COMBINED STORAGE SYSTEM DEVELOPMENTS FOR DIRECT STEAM GENERATION IN SOLAR THERMAL POWER PLANTS

Doerte Laing[1], Carsten Bahl[2], Michael Fiß[1], Matthias Hempel[1], Thomas Bauer[1], Mirko Meyer-Grünefeldt[3], Martin Eickhoff[3]

[1]German Aerospace Center (DLR), Institute of Technical Thermodynamics, Stuttgart, Germany.

[2]Ed. Züblin AG, Stuttgart, Germany.

[3]German Aerospace Center (DLR), Solar Research, Tabernas, Spain.

1. Introduction

Solar thermal power plants are a key technology for electricity generation from renewable energy resources. Thermal energy storage (TES) is indispensable for solar thermal power plant applications. It makes it possible to meet the intermediate load profile with dispatchable power, a benefit that has a high value to power utilities and that gives concentrating solar power (CSP) technology an edge over photovoltaic and wind power. The major high temperature collector technologies are parabolic troughs, linear Fresnel collectors (line focusing systems), power towers and dish collectors (point focusing systems). Most systems utilize a steam cycle that drives a turbine for electrical energy production. The primary heat transfer fluids (HTF) in the absorbers differ between these technologies. HTFs include water/steam, thermal oil, molten salt and air. Each HTF has its own unique properties and characteristics. This paper focuses on storage designs using water/steam as the HTF in the absorber. This so-called direct steam generation (DSG) has some major advantages. These advantages of the HTF include the following: low costs, low freezing temperature, non-flammable and non-hazardous to ground water. Also, the DSG design results in a comparably low number of heat exchangers and it has a high upper temperature limit (Eck and Hennecke 2009). DSG is utilized today in parabolic trough collectors (e.g. Solarlite), linear Fresnel collectors (e.g. Solar Power Group) and solar tower receivers (e.g. Abengoa PS10, eSolar, Bright Source). The technologies differ in terms of the temperature and pressure levels, as well as the enthalpy ratios for preheating to phase change and to superheating.

For DSG technology, cost-effective storage technology is to-date not commercially available. The only commercially available storage technology is a steam accumulator. This accumulator only produces saturated steam at a sliding pressure and is not cost-competitive for larger storage capacities due to the pressure vessel (Steinmann and Eck 2006). Therefore, the demand for storage systems that are adapted to the special characteristics of the two-phase fluid water/steam is increasing steadily.

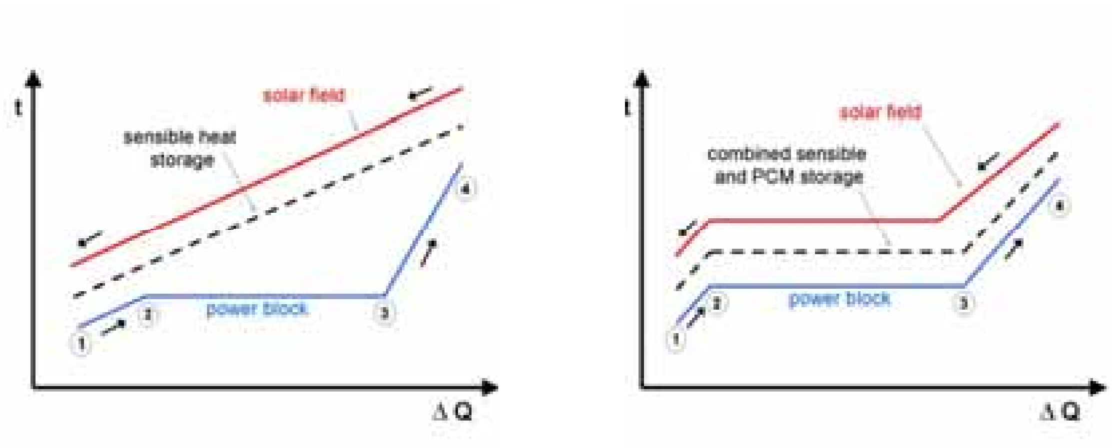


Fig. 1: Simplified temperature-enthalpy characteristics for sensible heat storage systems with a sensible heat transfer fluid in the absorbers (left) and combined sensible / PCM-storage for DSG in the absorbers (right). The sections in the power block steam cycle are 1-2 preheating, 2-3 evaporation and 3-4 superheating

Figure 1 on the left side shows the temperature-enthalpy characteristic of a sensible heat transfer fluid in a solar field absorber. Figure 1 on the right side shows the characteristic of a DSG solar field. It is important to note that the utilization of a sensible heat storage medium for DSG would result in a large temperature difference between solar field temperatures and power block temperatures (this inefficient design is not shown in Figure 1). This paper focuses on a combined sensible and latent heat storage system. Figure 1 on the right side shows the characteristic of such combined storage system.

