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Active fluidization storage applications for CSP

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Abstract

The current paper proposes three thermal storage concepts for solar thermal power plants, which are all based on sand powder as storage medium. The solid powder is used in a manner similar to fluid storage media such as molten salt. Fluidization is needed in order to produce fluid-like behavior of the powder. Applying powders as storage media for thermal energy storages offers advantages such as low cost, no freezing danger and hence no melting effort, no corrosion, local availability and high allowable temperatures. The storage media demand for all three concepts is estimated.

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1. Introduction: sandTES storage concept

The potential implementation of thermal energy storages (TES) in concentrating solar power plants (CSP) makes CSP technology competitive to Photovoltaic systems. For economic reasons storage costs have to be minimized. The cost of the storage material is the key factor for the determination of storage cost.

Many solid powders offer high energy densities while being an easy to handle low cost product. This makes them a cost effective alternative to rather costly state of the art TES materials such as molten salt. The usage of solid powders also overcomes the temperature limitations of at the moment of writing commonly applied storage materials.

The sandTES concept applies fluidization technology enabling the usage of solid powders in an active TES concept as storage media. A stationary fluidized bed heat exchanger (HEX) transfers heat from the primary heat

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transfer medium (HTF) to the storage powder, which can be stored in large quantities in isolated hoppers. The sandTES-concept itself is explained in more detail in [1], also a paper of this year's SolarPaces conference. In this work, only the designs of sandTES fluidized bed super-heaters and evaporators within CSP plants are roughly sketched. A suitable storage concept has to adapt to the mixed temperature/energy characteristics of the working fluid (water/steam), which is both latent (evaporation/condensation) and sensible (preheating/superheating). In this work the challenges for the application of TES within the Rankine Cycle are pointed out and three approaches applying the sensible sandTES concept as superheater and/or evaporator are presented:

- DSG with a combination of sensible TES and latent TES (SelaTES)
- DSG with a 3-tank-powder approach (latent TES part covered with a sensible storage medium)
- Direct Absorption Receiver and Direct Powder TES

Nomenclature

p	pressure
h	specific enthalpy
s	specific entropy
T	temperature
k	thermal transmittance
A	area
$\dot{Q}$	heat flow
$\dot{m}$	mass flow
c_p	isobaric specific heat capacity
ΔT_m	characteristic temperature describing the heat exchanger
Δh_{vp}	heat of evaporation/condensation
Δh_{fusion}	heat of fusion (heat released by a phase change of a PCM)

Subscripts

char	charge
dis	discharge
evap,vp	vaporisation
cond	condensation
turb	turbine
htf	heat transfer fluid
PCM	phase change material
DSG	direct steam generator

2. Challenges for implementing a TES to the Rankine cycle

Heat can only flow from regions of higher temperatures to regions of lower temperatures, as described by the second law of thermodynamics [5]. Consequently for charging a TES the temperature of the storage material has to be lower than the temperature of the primary heat transfer medium, transporting heat from the plant (source) to the TES (sink). For discharging it is the other way round, the TES is the source and the plant is the sink; the temperature of the storage material has to be higher than the htf's temperature.

Working/heat transfer fluids and storage materials can show either sensible or latent behavior. Sensible behavior is characterized that a change in internal energy (e.g.: triggered by a heat flow) is related to a temperature change. By latent behavior a phase change is meant, which can either be a change of the (crystal) structure or a change of the gaseous state of any material, taking place at constant temperature. For pure substances the temperature where liquid/gas phase change occurs is a function of the pressure.

The water/steam cycle often applied in electric energy conversion processes is referred as Rankine cycle. The working fluid water/steam of the Rankine cycle includes both latent (evaporation/condensation) and sensible behavior (preheating/superheating). From the thermodynamic view point the logical way for implementing a TES to the Rankine Cycle is using two different sub systems: a latent TES for evaporation/condensation and a sensible TES for (preheating)/superheating (Fig. 1a). Nevertheless, applying only one TES for the entire cycle appears to be advantageous in terms of investment costs, flexibility and simplicity. As a disadvantage, one has to combine a latent phenomenon with a sensible behaving material (one TES can only be a sensible TES) in one HEX resulting in large temperature differences of the involved streams, as can be observed from Fig. 1.

