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ADVANCED THERMAL ENERGY STORAGE TECHNOLOGY FOR PARABOLIC TROUGH

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ABSTRACT

The availability of storage capacity plays an important role for the economic success of solar thermal power plants. For today's parabolic trough power plants, sensible heat storage systems with operation temperatures between 300°C and 390°C can be used. A solid media sensible heat storage system is developed and will be tested in a parabolic trough test loop at PSA, Spain. A simulation tool for the analysis of the transient performance of solid media sensible heat storage systems has been implemented. The computed results show the influence of various parameters describing the storage system. While the effects of the storage material properties are limited, the selected geometry of the storage system is important. The evaluation of a storage system demands the analysis of the complete power plant and not only of the storage unit. Then the capacity of the system is defined by the electric work produced by the power plant, during a discharge process of the storage unit. The choice of the operation strategy for the storage system proves to be essential for the economic optimization.

INTRODUCTION

During the last decade research, development and demonstration of Concentrated Solar Power (CSP) was driven by the solar/fossil hybrid plant approach. Development was mostly dealing with components for concentrating and converting of solar radiation and was directed to receiver, heliostats, collector elements etc.

Now, increasing interest is directed towards Thermal Energy Storage (TES) for CSP. Driving forces for storage implementation are climate change and air pollution/CO_2 emission as well as legislative regulations and specific credits for “green” electricity. These forces argue for high solar contribution and “solar-only CSP plants”.

Strategic significance of solar storage technology is caused by several effects: improvement of plant operation, increased power block utilization, power conversion at nominal load, and improvement of revenues.

The overall objective of storage integration is to increase the solar annual contribution, improve efficiency and to reduce the Levelized Energy Cost (LEC). Therefore, energy storage integration is an important point for successful implementation of CSP technology. In order to achieve this LEC reduction potential, efficient storage technology with high life time and low initial capital costs is required.

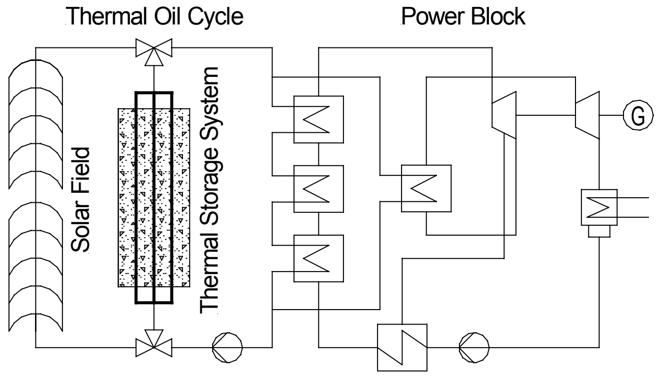

Fig. 1: Basic concept for integration of thermal energy storage into solar thermal parabolic trough power plants

This article focuses on storage systems for parabolic trough power plants. Today's parabolic trough power plants use a synthetic oil as heat transfer media in the absorber pipes. The thermal energy is transferred to the feedwater of a Rankine cycle at temperatures between 290°C and 390°C. The feasibility of direct steam generation in the absorber pipes has been proven by real scale experiments and offers the possibility of improved efficiency for future power plants. In both cases a thermal storage system would be installed parallel to the solar field (Fig.1).

Early systems utilized the heat transfer media itself as the thermal energy storage media, but due to the costs of the oil, this is not economical [1]. A promising approach is the application of phase change materials, but additional experiments are required to obtain sufficient data for the layout of larger storage systems.

In concepts using the sensible heat of solid media for thermal storage, the storage material contains a tube register heat exchanger to transfer the thermal energy to or from the heat transfer fluid [2]. The feasibility of such systems has already been proven in laboratory scale. Since the storage of thermal energy is not necessarily identical with the storage of exergy, the design of such a system demands the analysis of the complete power plant. An economic optimization of a storage unit is not possible without including the power cycle.

Research activities at DLR are aiming at the development and validation of new innovative concepts and approaches for energy storage for CSP technology with thermal efficiency of more than 90%, 30 year life time and specific cost of less than 20 €/kWh thermal capacity and less than 0.01 €/kW$_{electric}$. In order to meet these ambitious technical and economic goals, advanced TES concepts, based on innovative storage materials as well as innovative operation and heat transfer concepts have to be considered.

In the project WESPE [3], funded by the German Government, the focus lies on the development of an efficient and cheap sensible storage material and on the optimization of the tube register heat exchanger.

As an innovative storage material a castable ceramic, which is principally composed of a binder including Al_2O_3 and as aggregates iron oxide and various other materials has been developed. The binder is setting chemically under ambient conditions and forms a solid, stable matrix, which encloses the aggregates. With this material a density of 3600 kg/m³ is reached and the thermal conductivity is slightly higher than that of concrete. Alternatively a high temperature concrete has been developed with a high density of 2400 kg/m³. Eventually, the final material costs will determine, if the benefits of the better thermo-physical properties of the castable ceramic can overcome the higher costs.

Test storage units have been designed with a length of 23 m and 36 heat exchanger tubes. Four of these storage blocks will be built, two with the castable ceramics and the other two with the high temperature concrete as storage material. The test storage units will be tested on the Plataforma Solar de Almeria in Spain, integrated in the parabolic trough test loop (Fig. 2). This loop comprises 50 m LS-3 and 75 m EuroTrough parabolic troughs with a thermal power of 480 kW, using synthetic oil as heat transfer fluid. Within this test loop, either two storage blocks of same material can be operated in series connection, or two blocks of different material can be operated in parallel.

