the designed inlet pressure of the steam turbine. Consequently, the block must operate under part load conditions. This necessity for use of PCM-storages decreases the efficiency of the reference Rankine cycle from 42.3 % to estimated 40.3 %.

A possible indicator for the expected cost distribution of the discussed DSG storage systems is the ratio of stored latent and sensible heat, whereas the absolute salt masses could be indicative for the relative total system cost. For the designed reference system, this value is calculated with a factor 1.9. This means that almost the double amount of heat is stored inside the PCM-material than inside the sensible molten salt. If considered that the sensible molten salt module will be lower in price per stored kWh than the PCM module, the calculated heat ratio should become as small as possible.

2.2. Case 2: Adapted salt system

The course of the specific heat capacity over the temperature of steam changes as discussed inside the superheater. This second concept approaches with this issue by modifying the heat capacity and thus the course of the enthalpy at the salt side of the superheater. This can be done by changing the mass flow of the salt at a suitable position. For this reason, the intermediate tank is placed in between two superheater sections at a higher temperature of about 400 °C instead of directly beside the condensation/evaporation section as in the first concept.

A schematic overview of this storage concept is shown in figure 7. Compared to the schematics in figure 5, there is only a very small difference in the tank arrangement. This layout enables a PCM inlet temperature of the de-superheated steam (stream 3) of 330 °C without any recirculation of saturated water from stream 2 to stream 3 as needed in the reference system (see figure 5 (a)). The results of this system are also shown in figure 8 and table 2. This schematic enables a molten salt temperature of 543 °C in the hot tank. The lower necessary mass flow of the molten salt in the upper superheater section decreases the required amount of salt to 4,000 t. Additionally, the needed mass of the PCM decreases to approx. 12,600 t, which decreases also the assumed costs for the PCM module by the same range.

Furthermore, it becomes possible to superheat the steam during discharging up to approx. 535 °C. Compared to the temperature of the reference system of 477 °C, this improves the cycle efficiency substantially, which can be seen by the PB efficiency during storage operation in table 2. If the shown storage system is applied to the same PB, it would be possible to operate the power block at a part load of nearly 74 % which leads to a higher PB efficiency of about 41.5 %. The ratio of latent to sensible heat in the storage of 1.7 is a little bit lower than the one of the reference system. Since the relative costs of the PCM-storage section will be higher than that of the sensible storage, the reduced PCM fraction is advantageous with respect to the expected investment.

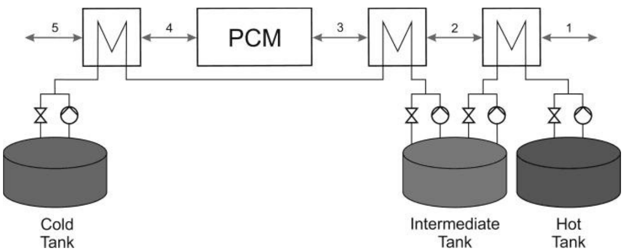

Fig. 7. Charging and discharging schematic of the adapted salt system

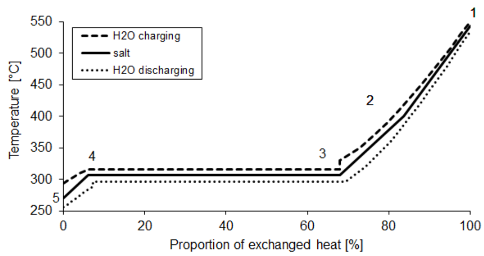

Fig. 8. Schematic temperature-heat diagram of the adapted salt system

2.3. Case 3: Adapted steam system

The third storage configuration is designed with two tanks for the pre- and superheating of steam aiming at the reduction of the investment cost of the storage system on the one hand and attaining the highest possible discharging steam parameters on the other hand. If the intermediate Tank can be avoided, only two tanks would have to be built. Furthermore, all of the molten salt could be used all over the temperature range, and thus more heat is stored per kg salt. The both three tank solutions as discussed in sections 2.1 and 2.2 have a large amount of salt that is stored in the intermediate tank and is not further heated to the higher temperatures of the hot tank. It is only used for the sensible temperature difference between the cold and intermediate tank. The two tank solution that is shown in figure 9 only needs a mass of 3,000 t salt, what can also be seen in table 2. For the PCM module approx. 13,300 t of sodium nitrate is used to store the latent heat of the condensing steam.

A two tank system may not be ideal to deal with the change of the specific heat capacity, since there is no change of the salt mass flow inside the sensible storage part. For this reason, it is necessary to introduce a bypass at the steam side during charging operation (see figure 9 (a)). Steam from the SF is entering the superheater (stream 1) and is de-superheated down to 350 °C (stream 2). There, a small mass flow of about 6 kg/s of the still superheated steam is passed around the PCM-storage to stream 3. Additionally, there is again a recirculation of saturated water to control the temperature of the remaining superheated steam at the entry of the PCM-storage. This recirculation is similar to the reference system explained in section 2.1.