For illustrating the charge and discharge processes, the temperature curves of both involved media (water/steam and the storage medium) are shown in one T,s-diagram. The authors are aware of the formal imprecision using only one T,s-diagram for two different media, but in that way the idea is transported best.

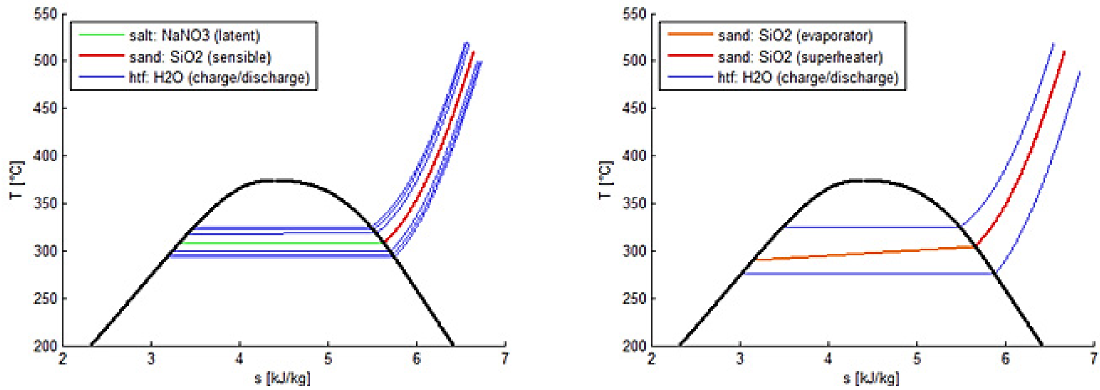

Figure 1: (a) temperature characteristics of the involved media in a DSG plant with latent/sensible TES, (b) temperature characteristics of the involved media in a DSG plant with sensible/sensible TES

The challenges of combining latent behavior of the working fluid and sensible character of a storage medium in storage cycle are explained in more detail in the following subsections in the context of DSG applying the sandTES concept.

2.1. indirect TES cycles of a DSG plant

In an indirect storage cycles for charging the TES the working fluid (or htf) is used to heat up the storage material and for discharging the same working fluid is heated up by the TES, whereas in a direct cycle the working fluid is directly stored (=used as storage medium).

So for charging the TES of a DSG, the temperature of the primary fluid (steam) $T_{htf,char}$ has to be higher than the temperature of the storage material (e.g.: powder) $T_{powder,char}$, as already described above. Or practically speaking: part of the in the solar field produced pressurized and superheated steam is expanded in a turbine (converted to electrical energy) and the other part is used to heat up the storage material (charge the TES).

For discharging the storage, the temperature of the storage material $T_{powder,dis}$ has to be higher than the temperature of the primary fluid $T_{htf,dis}$. In discharge mode of a DSG plant, the steam needed for electrical energy conversion is entirely delivered by the TES system.

From the view point of the turbomachinery the turbine inlet temperature is higher in charge mode than in discharge mode ($T_{turb,char} > T_{turb,dis}$), since ($T_{htf,char} > T_{powder,char} \geq T_{powder,dis} > T_{htf,dis}$), to satisfy the second law of thermodynamics. If the thermodynamic character of the htf would be sensible the charge and discharge pressures of the primary htf could be equal ($p_{htf,char} = p_{htf,dis}$), as consequently would be the turbine inlet pressures ($p_{turb\_in,char} = p_{turb\_in,dis}$). But in the Rankine cycle the htf undergoes a phase change (evaporation/condensation) taking place at constant temperature. To fulfill the second law of thermodynamics, the condensation temperature (charging) has to be higher than the evaporation temperature (discharging) of water/steam. As already mentioned above, for water/steam the phase change temperature is only dependent on the pressure. So in case of a storage cycle of DSG plant the discharge pressure of the htf has to be lower than the charge pressure, also influencing the turbine inlet pressures ($p_{turb,char} > p_{turb,dis}$). In a storage cycle of an indirect TES cycle the pressure has to be slided.

The behavior of the storage material can either be latent or sensible. This is of importance for the evaporator, since all feasible TES systems of interests for superheaters are sensible and the thermal duty of the evaporator is far higher than the thermal duty of the superheater. The overall behavior and energy balances of both a latent TES and a sensible TES used as an evaporator are discussed in the following.