2. Sensible heat storage concepts

2.1. Steam accumulator

State-of-the-art for thermal storage used in process heat applications is the steam accumulator technology (also called the Ruths storage systems). Steam accumulators use ***sensible heat*** storage in pressurized saturated liquid water, although a gas-liquid phase change occurs during charging and discharging (Figure 2). These systems benefit from the high volumetric storage capacity of liquid water for sensible heat. Steam accumulators are charged by condensation of steam fed into the pressurized liquid volume. During discharge, steam is produced by lowering the pressure of the saturated liquid. Since water is used both as the storage and working medium, high discharge rates are possible. Hence, this storage concept can be suitable for buffer storage applications to compensate cloud passing. Also, it may be used to support other storage concepts that have larger storage capacities and require longer start-up procedures. The storage capacity corresponds to the variation of sensible energy of the liquid volume during the discharging process. Since the water in the volume is in the saturation state, a change in temperature is correlated to a change of pressure of the saturated steam provided during the discharge process. A large decrease in pressure is advantageous considering the volumetric storage capacity. On the other hand, efficiency considerations limit the acceptable pressure variations in the system. The maximum temperature is limited by the critical point of saturated water (374 °C, 221 bar). The cost of a steam accumulator is dominated by the pressure vessel. Hence, the cost-effective capacity of steam accumulators is limited by the size of pressure vessel (Goldstern 1970, Steinmann and Eck 2006).

The PS10 central receiver power plant is the first commercial solar thermal power plant in Europe. Operation began in 2007 and a steam accumulator for the compensation of cloud transients is integrated in the system. Four tanks with a total storage capacity of 20 MWh enable a 50 % load operation of the 11 MW_{el} for about 50 minutes. The storage system is charged with saturated steam at 45 bar; during the discharge process saturated steam is produced at a varying pressure.

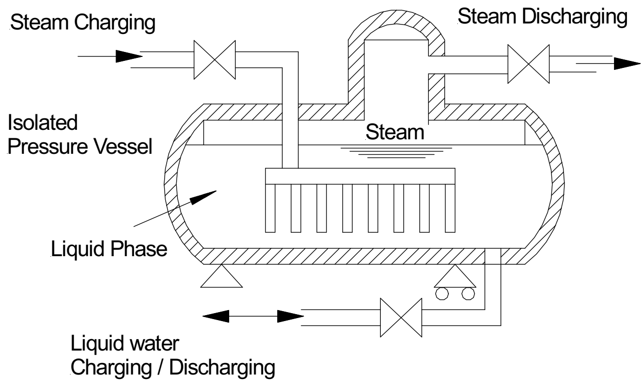


Fig. 2: Schematic layout of a sliding pressure steam accumulator.

2.2. Molten salt

For temperatures above 100 °C, molten salts are attractive candidates for sensible heat storage in liquids. The major advantages of molten salts are a high thermal stability and a low vapor pressure. The low vapor pressure results in storage designs without pressurized vessels. In general, there is experience with molten salts from a number of industrial applications related to heat treatment, electrochemical reactions and heat transfer. The use of salts requires consideration of the lower temperature limit defined by the melting/solidification temperature. One major difficulty with molten salts is unwanted solidification during operation. Solidification must be prevented in the piping, the heat exchanger and in the storage tanks. Hence, often auxiliary heating systems are required. Other limitations of molten salt storage may arise due to aspects such as costs of the storage media, the risk of corrosion and difficult handling of hygroscopic salts. The thermal stabilities of the salts used define the upper temperature limits. Salt mixtures, rather than single salts, have the advantage of having a lower melting temperature and similar thermal stability limits as the single salts. Typically a non-eutectic salt mixture of 60 wt% sodium nitrate and 40 wt% potassium nitrate is utilized and is commonly called solar salt. This mixture has a thermal stability limit of about 550 °C.

For DSG, a single molten salt storage system only based on sensible heat storage would either result in a large temperature difference between solar field and power block (see Figure 1) or require a large salt volume. Hence, for DSG plants, a single molten salt storage system is an unattractive option (Birnbaum 2010). On the other hand, sensible molten salt storage is a feasible option for preheating and superheating water/steam.

2.3. High-temperature concrete

Early solid media sensible heat storage developments at DLR within the framework of the project PARASOL/WESPE were funded by the German government from 2001 until 2003 (Laing 2006). Initially, two different storage materials were developed. These were high temperature concrete and a castable ceramic. At the Plataforma Solar de Almeria, four modules with a capacity of about 350 kWh were tested. High-temperature concrete showed advantages in terms of lower costs, higher material strength and easier handling compared to the castable ceramic and was therefore used for further developments.

Concrete is a composite material that consists of two major components. These are mineral aggregates and hardened cement paste. The paste contains free (evaporable) water and forms a matrix with the embedded aggregates. In a follow up project, Ed. Züblin AG joined the concrete storage development and a major focus was directed towards cost reduction (Laing 2008). A concrete storage module is principally composed of a tube register, two fluid headers and concrete as the sensible storage material (Figure 3), where additional components such as insulation and foundation are not shown. The tube register is used for transporting and distributing the heat transfer fluid while sustaining the fluid pressure; the solid media stores the thermal energy as sensible heat. A durable and safe construction is achieved by this division of the functions. For the charge and discharge processes, the flow direction of the heat carrier fluid is reversed. Hence, such concrete storage modules have a defined cold and hot end during operation.