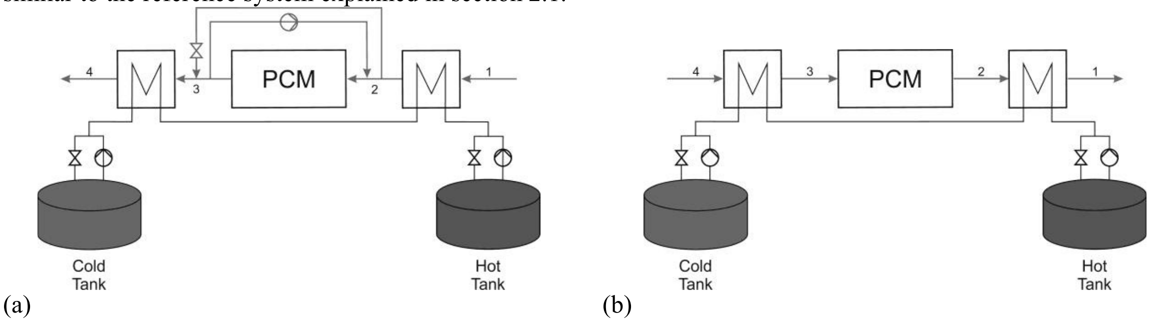

Fig. 9. Charging (a) and discharging (b) schematic of the adapted steam system

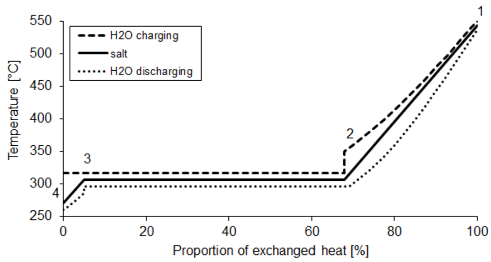

Fig. 10. Schematic temperature-heat diagram of the adapted steam system

In stream 4 at the water/steam outlet of the PCM-storage the steam quality is approx. 3 %. Before this excess steam mass flow can be returned to the feed-water pump of the SF, it has to be mixed with the feedwater of the PB or used for further preheating to provide a liquid stream to the SF. Considering the current full load operation strategies for CSP plants, this should not be a limitation and at this stage of the process development a suitable use of the enthalpy of the remaining steam in the peripheral process is assumed.

During the discharge operation of the storage system there are no bypasses or recirculation streams needed (all valves are closed). In figure 9 (b) the discharging schematic is shown, which is thus much easier to realize. The feed-water from the PB is first preheated (stream 4 to 3), evaporated inside the PCM-storage (stream 3 to 2) and then superheated up to a temperature of 536 °C (stream 4).

Due to the higher temperature of the produced steam during storage operation, it is possible to operate the PB almost at the same conditions as in case 2 (see table 2). The high outlet temperature of the steam that is passed from the superheater during charging is responsible for a high ratio of latent to sensible heat of 1.9. A large fraction of the sensible heat from de-superheating is shifted into the PCM-section. Thus, almost the same proportion of heat is stored inside the PCM as in the reference system, whereas as mentioned before, a significantly smaller amount of molten salt is used then for the entire sensible temperature range. In figure 10, a schematic diagram of the adapted steam system is depicted.

2.4. Case 4: Pressure adapted system

The last presented system again has a two tank molten salt system for the sensible heat. In this case, there is no need for any kind of bypass or recirculating system. In this design, the pressure dependence of the specific heat capacity of steam is used. Accordingly, the pressure is reduced continuously in the steam line to maintain a constant specific heat capacity in the entire superheating section. Figure 8 shows the charging and discharging schematic of this system. The SF outlet pressure is raised up to approx. 135 bar at a temperature of 550 °C (stream 1). This pressure might be too high for a SF with parabolic trough collectors, but is deemed feasible for solar towers or linear Fresnel collectors. Therefore, such a storage application is assumed to be conceivable.

To modify the specific heat capacity of the charging steam, throttles (stream 2) between several superheater sections can be used. At the outlet of the superheater (stream 4) the steam has a temperature of 330 °C and a pressure of about 107 bar. Thus, 28 bar of pressure reduction is required for the adaption of the specific heat capacity of the steam. During the discharge of the storage system there is no need of any throttles inside the superheater section. For that reason, a bypass (stream 3) depicted in figure 11 is considered.