2.2. Combining latent/latent behavior in an indirect TES cycle of a DSG plant

In charge (discharge) mode the primary fluid is condensed (evaporated). The heat of condensation (heat of evaporation) Δh_{vp} is stored in (delivered from) the storage medium in form of internal energy, which also induces a phase change of the storage medium in case of a latent TES. If the character of the storage medium is latent, we can write for the energy balance of the TES:

$$\dot{Q}_{cond/evap} = \dot{m}_{PCM,freezing,melting} \Delta h_{fusion} = \dot{m}_{htf} \Delta h_{vp} = kA\Delta T_m \quad (1)$$

In Eq. 1 can be seen for condensing (evaporating) a fluid mass flow $\dot{m}_{htf}$, a certain mass flow of the phase change material PCM $\dot{m}_{PCM}$ has to melt (freeze) in order to “store (release)” the released (needed) energy. Since all phase changes occur at constant temperature, also the temperature differences between htf and PCM stay constant, as can be seen in Fig. 1a. From integrating Eq.1 over time, the demand of the PCM material can be estimated. The solidus temperature of the PCM ($T_{PCM,solidus}$) has to lie between the charge and the discharge temperature of the primary fluid: ($T_{htf,char} > T_{PCM,solidus} > T_{htf,dis}$).

By the choice of the type of PCM, the primary fluid system pressures $p_{htf,char}$ and $p_{htf,dis}$ are fixed and can only be influenced by the heat transmission behavior of the heat exchanger in a very limited range. Higher values of kA (=good heat transmission) result in larger HEX-areas and higher pressure losses of the primary HTF resulting in a non-uniform solidification/melting front. This phenomenon and the over the melting/solidification process varying heat transmittance k is explained in detail in [2].

2.3. Combining sensible/latent behavior in an indirect TES cycle of a DSG plant

When a sensible TES (e.g.: sandTES) is used as evaporator, also the temperature increase (decrease) of the storage medium (e.g.: sand, powder) has to be taken into account, since a change of internal energy is related to change in temperature for sensible TES, as is shown in Eq. 2:

$$\dot{Q}_{cond/evap} = \dot{m}_{powder} c_{pm} \left(T_{powder}^{in} - T_{powder}^{out}\right) = \dot{m}_{htf} \Delta h_{vp} = kA\Delta T_m \quad (2)$$

The specific energy a sensible TES can store (release) $c_{pm}\left(T_{powder}^{in} - T_{powder}^{out}\right)$ is far lower compared to the specific energy a latent TES can store (release) Δh_{fusion}. This results in larger needed mass flows of the sensible storage medium. Unlike latent TES, where by the chosen PCM the plant’s pressure levels are defined, the overall behavior of a sensible TES is more flexible and complex: The pressure level of water/steam can be chosen independently from the storage material. The change of specific energy of a sensible TES material is dependent on its temperature increase (decrease) $T_{powder}^{in} - T_{powder}^{out}$ and the total energy flow of the TES system is won by multiplying the specific energy with the mass flow.

As a consequence the capacity of a sensible TES can either be increased by higher mass flows or by a larger increase (decrease) of the temperature of the storage medium. But both are not for free: increasing the mass flows of the storage medium increases the total demand of storage media (hopper size) and increasing the temperature difference $\left(T_{powder}^{in} - T_{powder}^{out}\right)$ results in larger pressure difference between charge and discharge mode $\Delta p_{char-dis}$.

By integrating Eq. 2 over time the storage demand for such a system can be evaluated. For optimizing such a system, a compromise has to be found between the opposed criteria of small storage volumes and good cycle efficiencies of the steam turbine.

Until now only the evaporator section of the TES of DSG has been discussed. Generally speaking the specific energy needed for vaporization is far larger than the energy needed for superheating. Thus, if only one sensible TES is applied, the required storage medium mass stream in the evaporator is significantly higher than the one in the super heater. Such a system can only be realized via a 3-tank-system, enabling higher mass streams of the storage material through the condenser/evaporator (between tank 1 and 2) and smaller mass streams through the super heater (between tank 2 and 3).