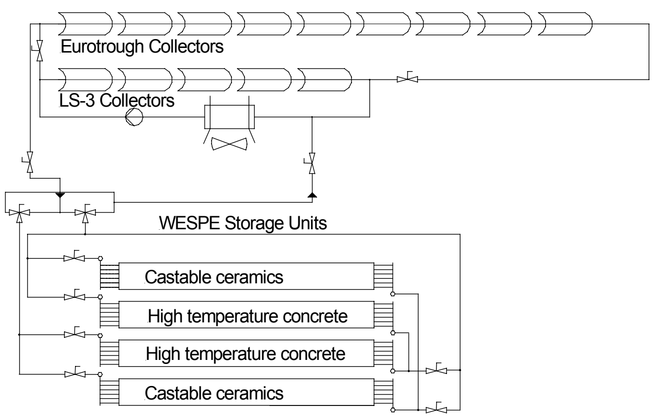

Fig. 2: Integration of test storage units into parabolic trough test loop at PSA

The test storage units will be built in spring 2003 and tested throughout the second half of 2003.

NOMENCLATURE

c	=	mass specific heat capacity, J/(kg K)
da	=	distance between centerline of flow channels, m
di	=	inner diameter of flow channels, m
k	=	thermal heat conductivity, W/(m K)
L	=	length of storage unit, m
ρ	=	density of storage material, kg/m³

EVALUATION CRITERIA FOR THERMAL STORAGE SYSTEMS

The development of a thermal storage system demands the selection of the storage medium, the definition of geometric parameters and the choice of an operation strategy. Different aspects have to be considered:

- Since the energy provided by a storage system, integrated in a power plant, is used to drive turbines, an isolated analysis of the storage unit based on a first law approach is not sufficient. The application of exergy-principles still neglects the characteristics of medium-temperature Rankine cycles, used in parabolic trough power plants. Therefore the evaluation and thermo-economic optimization of a thermal storage system demands the analysis of the complete process, including the solar field and the thermodynamic cycle. The capacity of the system is then defined by the electricity generated during the discharge process.
- The storage system has to fulfil demands concerning the power transferred during the charging and discharging process. Usually a higher heat transfer rate is related to an increase of thermodynamic irreversibilities, thus reducing the capacity of the system as defined before.
- The storage material used should be non-combustible, non-toxic, cheap and available. The lifetime must be sufficient even at higher temperatures.

PHYSICAL MODEL AND STORAGE SIMULATION TOOL

A typical storage unit is composed of parallel tubes for the oil passing through the unit. The tubes are separated by the storage material, the distance between the axis of the tubes is da (Fig.3). For the physical model identical conditions in all parallel tubes are assumed. The storage unit is composed of parallel storage elements. A storage element is considered as a hollow cylinder of storage material with diameter da, in contact with a tube of inner diameter di. The storage material is characterized by the thermal heat conductivity k, the mass specific heat capacity c and the density ρ.

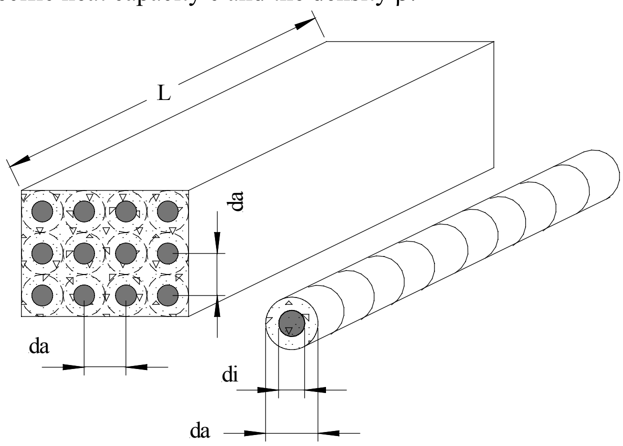

Fig. 3: Physical Model for the storage unit and parameters describing the geometry

Analytical descriptions of the transient behavior of storage systems are restricted to certain boundary conditions and simple geometries. The development of storage systems for solar applications with varying boundary conditions demands the application of a simulation tool. Based on the simulation language Modelica [4,5] the simulation environment StorageTechThermo for storage systems was developed. Here, a storage element is composed of storage modules which are connected in series (Fig.4). The module is composed of components representing the oil volume, the tube segment and the storage volume. Physical models describing the convective heat transfer and the pressure loss are included. The transient temperature field in the storage material is assumed to be axially symmetric around the tube.