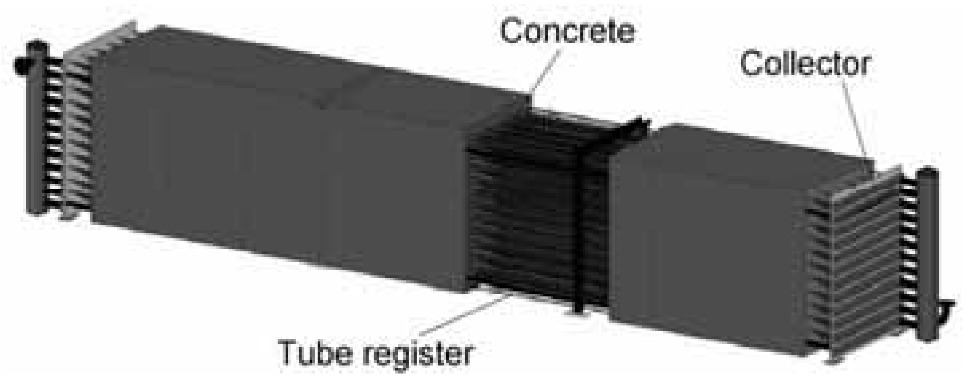


Fig. 3: Schematic layout of a concrete storage module showing the main elements tube register, concrete storage material and heat transfer fluid collector (without insulation).

The first test module built within the ITES project was damaged during the start-up phase. During initial heating of the concrete, residual water evaporates and can build up a critical vapor pressure if the permeability is too low for the rate of heating. The analysis of the damaged module led to an improved concept with a sufficient permeability of the concrete and a suitable thermo-mechanical design.

A special focus was set on the mismatch of the thermal expansion between concrete and tubing. In previous lab tests, the coefficients of thermal expansion (CTE) of the concrete and the tubes were determined. In a temperature range of 100 to 350 °C, the values were estimated with 9.0 to 12.0 x 10^{-6} 1/K for concrete and 13.5 to 15.0 x 10^{-6} 1/K for the tubing. Without additional measures, this mismatch would lead to longitudinal and radial stresses in the tubing as well as in the concrete. To limit the stresses to an acceptable level, a special interface material was installed. This special material reduces the friction between tubing and concrete and is compressible to allow a slight deformation to reduce the stresses without reduction of thermal transmission.

A second improved 20 m³ concrete module was built in Stuttgart, Germany. The module was commissioned in May 2008. In August 2011, this module had accumulated about 10.000 hours of operation at temperatures higher than 200 °C and about 386 thermal cycles. During this time, the performance of the storage was absolutely constant.

Earlier work on concrete development focused on parabolic trough power plants with thermal oil as the heat transfer fluid up to a maximum temperature of 400 °C (Laing et al. 2006, 2008, 2009). For DSG, higher temperatures are feasible and concrete testing up to 500 °C was performed (Laing et al. 2011b). The stability of the cement paste has a decisive impact on the concrete strength. Oven experiments and strength measurements up to 500 °C showed that mass loss and strength values of the concrete stabilize after a period of time and a number of thermal cycles. Hence, the utilization of high-temperature concrete as a sensible heat storage up to 500 °C seems feasible. Detailed results of material investigations related to the thermal stability of concrete up to 500 °C are presented in other publications (Laing et al. 2010a and 2011b).

The following discussion focuses on a third larger concrete unit, built at the power plant Litoral of Endesa in Carboneras, Spain for the combined DSG storage system. Although high temperature concrete for 500 °C has been developed, the operation temperature of this concrete storage unit is still limited to 400 °C. This concrete module has the following dimensions (without thermal insulation): total length 13.60 m; length of storage concrete 12.60 m; height 1.32 m; width 1.35 m; tube spacing 100 x 110 mm (triangular).

The higher design parameters (128 bar / 410 °C instead of 20 bar / 400 °C) require greater wall thicknesses and a redesign of the headers compared to the module tested in Stuttgart. The concrete body is longer (12.6 m instead of 8.4 m) in order to study the axial temperature distribution over a greater length, but not as high (1.3 m instead of 1.7 m) to limit the investment costs. Again, the tubes are arranged in a triangular pitch, but more densely to achieve higher heat transfer rates.

The construction of the concrete storage test module includes different process steps. The tube register was prefabricated in the workshop, transported to the site and lifted onto the previously prepared foundation by a crane. To reduce heat losses, a pressure-resistant thermal insulation (30 cm FOAMGLAS®) had been installed beforehand. Afterwards, additional reinforcement and measurement equipment was installed. To measure the thermal performance of the test module and control the start-up process, the concrete block is equipped with a number of temperature and vapor pressure sensors. The steam temperature is measured by a pair of PT100 sensors near the flanges on both the inlet and outlet of the storage module. The temperature within the concrete is measured at three cross-sections of the test module. Each measurement cross-section is equipped with several thermocouples (Type K, Class 1) in equivalent positions. Special focus was directed towards the measurement of vapor pressure, in order to control the start-up process. A number of capillary steel tubes inside the concrete module are used to connect the pressure tapping points to pressure transducers outside of the module (Laing 2010b). Subsequently, a formwork was installed and the storage block was poured with heat storage concrete. Finally, the module was covered with 40 cm of high-temperature mineral wool for lateral and top thermal insulation and covered with troughed sheets (Laing 2011a).