2.4. Pressure dependence of the heat of evaporation/condensation

Furthermore increasing the complexity of a conceptual design of a TES for DSG is the fact that the heat of evaporation Δh_{vp} is significantly pressure dependent (the higher the lower pressure is). Thus, since the operating pressure is higher in charge mode than in discharge mode ($p_{htf,char}>p_{htf,dis}$), the specific heat of condensation in charge mode is lower than the specific heat required for vaporization in discharge mode ($\Delta h_{vp,char} < \Delta h_{vp,dis}$). Depending on the storage strategy, the mass stream of the storage powder has to be increased during the discharge process, if (turbine) power should be kept constant.

2.5. direct TES cycles of a DSG plant: the direct powder storage cycle

The inconvenience of indirect storage cycles is that the temperatures of the storage medium have to be in between the temperatures of water/steam in charge and discharge mode ($T_{htf,char}> T_{powder,char}\geq T_{powder,dis}> T_{htf,dis}$), which also leads to different pressures in charge and discharge mode ($p_{htf,char}>p_{htf,dis}$) (Fig. 2a).

By applying the Direct Absorption Receiver Technology [2] a direct TES cycle can be created applying a powder as primary heat transfer medium. The powder is heated up directly in a solar tower, to temperatures T_{powder} far higher than typical temperatures of the Rankine cycle. For electrical energy conversion water/steam is used as working fluid; via heat exchangers (e.g.: fluidized bed HEX) the heat is transferred from the powder to the working fluid – like a discharge semi-cycle of sensible TES direct cycle, but at far higher feasible temperatures increasing the DSG plant efficiency, as shown in Fig. 2b. For evaluating the needed mass flows Eq. 2 is integrated.

Since the specific energy $c_{pm}\left(T_{powder}^{in} - T_{powder}^{out}\right)$ of the storage powder applied in the direct powder storage cycle is far higher than in direct TES system also using powders as storage material, the storage powder mass flow is significantly lower in the direct powder cycle. This is illustrated in Fig. 2.

During day more powder than needed for electrical energy conversion is heated up and the excess powder is stored in large hoppers, which are discharged on demand. In the direct powder storage cycle, higher steam pressures and temperatures than in indirect storage cycles can be reached, and as a consequence the turbines can be operated at a constant pressure level.

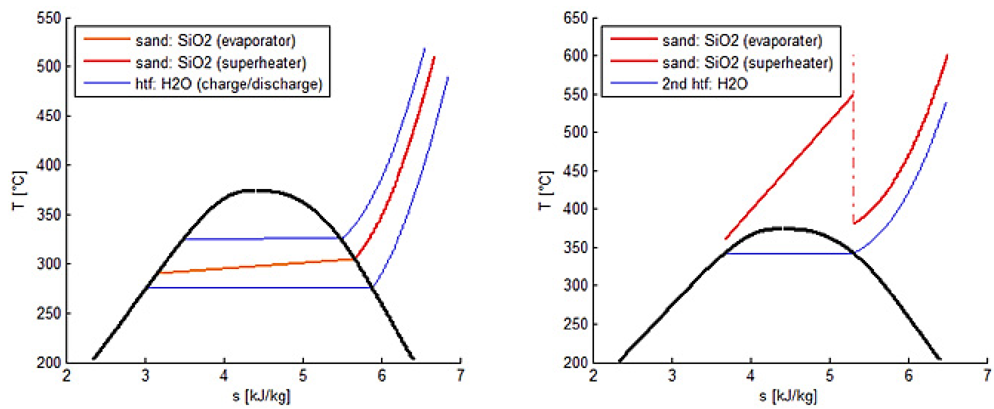

Figure 2: (a) temperature characteristics of the involved media in a DSG plant with sensible/sensible TES, (b) Temperature characteristics in the direct powder storage cycle

3. Storage concepts applying sandTES active fluidization storages for DSG

The evaluation and comparison of different storage concepts for DSG is a challenging task, since the individual operation strategy influences results significantly.

The in the following presented plant designs are investigated deeply by the authors, with special focus on the TES system. These concepts are developed at Technical University of Vienna and for them very detailed models are developed ([1,2] and section 4). For the purpose of this work a rough estimate for the storage demand is delivered below. The mass flows have been found by evaluating Eq.1 and Eq. 2 for the in tables shown parameters of each plant's Rankine cycle. In future works more profound data won by a deep numerical investigation will be presented.