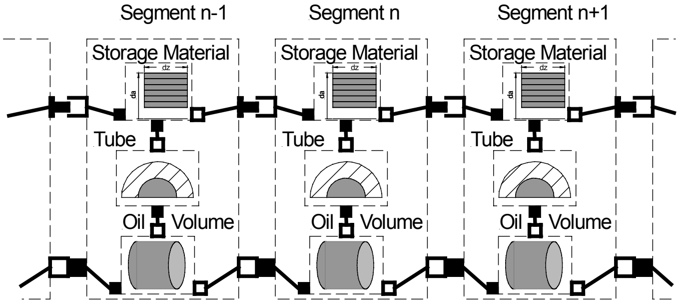

Fig. 4: Part of the Modelica-model representing a single tube and the surrounding storage material. The tube and the storage material are discretized in axial direction, the storage material is also discretized in radial direction

SENSITIVITY ANALYSIS USING A DIFFERENTIAL STORAGE ELEMENT

In order to reduce the number of parameters for a first sensitivity analysis, a differential storage element is used. Here, the variation of temperatures in axial direction is neglected. The simulations start with a sudden increase of oil temperature from 350°C to 390°C, which corresponds to the conditions at the inlet of the storage system at the beginning of the charging process. The oil is considered as an infinite power source during the charging period that lasts 3600 s. During the following break of 3600 s the storage volume is considered to be a closed system without thermal losses to the environment. Finally, the oil temperature is reduced to 350°C and the storage is discharged. If not varied, thermal conductivity of the storage material is 1.2 W/(m K), density is 2200 kg/m³ and specific heat capacity is 1000 J/(kg K). The diameter of the flow channel (di) is 0.02m, the distance between two parallel channels (da) is 0.08m. To illustrate the effects of parameter variations, the temperature pattern in the middle between two tubes is used. During charging, this temperature is the minimal temperature in the storage medium. Additionally, the thermal power transferred to the storage medium from the thermal oil is regarded.

Variation of Thermal Conductivity

The time needed to reach again stationary conditions after a sudden change of the oil temperature depends on the thermal conductivity of the storage material. Fig. 5 shows the variation of the temperature at maximum distance to the tube for various values of the thermal conductivity k reaching from 1.0 W/(m K) to 5.0 W/(m K). The thermal power transferred to the storage system for various values of the thermal conductivity is shown in Fig. 6. Both figures show that only significant variations of the thermal conductivity distinctly affect the performance of the storage system.

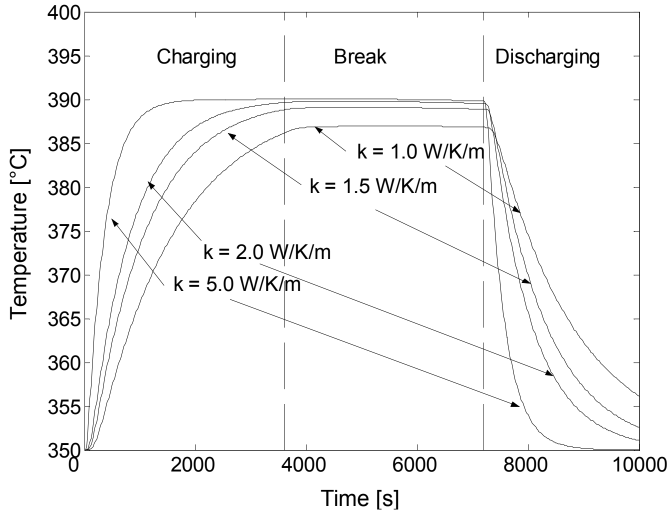

Fig. 5: Influence of thermal conductivity of storage material on storage temperature at distance da/2 from tube

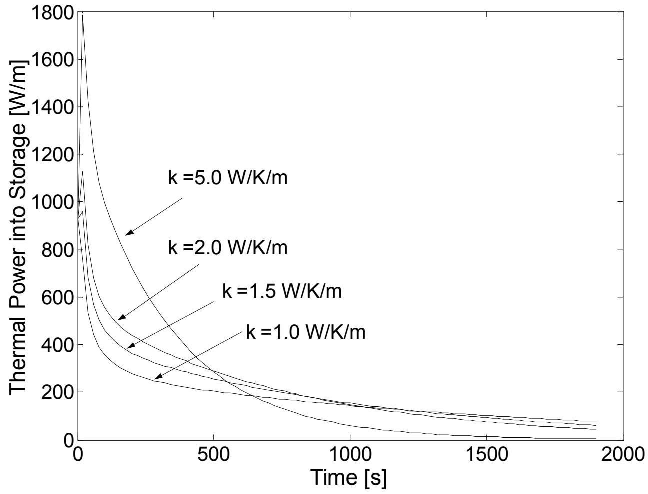

Fig. 6: Thermal Power transferred to differential storage element during charging with varying thermal conductivity of storage material

Variation of Volumetric Heat Capacity ρc

For a given geometry the capacity of the system for storing sensible heat is determined by the product of specific heat c and density ρ of the storage medium. Fig. 7 shows the effect of variations of the volumetric heat capacity on the temperature at maximum distance to the tube in the storage medium. The value of the distance between two tubes is adjusted to the volumetric heat capacity to keep the thermal capacity of the system constant. Selected values for the volumetric heat capacity vary between 1500 (rock) and 3500 kJ/(m³ K), which is a typical value for steel.