Commissioning of the storage unit includes the first heating of the storage block to expel the excess water in the concrete. During this process, water evaporates and builds vapor pressure within the concrete. If the vapor pressure exceeds a critical value, serious damage may occur. The storage test module was therefore closely monitored during initial heating. During the first heating steps, the expulsion of water from the concrete can be seen as a steam cloud at the top of the storage (Laing 2010b).

3. Phase change material (PCM) storage concepts

Regarding efficiency, a fundamental demand for thermal energy storage is the minimization of temperature differences between the HTF and storage medium. This requires an isothermal storage medium for processes using water/steam with a condensation/evaporation process. An obvious solution is a latent heat storage system with a phase change material (PCM). For a given PCM, the melting temperature is a material constant at a given pressure. The selection of the PCM strongly depends on the saturation temperature resulting from the pressure in the steam cycle. The vapor pressure curve directly links the saturation temperature to an operating pressure of the PCM module. DSG-processes with an operation range of 30-150 bar require melting temperatures between 230 °C and 350 °C (Figure 4). PCMs absorb energy during melting and release heat during solidification. In the case of $NaNO_3$ with a melting temperature of 306 °C, a driving temperature difference of e.g. 10 K means that the steam has to condensate at 107 bar / 316 °C while charging the system and water has to evaporate at 81 bar / 296 °C during discharge. Table 1 lists selected alkali metal nitrate and nitrite PCMs with their physical properties.

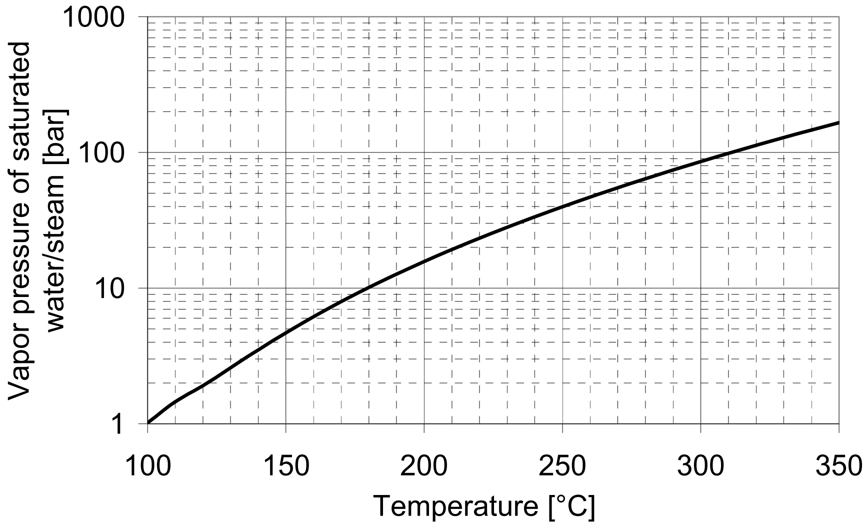


Fig. 4: Condensation/evaporation temperature of saturated water/steam.

Tab. 1: Physical properties of nitrate and nitrite salts and their mixtures. Shown are own measurements and data from Janz et al. (1979, 1981) with the melting temperature T, melting enthalpy H, thermal conductivity λ, heat capacity Cp, density ρ and volume change on melting ΔV/V, where s refers to the solid phase and l to the liquid phase near the melting temperature.

Salt system (Composition in weight%)	T [°C]	H [J/g]	λ_s [W/mK]	λ_l [W/mK]	$C_{p,s}$ [J/gK]	$C_{p,l}$ [J/gK]	ρ_l [g/cm^3]	$\Delta V/V_s$ [%]
KNO_3-$NaNO_3$ (54-46)	222	100	n.a.	0.46-0.51	1.42	1.46-1.53	1.95	4.6
$LiNO_3$	254	360	1.37	0.58-0.61	1.78	1.62-2.03	1.78	21.5
$NaNO_2$	270	180	0.67-1.25	0.53-0.67	n.a.	1.65-1.77	1.81	16.5
$NaNO_3$	306	175	0.59	0.51-0.57	1.78	1.61-1.82	1.89-1.93	10.7
KNO3	337	100	n.a.	0.42-0.50	1.43	1.34-1.40	1.87-1.89	3.3

As can be seen from Table 1, all salt systems show a high mass specific heat of fusion in the range from 100 to 360 kJ/kg and similar density values of around 1900 kg/m³. However, all known PCMs suffer from a low thermal conductivity value. The thermal conductivity of the PCM significantly affects the power density of the storage system. For DSG plants, the focus is currently on systems for daily operation with charging/discharging times in the order of several hours. Simple PCM storage designs cannot meet this high power density demand. Hence, advanced PCM concepts with enhanced heat transfer designs are required (Figure 5). Within the European project DISTOR (Energy Storage for Direct Steam Solar Power Plants), several of these concepts were experimentally investigated (Steinmann and Tamme 2008). It was found that the concept of PCM capsules embedded in a steam accumulator is less suitable. Also, designs with PCM-graphite composites with increased conductivity were less promising for DSG applications.