The temperature of the hot salt tank that can be attained in this configuration is limited to a temperature of 536 °C. This is caused by the course of the almost linear heat capacity of the molten salt. If a higher temperature is desired, the charging pressure of the SF has to be increased further. The little mean temperature difference during the charging operation leads to an oversized superheater during discharge operation. Therefore the temperature of the produced superheated steam almost attains 536 °C which is close to the value of the temperature-optimized process in case 3. A schematic diagram of the pressure adapted system is shown in figure 12. Nevertheless, the performance of the new PB design during charging and discharging is worse since the power block is designed for a live steam pressure of about 135 bar achieving an efficiency of 43.0 % at design conditions. Because of the significant throttling, during discharging the power block is operated at a part load of approx. 60 %. This causes a lower cycle efficiency of about 41.7 %. The ratio of latent to sensible heat for the pressure adapted system is 1.8 and the necessary mass of molten salt is 3,200 tons. For the PCM module 12,900 t of sodium nitrate are required.

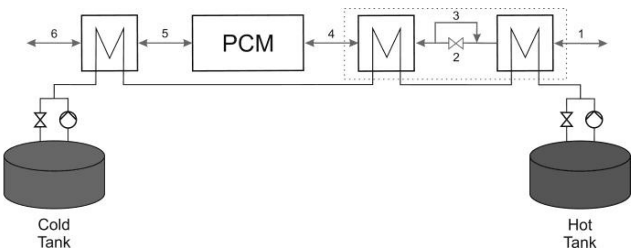

Fig. 11 Charging and discharging schematic of the pressure adapted system

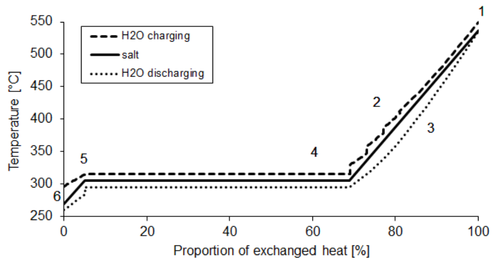

Fig. 12. Schematic temperature-heat diagram of the pressure adapted system

2.5. Preliminary comparison

Every of the four discussed approaches are suited to design a storage system for a DSG power plant. The main issue is the overall efficiency of the storage process. The other main aspect is the installation costs of such a storage system. The ideal storage concept provides simplified steam with high steam parameters by minimized cost for investment.

The reference storage system has a simple design. Unfortunately there is a recirculation of saturated water. This leads to a more complex system. A big disadvantage of the reference system is its poor cycle efficiency, caused by the low temperature of the live steam during discharging operation. Therefore, the biggest loss in the efficiency of the PB of all four systems occurs.

In the second case a system layout with a modification in arrangement of the intermediate tank was discussed. With this design it is possible to fit the salt enthalpy flow to the steam side of the heat exchanger. Compared with the reference system there are only improvements concerning cycle efficiency and complexity of the system. Thus, the PB losses only approx. 0.8 % of its efficiency and the recirculation bypass of the reference system isn´t necessary. Additionally the PCM-module is approx. 7 % smaller than in the reference system.

Aiming at the further reduction of investment cost, a third two tank storage system was introduced. Due to the missing possibility to influence the salt side, several adaptions on the steam side had to be made. There are no efficiency differences compared to the second system. A bypass with superheated steam enables the high salt temperature of the hot tank but leads to a two phase flow at the outlet of the preheater during the charging process of the storage. The amount of necessary PCM is higher than in the second case, but still lower than in the reference system.

The last presented possibility to design a thermal storage concept for a DSG power plant was the continuous decrease of the live steam pressure in the storage system during charging. The advantage of this approach is the simple design of the storage system. Neither a recirculation nor a bypass of superheated steam is necessary and an intermediate tank is also not required. The high pressure in the SF will cause additional investment for the SF and the throttling of the superheated steam during charging causes a significant efficiency reduction during discharging.

3. Conclusions and outlook

The aim of this paper is to identify a complete storage concept for solar thermal power plants with direct steam generation that pays special attention to the temperature dependence of the steams specific heat capacity and at the same time allows a maximum live steam temperature during discharging. For this study, a PCM-storage using sodium nitrate was chosen for the evaporation/condensation section of the storage system and a molten salt system for the sensible section. Four concepts have been identified and presented that fulfill the mentioned requirements.

In this paper the design point of the system is considered only. This is acceptable for this early stage of the investigation to identify suitable solutions. Based on the preliminary analysis performed, it is not possible to perform a final ranking of the different solutions. The approaches differ in complexity, efficiency reduction during discharging and required storage capacities. Thus, a final assessment requires the estimation of the according investment costs and the determination of the electricity yield for representative sites. The determination of the yield has to consider plant operation for at least one year to consider all seasonal variations of the irradiance and thus the according part load characteristic of the solar thermal power plant including storage

Despite the tentativeness of the presented study, it is already shown, that storage concepts are available for DSG solar thermal power plants that consider the unfavorable specific heat characteristic of superheated steam and at the same time allow a maximized molten salt temperature in the hot storage tank and thus a maximized live steam temperature during discharging.

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