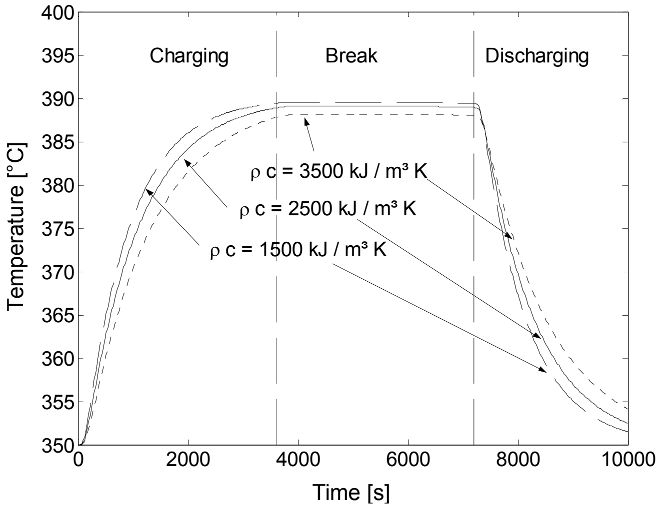

Fig. 7: Influence of volumetric heat capacity on storage temperature at distance da/2 from tube

Fig. 8 shows the corresponding values for the thermal power transferred to the storage medium during charging. These results show that for a constant total heat capacity the performance of the storage is only slightly influenced by the volumetric heat capacity.

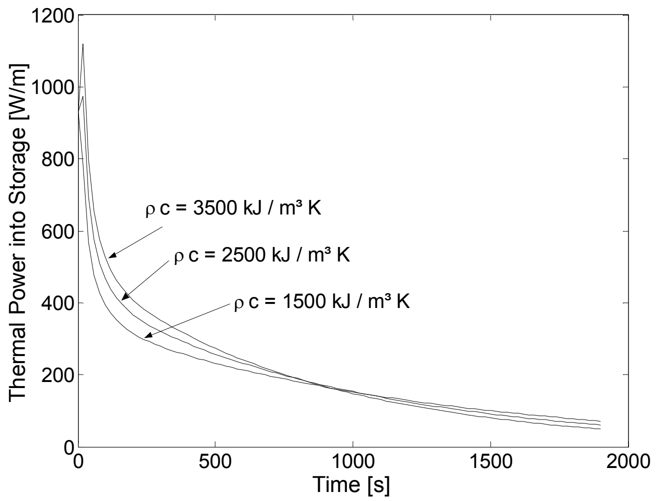

Fig. 8: Influence of volumetric heat capacity on thermal power transferred to storage medium during charging period

Variation of Diameter of Flow Channel

The expense for the tubes forming the flow channels for the oil inside the storage medium represents a significant share of the total investment costs. A proper selection of parameters like tube diameter and distance between tubes is essential for the economic optimization of the storage system. Fig. 9 shows the influence of the flow channel diameter di on the temperature at maximum distance to the tube in the storage medium. The volume of the storage medium is kept constant by adjusting the distance between the tubes.

Due to the increased heat transfer area, the temperature variation is faster for bigger diameters of the flow channel, the corresponding heat flow rates are shown in Fig. 10. Assuming constant values for wall thickness and length, the amount of steel needed for the tubes increases proportional to the diameter. The ratio of diameter to transferred power indicates that less steel is necessary if a smaller diameter is used, since an increase in diameter does not result in a corresponding increase of transferred power.

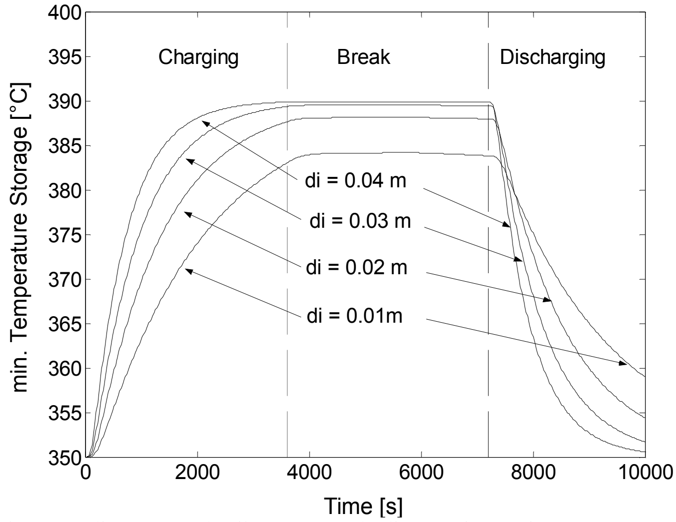

Fig. 9: Influence of diameter of flow channel on storage temperature at distance da/2 from tube

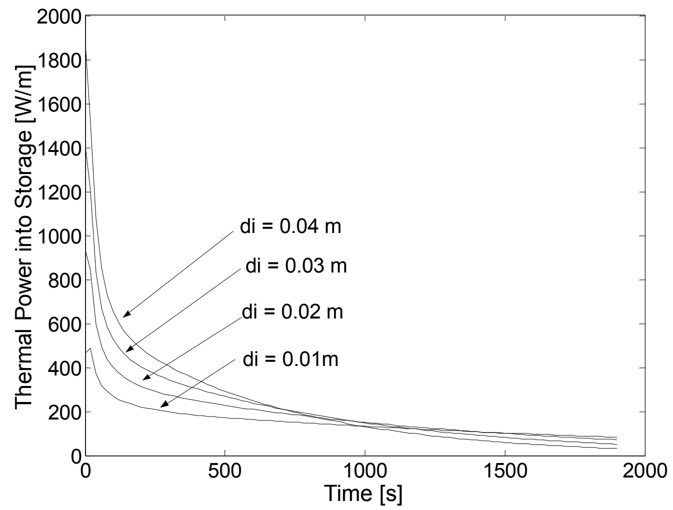

Fig. 10: Thermal power transferred to storage system for various diameters of flow channel

Variation of Distance between Flow Channels

Fig. 11 shows the calculated temperature at maximum distance to the tube for different distances between the flow channels. It can be seen that if a value of 0.08 m is exceeded, a radial temperature gradient exists in the storage medium at the end of the charging period.