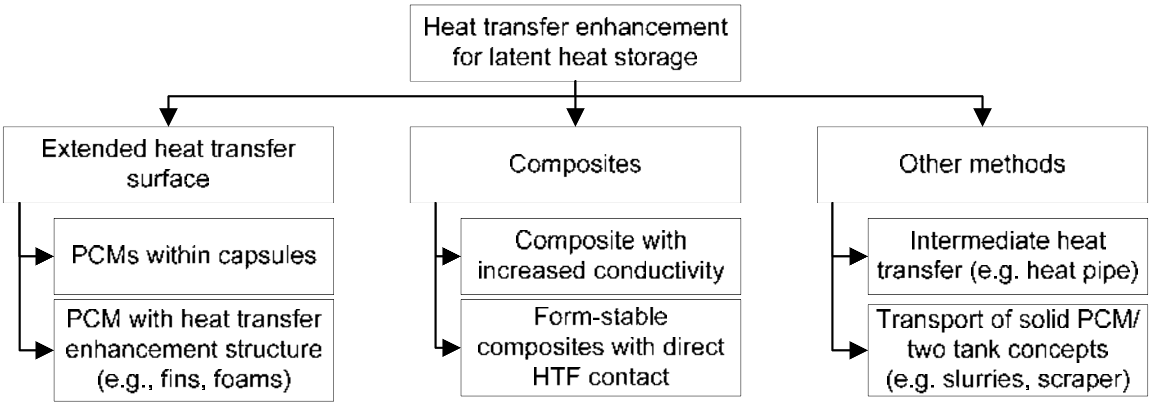


Fig. 5: Heat transfer enhancement concepts for latent heat storage systems.

It was found that enhanced heat transfer structures using fins are effective (Figure 5). The selected concept uses embedded fins, made of either graphite foil or aluminum, in the PCM volume and tubes for the pressurized HTF (Steinmann et al. 2009) (Figure 6). Graphite foils show good chemical compatibility in alkali metal nitrates and nitrites and mixtures thereof at temperatures up to 250 °C with the exception of lithium salts (Bauer et al. 2009). Aluminum has been tested up to temperatures of 330 °C in a PCM demonstration unit (Laing 2011c).

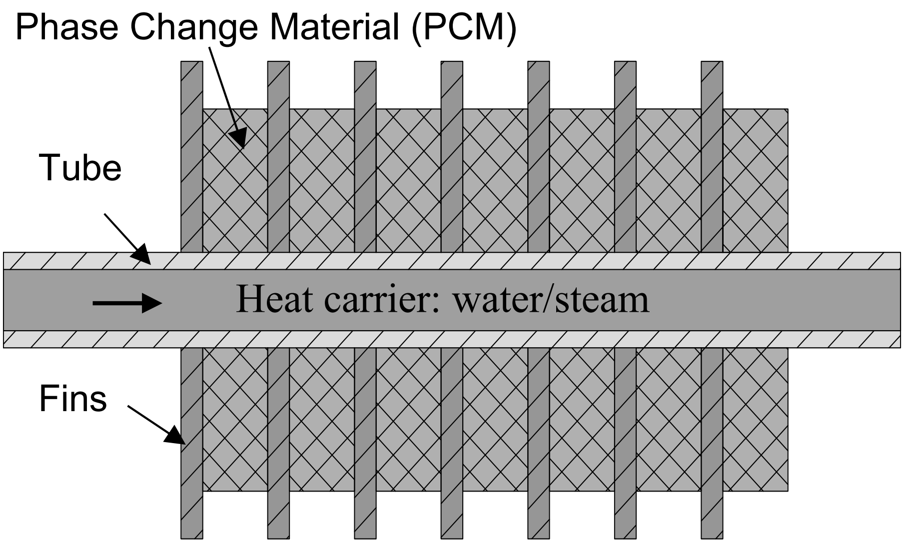


Fig. 6: Simplified scheme of the finned concept for heat transfer enhancement.

Several latent heat storage units have been designed and measured by DLR. Table 2 gives an overview of these units and PCM tests with their characteristic thermal power and capacity values, as well as fin materials and PCMs. Some units utilize PCMs with a low melting temperature (142 and 194 °C). The application of these storage units is industrial process steam recovery (Steinmann 2009, Johnson 2011a). Solar industrial process steam applications could also utilize such storage systems.

Tab. 2: Overview of latent heat storage units and PCMs tested by DLR
(Steinmann 2009, Laing 2010a, Bauer 2010, Johnson 2011).

Name	Max. power [kW]	Capacity [kWh]	PCM	Mass PCM [kg]	Melting Temp. [°C]	Fin Material
DISTOR I	2	3.5	KNO_3-$NaNO_3$(eu)	130	222	Graphite foil
PROSPER	15	7	KNO_3-$NaNO_2$-$NaNO_3$(eu)	400	142	Graphite foil
PROSPER Plus	various	10	KNO_3-$NaNO_2$-$NaNO_3$(eu)	500	142	Graphite foil
	100	200	KNO_3-$NaNO_2$-$NaNO_3$(eu)	5000	142	Graphite foil
DISTOR II	100	55	KNO_3-$NaNO_3$(eu)	2000	225	Graphite foil
DLR-S1/ITES 1	4	8	$NaNO_3$	156	306	Aluminium
DLR-S2	4	5	KNO_3-$NaNO_3$#	150	220 - 260	Aluminium
DLR-S3	4	12	$LiNO_3$-$NaNO_3$(eu)	150	194	Aluminium
DLR-B1	7	15	$NaNO_3$	320	306	Aluminium
ITES II	700	700	$NaNO_3$	14000	306	Aluminium