3.1. DSG with sensible TES (sandTES) and latent TES (PCM-NaNO3) -- SelaTES

In the plant shown in Fig. 3, Sodium Nitrate ($NaNO_3$) is applied as PCM for the latent TES and silica sand (SiO_2) is used as storage powder for the sandTES concept acting as superheater. As discussed in paragraph 2.1, the $T_{solidus}$ of the PCM (306°C for $NaNO_3$) defines the plants operation pressure in charge and discharge mode. When a latent TES is used, the plant operation pressure has not only to be switched between charge and discharge mode. It needs to be permanently adjusted, since the heat transfer behavior of a latent HEX is decreasing by the advancing melting/solidification process. For maintaining a constant power output, the temperature difference between water/steam (hence also steam pressure) and the solidus temperature $T_{solidus}$ of the PCM has to be permanently increased. The model for the latent HEX is discussed in more detail in [2]. In this plant layout the storage system can adapt well to the Rankine cycle and handle the different thermodynamic properties of water and steam.

In table 1 characteristic data for this DSG plant are shown:

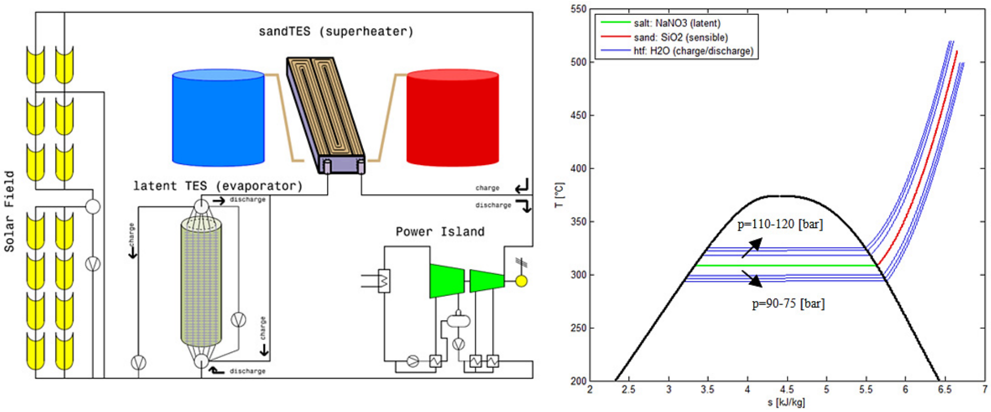

Figure 3: Latent/sensible TES DSG solar thermal power plant.

Table 1: Example of a DSG plant with Latent/sensible TES (sandTES +$NaNO_3$- PCM = SelaTES)

Evaporator/Condenser		**Superheater**		
Type	latent	type	sandTES	
storage material	$NaNO_3$	storage material	SiO_2	
spec. storage material demand*	*36,34* [$m^3/MW_{el}h$]	spec. storage material demand*	*09,14* [$m^3/MW_{el}h$]	
charge		**discharge**		
p_{turb}		110-120 [bar]	p_{turb}	75-90 [bar]
T_{turb}		520,0 [°C]	T_{turb}	490,0 [°C]
)*in discharge mode				

3.2. DSG with sensible TES (sandTES) in a 3-tank-powder approach

The sandTES concept is the only TES in the plant shown in Fig. 4. As storage medium silica sand (SiO_2) is applied. As in the plant presented above (and as discussed in paragraph 2.1) the plant pressure level has to be switched between charge and discharge mode, but no temperature is fixed as the solidus temperature of the PCM of the plant shown above. The pressure in charge mode results from the solar field and/or power plant design. Since the sandTES concept is a sensible TES, the powder temperature is changing in the evaporator/condenser. A higher temperature difference between charge and discharge mode is needed than in the cycle applying a latent TES; thus a higher pressure difference. Since far more energy is needed for evaporating water than for superheating steam, a significant higher mass flow rate of the storage powder is required in the evaporator than in the superheater. This is only possible in three tank layout.