For the calculation of the thermal power transferred to the storage medium an identical storage volume for all distances was assumed. The results in Fig. 12 show that increasing the distance results in a reduced variation of the power transferred during the charging period.

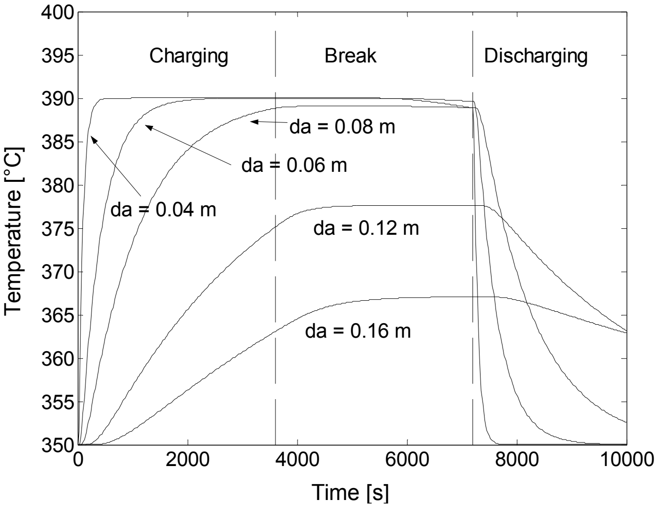

Fig. 11: Influence of distance between flow channels on storage temperature at distance da/2 from tube

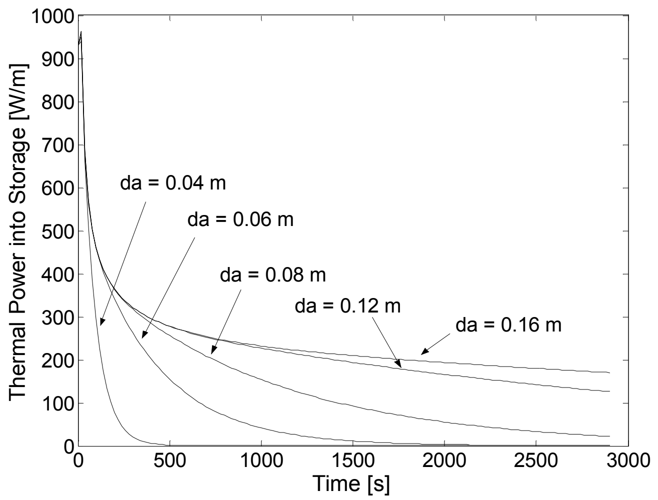

Fig. 12: Thermal power transferred during charging period to storage material for different values for distance between flow channels

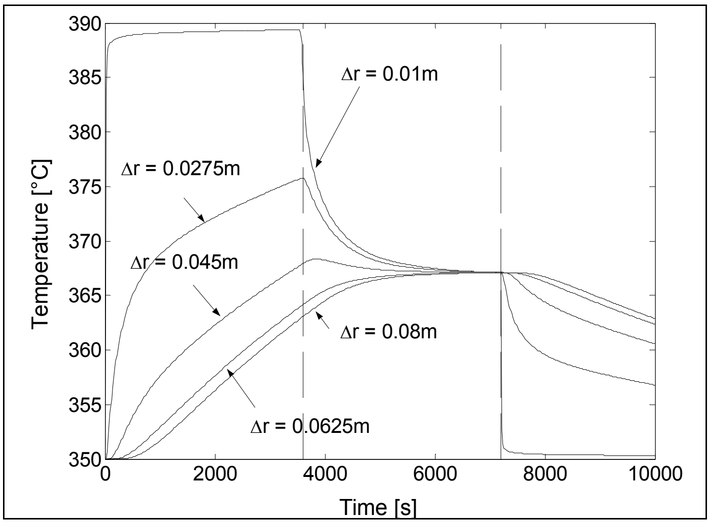

Fig.13: Temperature in storage material at different distances Δr from flow channel. Distance between axis of flow channels is 0.16 m

For a distance of 0.16 m between flow channels, Fig. 13 shows the temperature pattern at various radial positions from a flow channel in the storage medium. Since the distance between the flow channels is too big, there is still a radial temperature gradient in the storage material at the end of the charging period. During the break, before the discharge starts, this temperature gradient is leveled out. Although no thermal energy is lost, this represents a significant loss in quality of the stored energy. Therefore, in a storage unit integrated in a power plant, temperature gradients inside the storage medium must be minimized. If during the charging period not enough energy is available to use the full capacity of the storage systems, only a reduced number of flow channels should be used.

ANALYSIS OF THERMAL STORAGE UNIT

While the differential storage element helps to evaluate the sensitivity of the various parameters, the analysis of a real scale storage unit also demands the consideration of the axial temperature variations. Some examples are described below. Basic parameters used for the tube register have been 0.02 m for the inner tube diameter with a distance between two flow channels of 0.08 m and concrete as storage material. The results are calculated for a single storage element. A complete storage is then build up by multiplying this capacity until the required capacity is reached. This number of storage elements will then be operated in parallel, as described in Fig. 3. Thermal losses to the environment and inhomogeneities inside an up-scaled storage are neglected and will be implemented into the model at a later stage.