Non-eutectic mixture using a melting range

The following discussion focuses on the largest unit, with 14 tonnes of sodium nitrate ($NaNO_3$) for the combined DSG storage system. Detailed thermo-physical properties of $NaNO_3$ have been reported (Bauer 2009). Figure 7 shows a sketch of this module with dimensions. The latent heat value of the module is about 680 kWh. In order to reach practicable charge and discharge times, the module is equipped with aluminum fins. In charging mode, steam with a temperature slightly above saturation properties (typically ~107 bar, ~320 °C) condenses in the module. A condensate drain assures that the medium leaves the module only in liquid form. When the salt is completely molten, the tubes within the PCM module are flooded with liquid water at a temperature just below saturation properties (typically ~81 bar, ~295 °C). The saturated steam produced by the module during the discharge process then flows to a steam separator. The liquid water from the steam separator is recirculated either by natural recirculation or by a pump.

The PCM storage module is equipped with a number of thermocouples (Type K, Class 1), installed in four cross-sections from bottom to top of the storage module. In contrast to the molten salt storage technology, a PCM storage does not need to be filled with molten salt but can be filled directly with fine to medium grained solid salt, eliminating the need for an external melting unit in the filling process. In the PCM storage, the salt can be melted directly inside the storage unit, using the high power of the finned tube heat exchanger. This fast and efficient filling process has been tested successfully in the Carboneras demonstration unit (Laing 2010b).

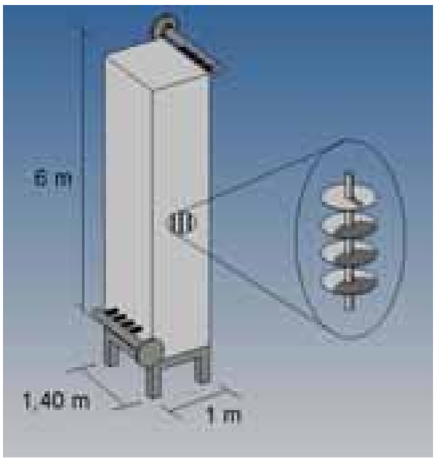
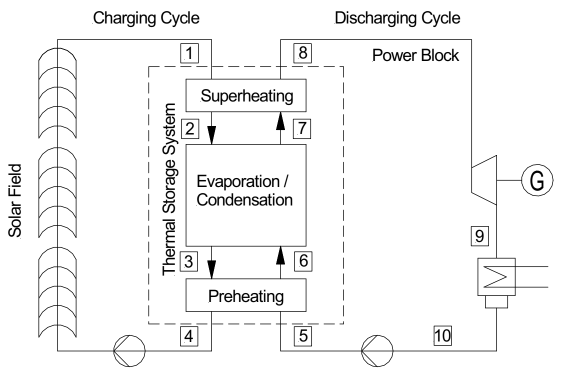


Fig. 7: Scheme of the 14 ton PCM module with finned heat carrier tube, collector and container without insulation.

4. Combined storage system for parabolic trough DSG

4.1. General design of the combined storage system for a 50 MW_{el} DSG power plant

The integration of a combined latent and sensible heat storage system in a DSG solar power plant was analyzed by Birnbaum (2010). The combined system consists of the preheating, evaporation/condensation and the superheating module. Figure 8 shows the integration of such combined system in a DSG power plant and the T-s diagram of the process. Figure 9 gives details of the combined system with the three modules.



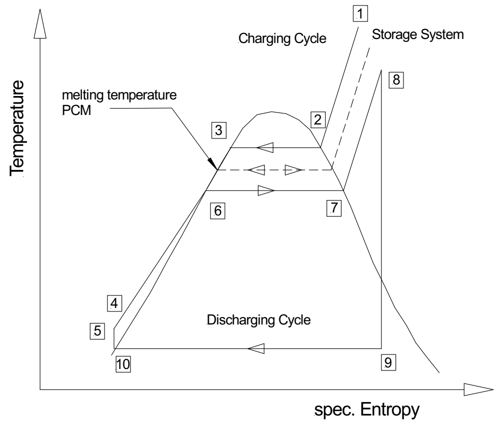


Fig. 8: Integration of energy storage in a simplified parabolic trough DSG power plant (left) and T-s diagram for charging and discharging process of steam in the DSG power plant (right).

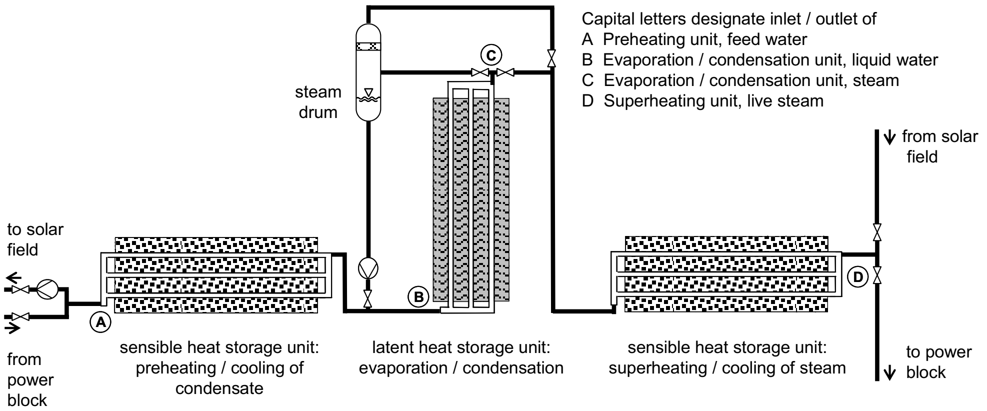


Fig. 9: Overview of a three-part thermal energy storage system for DSG combining sensible and latent heat storage.