In table 2 characteristic data for this DSG plant are shown:

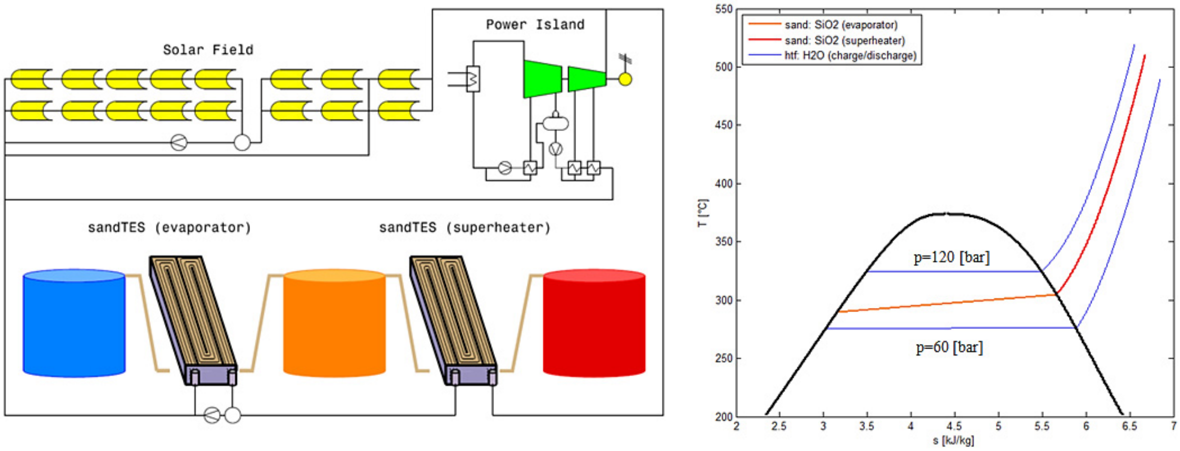

Figure 4: DSG with three-tank powder TES

Table 2: Example of a DSG plant with sensible TES (sandTES) in 3-tank-powder approach

Evaporator/Condenser		**Superheater**	
Type	sandTES	type	sandTES
storage material	SiO_2	storage material	SiO_2
spec. storage material demand*	*168,21* [$m^3/MW_{el}h$]	spec. storage material demand*	*8,90* [$m^3/MW_{el}h$]
charge		**discharge**	
p_{turb}	120 [bar]	p_{turb}	60 [bar]
T_{turb}	520 [°C]	T_{turb}	490 [°C]

)*in discharge mode

3.3. Direct powder system

The plant shown in Fig. 10 applies the Direct Powder cycle. The storage medium silica sand (SiO_2) is used as primary heat transfer medium. In Direct Absorption Receiver, the storage medium is heated up to 650°C, the maximum temperature a metallic hopper can handle.

Water is evaporated and superheated in sandTES type fluidized bed HEXs. Since there is no dedicated charge or discharge mode, the plant operation pressure is constant and can be higher than the in plants described above. Above an operation pressure of about 120 bar, a reheater is needed to prevent condensation in the low pressure turbine.

With a Direct Absorption Receiver the storage medium sand can be heated at significant higher temperature than in the cycles presented above, thus resulting a lower storage volumes or hoppers.

In table 3 characteristic data for this DSG plant are shown:

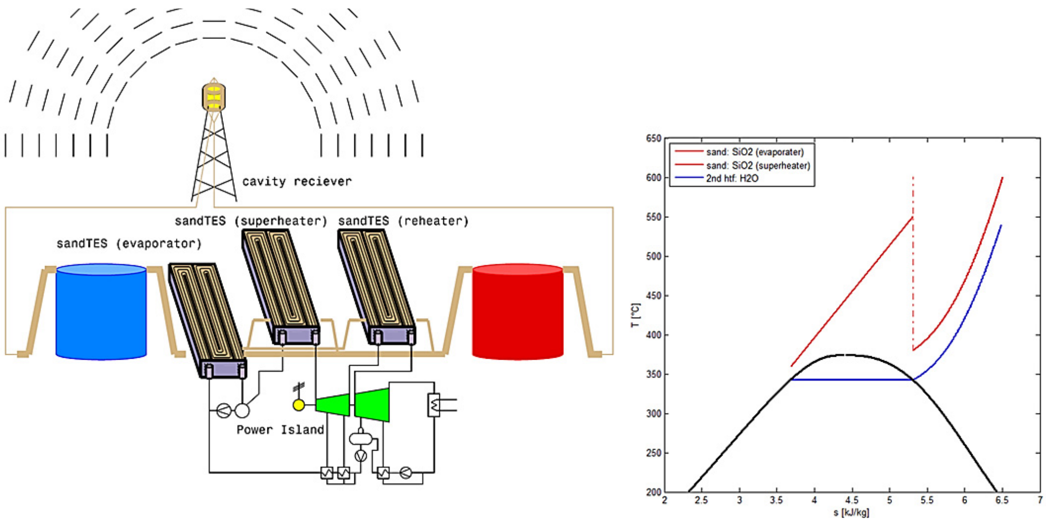

Figure 5: Direct Powder system

Table 3: Example of a DSG plant with Direct Absorption Receiver and Direct Powder TES

Evaporator/Condenser		**Superheater**	
type	sandTES	type	sandTES
storage material	SiO_2	storage material	SiO_2
spec. storage material demand*	*19,98* [$m^3/MW_{el}h$]		
Water/steam			
p_{turb}	*150* [bar]		
T_{turb}	*600* [°C]		

)* incl. mass flow coming from superheater and reheater

4. Design of HEXs & applied models

In this section the TES designs developed at Technical University of Vienna and their models are sketched. These TES concepts will also be investigated with test rigs, which are under construction at the time of writing. The developed models will be validated by or at least compared to the performance data the test rig will deliver.

Furthermore the Direct Absorption Receiver developed by DLR is sketched.

4.1. Latent-HEX

The latent TES consists of a tank filled with salt, finned tubes, a drum, a mixing chamber, two control valves for varying the pressure in charge and discharge mode and a circulation pump. A vertical flow arrangement is chosen as shown in Fig. 6a.

For modelling the latent HEX, the following approach was chosen: The solidification and melting process of a slice of a HEX is simulated via a 2-D computational fluid dynamics simulation. Based on these simulations, a correlation of the heat transfer coefficient dependant on the liquid fraction was regressed. The behaviour of the solidification/melting process is aggregated in this heat transfer coefficient correlation, which is introduced into a 1-D model of the HEX. In this model, a PCM-HEX is vertically subdivided into cells. The cell liquid fraction is variable over height and over time. Free convection and sub cooling/superheating of the PCM are not yet taken into account. The physics of the flow and phase transition of water/steam flow inside the tubes is described with the well known drift-flux model and correlations for the evaporation and condensation process. The model of the latent HEX is explained in more detail in [2].

4.2. sandTES-HEX as evaporator

The sandTES evaporator is an advanced model of the classical sandTES model (superheater). The tube bundle is subdivided in cells (sub-HEXs) forming a heat exchanger network. Different flow characteristics can be considered by appropriate connections of the sub-HEXs, forming a 2-D-modell.

As in the model of the latent-HEX, the 2-phase-flow is described by the drift-flux model and correlations for the evaporation and condensation process. But also the powder mass flow influences the performance significantly, that’s why also the fluidization field is modelled in detail.

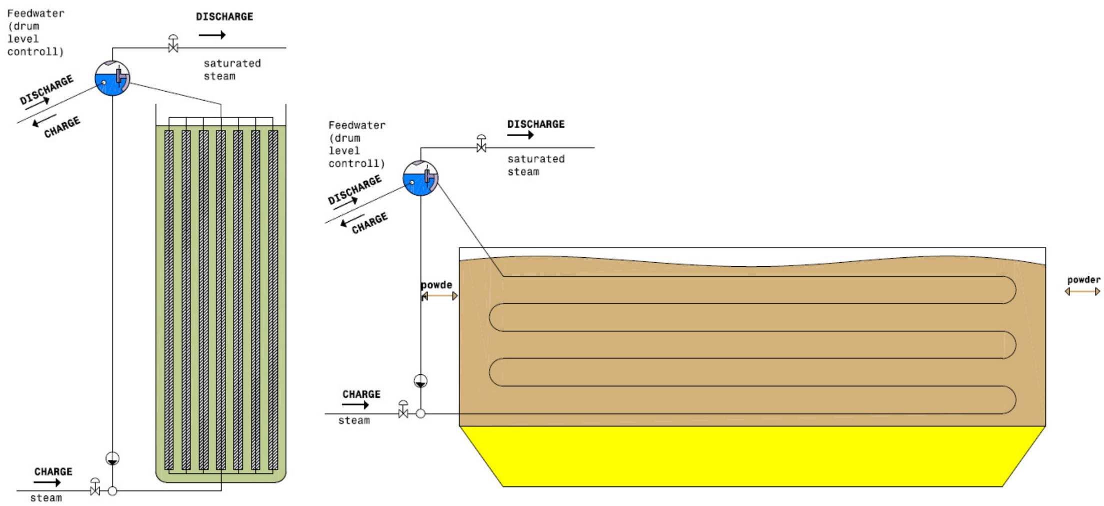

Figure 6: (a) concept sketch of latent HEX, (b) concept sketch of sandTES-HEX as evaporator