In Fig. 14 the temperature distribution at the beginning and end of charging and discharging, respectively, for a storage with a length of 500 m is shown. Here the oil inlet-temperature for charging was 390°C and for discharging 265°. Charging and discharging times have been 1 hour each with a break of 15 minutes in between. Mass flow rates have been chosen such that the condition for maximum oil-outlet temperature for charging of 315°C and minimum oil-outlet temperature for discharging of 350°C have been approximately met. Seg.1 is the radial storage segment closest to the heat exchanger tube and Seg.5 is the segment in the middle between flow channels.

The top four lines in Fig. 14 show the temperature distribution along the storage length after 1 hour of charging. The oil (upper line) enters the storage with a temperature of 390°C at the length 0 m and leaves the storage with approx. 315°C at the length 500 m. The temperature distribution of storage segment 1 (second upper line), is very close to the oil temperature, because it is the first segment around the heat exchanger tube. The forth upper line is the temperature distribution in the outermost segment (Seg.5) of a single storage tube, showing the temperature drop in radial direction.

The third line from the top shows the temperature distribution for segment 1 and 5 after a break of 15 minutes after charging. Due to the good thermal conductivity, the radial temperature difference between Seg. 1 and 5 has been evened out at the end of the break at a temperature level closer to that of segment 5, because here is the higher storage volume and therefore capacity. This temperature distribution is the start condition for discharging of the storage.

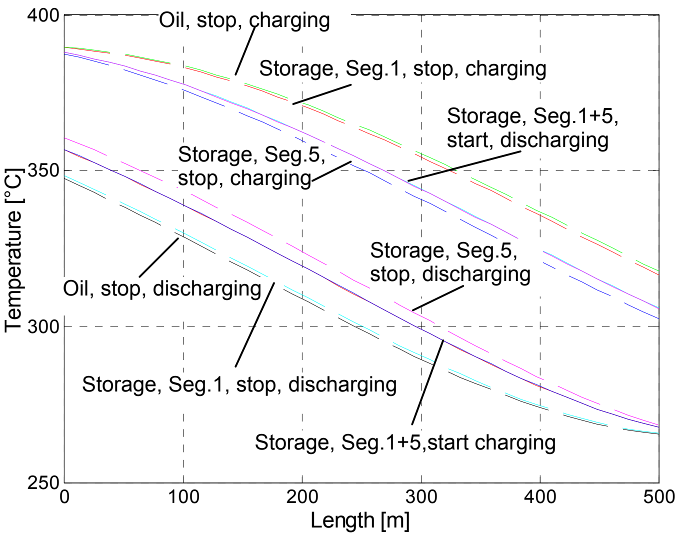

Fig. 14: Temperature distribution in the storage versus length for beginning and end of charging and discharging, respectively

The distribution after 1 hour of discharging is illustrated by the four bottom lines in Fig. 14. During discharging, the oil enters the storage at the length 500 m with a temperature of 265°C. After one hour discharging it leaves the storage at length 0 m with a temperature of approx. 350°C (bottom line). This is the minimum outlet temperature acceptable for the thermodynamic cycle. Again the temperature distribution of segment 1 is very close to the oil temperature, while thus of segment 5 is higher due to the thermal resistance of the storage material. The third line from the bottom shows again the storage temperature along the length after a break of oil flow of 15 minutes. This temperature pattern is the starting condition for the next charging cycle.

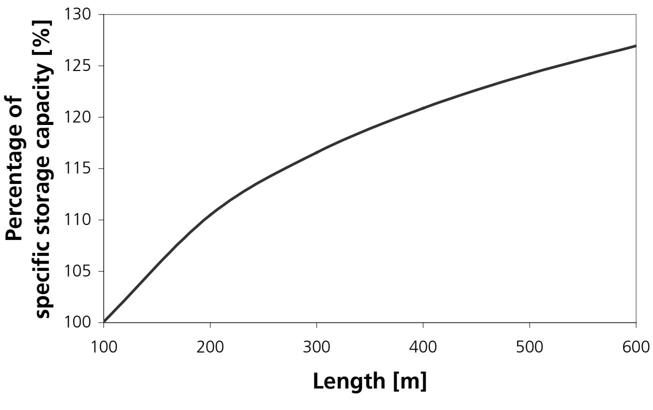

Fig. 15: Variation of storage length

Fig. 15 shows the specific storage capacity (energy stored / volume of storage material) for varying storage length, based on the specific capacity of a storage with 100 m length (100%). For comparison, the length of the storage has been increased, while the mass flow has been adapted such that the conditions for outlet temperatures (315°C and 350°C) are met. It can be seen that under these conditions the specific storage capacity increases noticeably with increasing length.

Additionally, the mass flow rate increases with increasing length. Therefore the number of required parallel heat exchanger tubes decreases, which also reduces the number of flow collectors and distributors and therefore costs.

It must be noted, though, that the optimisation of storage length also requires a consideration of pressure losses.