Based on a commercially available steam turbine and suitable PCMs, two configurations with the steam parameters 110 bar / 400 °C and 156 bar /500 °C were analyzed. Suitable PCMs are potassium nitrate (KNO_3) at 156 bar and sodium nitrate ($NaNO_3$) at 110 bar (Birnbaum 2010). For further considerations, the first concept with 110 bar / 400 °C and $NaNO_3$ as PCM was selected. A driving temperature difference between melting temperature and HTF of 10 K can be assumed. This means that the steam has to condense at 107 bar / 316 °C while charging and water has to evaporate at 81 bar / 296 °C during discharging of the system (a pressure loss of 3 bar between 110 bar and 107 bar is assumed). The remaining boundary conditions of the storage system depend on the power block and the solar field. The division of the total required storage capacity into the latent heat storage for evaporating the water and the sensible concrete storage units for preheating and superheating strongly depends on these interface conditions.

The determination of the optimum final feed water temperature (FFWT) is a compromise between the thermodynamic efficiencies of the power block and the solar field. This temperature should be as high as possible for the highest power block efficiency. In the solar field, however, a high FFWT raises the thermal losses, and therefore, lowers the solar field efficiency. At full load, a FFWT value of 260 °C was selected (Birnbaum 2010).

With these boundary conditions, parameters for a combined storage system for a 50 MW_{el} DSG plant were estimated. From the specific enthalpies, the heat stored or released was calculated for a cycle with a total amount of heat transferred of 545 MWh. This corresponds to 6 hours of operation of the turbine with steam from the storage system. During discharge, the gross power of the turbine is reduced from 50 MW_{el} to approximately 35 MW_{el}, due to the lower pressure. The charging time is almost 6.5 hours to balance out the lower enthalpy difference available. Table 3 shows the division of the total amount of heat into the three parts of the combined storage system for charging and discharging (Laing 2010a).

Tab. 3: Enthalpy of water / steam at the interfaces of the thermal storage system (Laing 2010a).

		Temperature	Enthalpy	Enthalpy difference		Heat stored/released
		°C	kJ/kg	kJ/kg	%	MWh
Discharging (81 bar)						
A		242.5	1050			
B	A-B: preheating	296.9	1322	272	13	72
C	B-C: evaporation	296.9	2757	1435	70	380
D	C-D: superheating	390.0	3108	351	17	93
	A-D: total			2058		545
Charging (107 bar)						
A		260.0	1134			
B	A-B: cooling of condensate	316.0	1437	304	16	85
C	B-C: condensation	316.0	2712	1274	65	357
D	C-D: cooling of steam	400.0	3082	370	19	103
	D-A: total			1948		545

4.2. Test results of the combined storage system for DSG

In order to validate the combined DSG storage concept, a PCM and a concrete storage module with a total storage capacity of approximately 1000 kWh were installed in the research projects ITES and REAL-DISS at the power plant Litoral of Endesa in Carboneras (Figure 10). The combined storage system comprises of a PCM storage module for evaporating water and a concrete storage module for superheating steam. A concrete module for preheating liquid water is not installed. Since the superheating step is more challenging, the project resources for concrete storage were completely allocated to a superheating module.

Fig. 10: Demonstration storage system with concrete superheater (left) and PCM-Storage (right) in the water/steam test loop at the power plant Litoral of Endesa in Carboneras, Spain

The combined storage system was built in 2009 (Laing 2010b and 2011a). In July 2010, the commissioning was successfully completed (Laing 2010b). After improvements on the installation, cycle testing started at the end of 2010. For the PCM storage operation, two different options, constant pressure and sliding pressure operation have been tested. For the operation with constant system pressure, the mass flow through the storage and the charging/discharging power falls continuously, while for the sliding pressure operation, the charging/discharging power can be controlled at a constant value.

In combined operation, the concrete and PCM storage modules are coupled; the concrete storage is charged using the sensible heat of the superheated steam and the PCM storage by the latent heat of the condensing steam. In Figure 11, an exemplary day for combined operation in sliding pressure operation is shown.