4.3. sandTES-HEX as superheater

The sandTES superheater is the classical sandTES fluidized bed HEX design discussed in detail in [1]. For assessing the performance of the sandTES-concept for various applications, a 1-dimensional stationary model is developed, which allows the HEX to be divided in several cells. For each cell the fluidization characteristics are individually calculated considering each cell’s specific boundary condition (e.g.: air mass flow predetermined by the windbox the cell is connected to) and thermodynamic properties of the storage medium and the primary heat transfer medium. The energy equation is considered via the application of the NTU-method [4].

Special care is taken for modelling the fluidization concept, with all components needed: nozzle floor, windboxes, recuperators, etc...

4.4. Direct absorption receiver

The solid powder is transported up the Solar Tower to the inlet of the direct absorption receiver (DAR). From there the solid particles fall down along the inner radius of a cavity, thus forming a free falling curtain parallel to the cavity wall and absorbing the irradiation. According to [3], DAR can heat up particles up to 1000 °C and offer design point efficiencies up to 90%. The concept of DAR can be found in more detail in [3]

The heating of the storage powder within the DAR is not modeled in this work; it is assumed that the storage powder can be easily heated up until a feasible maximum temperature of T_{powder}=650 °C, which can be handled in a metallic hopper.

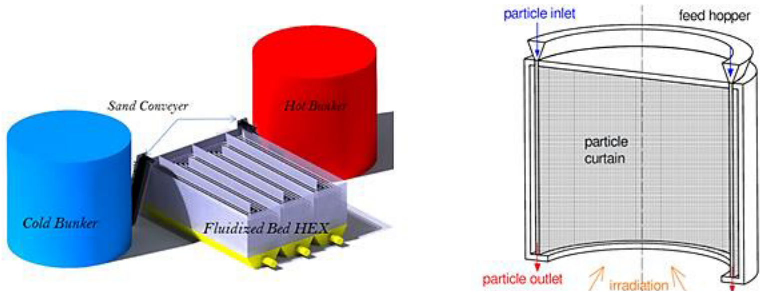

Figure 7: (a) sandTES superheater with hoppers, (b) principle of cavity receiver [3]

5. Conclusion

The challenges of implementing a TES to the Rankine Cycle within the field of CSP have been discussed in detail and the potential of using the sandTES Active Fluidization Concept in CSP has been presented. Three storage layouts are proposed applying the sandTES concept as superheater or/and evaporator. For each layout the specific storage material requirements have been evaluated enabling a first estimate of the overall storage costs.

Acknowledgements

Investigating a new Storage Concept in times where R&D budgets are small is not possible without a motivated team, overcoming the economic limitations via extraordinary engagement and smart ideas. We want to express our warm appreciation to everyone involved in the sandTES project at the Technical University of Vienna, especially the master and bachelor students doing the experimental work.

References

[1] K. Schwaiger et al.:"sandTES – an Active Thermal Energy Storagae System Storing High Temperature Heat in Low Cost Powders", SolarPaces conference 2013
[2] K. Schwaiger, M. Haider, H. Walter, M. Puigpinos, A. Proetsch: „SeLaTES: Thermal Storage of Superheated Steam", Solarpaces conference 2012, Marrakesh
[3] W Wu, B Gobereit, Cs Singer, L Amsbeck and R Pitz-Paal: "Direct Absorption receivers for high Temperatures", Solarpaces 2012, Marrakesh 2012
[4] VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurswesen (2010), "VDI heat atlas, second edition", Springer-Verlag Berlin Heidelberg
[5] H. Baehr, S. Kabalac:"Thermodynamik", Springer Verlag Berlin Heidelberg, 2006