ANALYSIS OF THERMAL STORAGE UNIT INTEGRATED IN A SOLAR THERMAL POWER PLANT

The evaluation of the quality of the thermal energy demands the consideration of the power cycle. A reheat cycle is assumed with a maximal pressure of 100 bar and a maximal superheating temperature of 370°C (Fig. 16). The thermal energy is transferred to the process at different temperature levels of the feed water. From Fig. 17 it becomes obvious that the predominant fraction of the energy is transferred at feed water temperatures not exceeding the evaporation temperature of the Rankine cycle of 311°C. An exergetic analysis does not account for this temperature distribution.

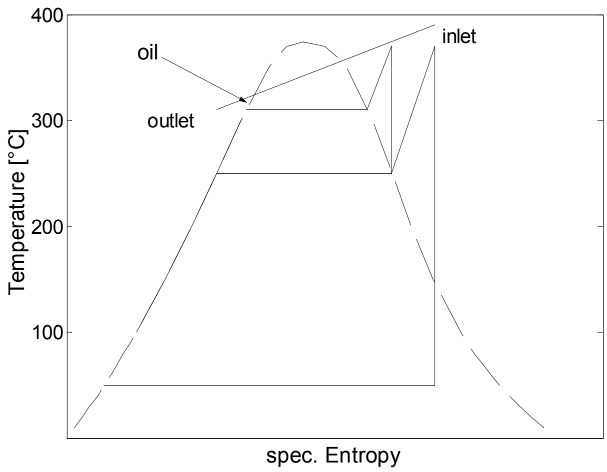

Fig. 16: Power cycle for basic concept in T-s diagram during discharge

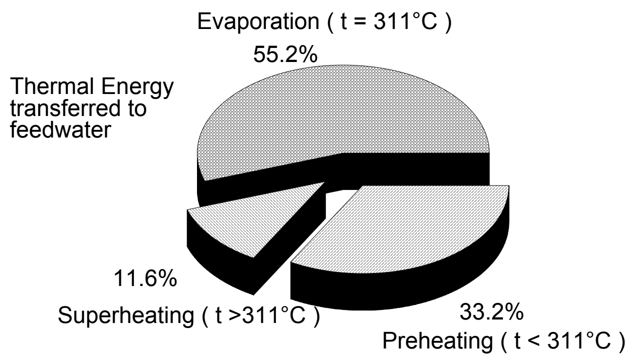

Fig.17: Distribution of thermal energy transferred to feed water of Rankine cycle of parabolic trough power plant

The basic concept suggested, for integrating a thermal storage system, is shown in Fig. 1: the storage unit is operated parallel to the solar field. During the charging period the inlet of the storage unit is connected to the outlet of the solar field. At the exit of the storage unit the temperature of the oil must not exceed a temperature level of about 315°C to avoid a destruction of the absorber pipes by overheating in the exit section of the solar field. During the discharge process thermal oil from the storage is fed into a heat exchanger to generate steam. The course of the oil-temperature during the discharge process is shown at the top of Fig. 16.

The major drawback of this basic concept is the limitation of the temperature differences between charging and discharging: The discharging process is ceased if the oil temperature at the outlet of the storage falls below 350°C, since overheating of the feed water is not possible any more. The temperature differences during charging and discharging are limited to 40°C.

Since the temperature difference in a sensible storage system corresponds to the storage capacity, the capacity for a given geometry can be increased by raising the temperature variation between charging and discharging. By dividing the absorber row in axial direction, the oil temperature at the exit of the storage unit can be higher during the charging process, since the temperature rise of the oil flowing trough the solar field is smaller (Fig. 18). As a result, the average temperature at the end of the charging process is increased in the storage material.

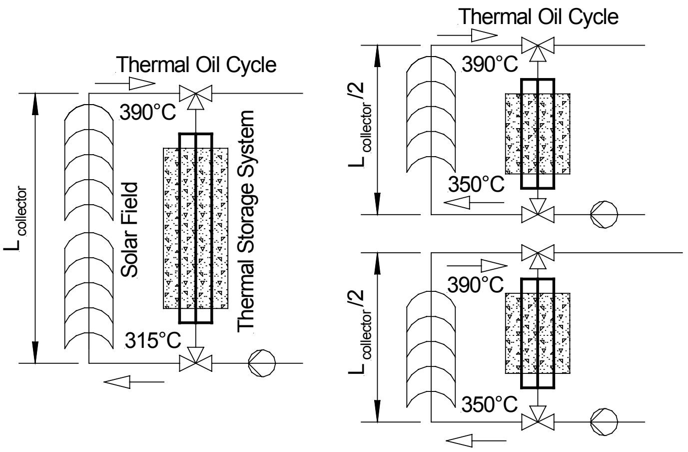

Fig. 18: Configuration solar field: basic concept (left) and modular charging concept (right); exemplary values to show effect on allowable storage outlet temperature

Another possibility to increase the capacity is an improved adaptation of the discharge-process to the characteristics of the Rankine cycle: oil is taken from the storage at different temperature levels (Fig. 19). In this modular discharge concept, oil leaving the storage unit below 350° can be used for evaporation or preheating. At the end of the discharge process, the average temperature in the storage material is lower than for the basic concept.