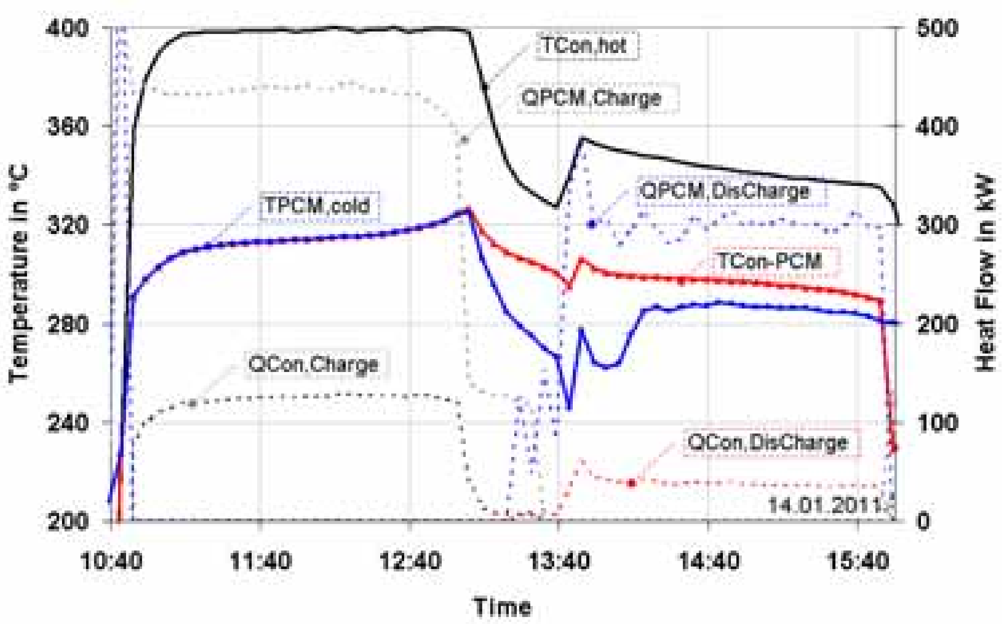


Fig. 11: Example of a charge/discharge cycle of the combined storage system in sliding pressure mode with measured inlet and outlet temperatures as well as obtained power levels.

Superheated steam at 400 °C ($T_{Con,hot}$) enters the concrete storage module on the hot side (Figure 11). Dry saturated steam leaves the concrete storage and enters the PCM storage module on the hot side. So, the outlet temperature of the concrete storage equals the inlet temperature to the PCM storage ($T_{Con\text{-}PCM}$). Saturated water exits the PCM-storage ($T_{PCM,cold}$) on the cold side, therefore $T_{Con\text{-}PCM}$ equals $T_{PCM,cold}$, as only latent heat is transferred. The charging heat flow Q_{Charge} is constant at approx. 450 kW in the PCM module and approximately 125 kW in the concrete superheater module.

At approx. 13:00 o'clock, the charging process is stopped and the switching process starts. At about 13:45 o'clock the discharging operation is started and water enters the PCM storage from the cold side ($T_{PCM,cold}$). When the level in the steam drum stabilizes at about half full, a constant discharge heat flow rate is available. Wet steam is produced in the PCM storage with the temperature $T_{Con\text{-}PCM}$ and is then separated in the steam drum into dry steam and saturated water. This dry steam enters the concrete storage at the cold side ($T_{Con\text{-}PCM}$) and is heated within. Superheated steam is produced at an almost constant rate with the temperature $T_{Con,hot}$ ranging from 356 °C at the beginning of discharge and 336 °C at the end of discharge.

Models of the PCM storage and the concrete storage were developed in Modelica. These models can be connected into a whole storage system for direct steam applications with the program DYMOLA. DYMOLA stands for Dynamic Modelling Laboratory and is designed to solve transient physical models numerically and is in particular suited for system modeling. The 2D heat conduction in the radial direction inside the storage material is described by a partial differential equation (PDE). To solve the PDE numerically, the concrete storage is approximated with a simplified model of Schmidt and Willmott (1981) and the storage side of the PCM storage is discretized with the finite difference method. The aims are to predict temperature, pressure, mass flow rate, heat loss, capacity and coupling of several modules. Furthermore, the models can be used to lay-up storage systems iteratively. This is possible due to the models' short computing time. In a recent paper, tests on each unit separately and combined testing, as well as comparisons of modeling results with experimental values are described (Laing 2011c).

5. Summary and conclusions

This paper addresses current limitations of direct steam generation (DSG) technology in terms of the availability of thermal energy storage systems for the two-phase heat transfer fluid water/steam. The paper presented work on the effective combined thermal energy storage concept to overcome this limitation. The combined thermal energy storage system is composed of a latent heat storage unit using sodium nitrate as a PCM and a sensible heat storage unit using concrete as a solid storage medium. The paper gave an overview of the principle and previous work on both individual storage concepts as well as the combined operation.

Commissioning and testing of a combined storage demonstration system with a total storage capacity of approximately 1000 kWh was described. It is the first demonstration of such a combined storage system for the two-phase heat transfer fluid water/steam. The system operates under pressure and temperature conditions as they occur in a DSG power plant with the main steam parameters of 110 bar and 400 °C. The combined operation of a PCM storage module for evaporating water and a concrete storage module for superheating steam in sliding pressure mode was successfully demonstrated. Good system operability of the single systems and the combined mode was achieved.

For large scale implementation of such a storage system, the single storage modules will be increased to a feasible module size. Then, the required storage capacity for the evaporation section will be built by connecting PCM modules in parallel. For the superheating section, the required number of concrete modules can be designed in series and in parallel. This modular setup makes it easy to deliver a specified storage capacity. As the next step, a scale-up to pre-commercial scale of 10-20 MWh capacity is planned.

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