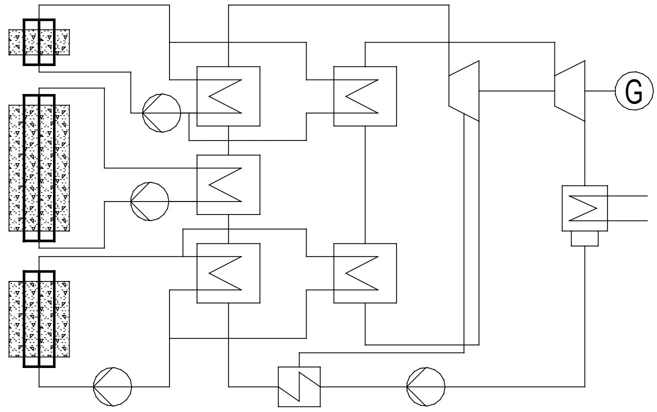

Fig. 19: Modular discharge concept; re-heating at two different temperature levels

The modular charging concept can be combined with the modular discharging concept thus increasing the average storage temperature at the end of the charging process while decreasing the average temperature at the end of the discharging process.

The four different concepts were compared for an identical storage geometry. Boundary conditions are determined by the outlet temperature of the solar field which is restricted to 390°C. In this analysis, the size of the solar field is not limited, i.e. the mass flow rate of the oil during the charging period is only limited by the boundary condition. The duration of the charging and discharging process is 3600s each.

Fig. 20 shows the electrical power provided by the power plant during the discharge of the storage unit, the corresponding electric energy is shown in Fig. 21. These results show that a modified charging and discharging strategy improves the performance of the system significantly. By combining the modular charging with the modular discharging, the capacity of the system is increased by about 200% without modifications on the geometry of the storage system.

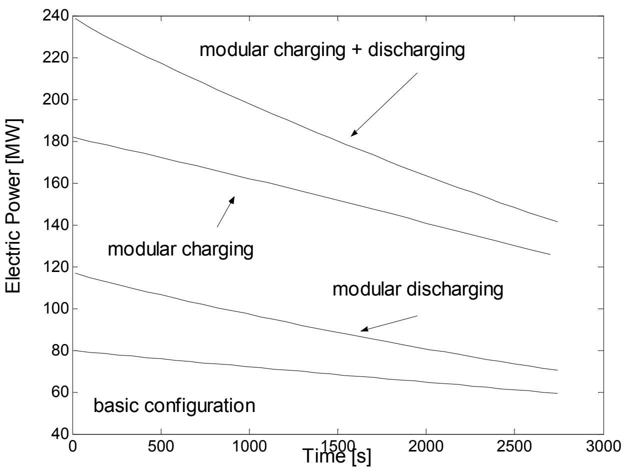

Fig. 20: Calculated values for electric power provided by power plant during discharge for different charging and discharging strategies; identical storage geometry

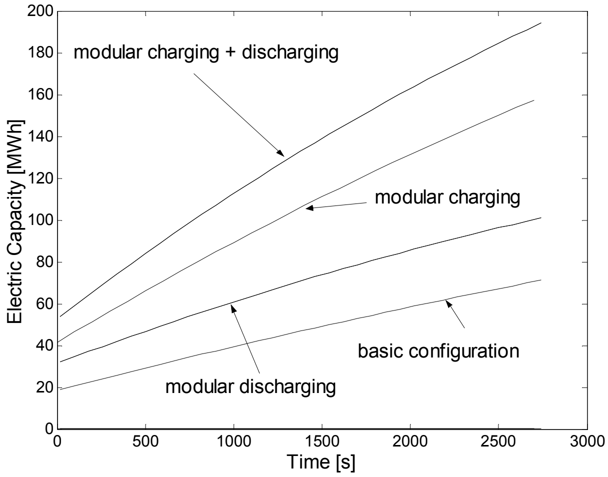

Fig. 21: Results for electric energy provided by power plant during discharge of storage for different charging and discharging strategies; identical storage geometry

OUTLOOK

The simulation results show the importance of the strategy chosen for charging and discharging of the storage unit. Further improvements could be achieved by introducing a sequential discharge of the storage unit. Here, not all storage segments are discharged simultaneously. A segment is initially used to superheat steam. If the oil temperature drops below a certain level, the segment is used to evaporate steam and the discharge of another segment is initiated to provide energy at the temperature level needed for superheating.

The techniques described above demand additional piping and an elaborate control strategy, but the gain in capacity probably easily outweighs these costs.

Further developments will also consider phase change materials as storage medium. Here, the combination of sensible and latent heat storage will be regarded. The application of phase change material is especially interesting for the development of storage units for the direct steam generation (DSG) in parabolic troughs. After the feasibility of DSG has been demonstrated [6], the development of storage capacity represents a further element supporting the introduction of DSG-technology.

CONCLUSION

From the simulation results presented in this paper, the influence of the various parameters describing the thermal storage system can be determined. The potential for improvements by selection of an optimized storage medium seems to be limited. Concerning the geometry of the storage system, the choice for the distance between the flow channels is important. After the charging process has ceased, the radial temperature distribution around the flow channels has to be nearly homogenous. If there's a distinct temperature profile within the storage material, entropy will be generated during the temperature equalization before the discharge starts. This will reduce the capacity of the storage even if there are no thermal losses to the environment. The choice for the strategy for charging and discharging the storage system represents a key element for the optimization of the storage system. The capacity of a sensible storage system can be increased by extending the difference between the average temperatures at the end of the charging process and the end of the discharging. Compared to a parallel integration of the storage unit, the concepts described in this paper increase the electric capacity by 200%. The development of optimized operation strategies is essential for improving the economics of thermal storage units.

ACKNOWLEDGMENTS

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