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Using sand and other small grained materials as heat storage medium in a packed bed HTTESS

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Abstract

Packed bed heat storage systems offer a great potential for the further reduction of the LCOE of CSP-plants. The use of cost effective and local available storage materials like gravel or silica sand is a key factor for such systems. But also concerning the performance during charging and discharging of the system, the storage material has a huge influence.
In this paper the influence of small grained storage material is investigated using theoretical models and experimental results. The results show, that with small grained materials with diameters of 2 mm or less a very sharp temperature behavior could be achieved during charging. The boundary layer between the hot and the cold storage material (the so called thermocline) is very sharp for all considered air flow rates. The paper concludes with a simplified model of the thermocline for the design of the storage system and the selection of the most critical parameters.

Keywords: Concentrated solar power, thermal energy storage, storage material, packed bed, thermocline

1. Introduction

Heat storage systems are one key part for the successful development of the CSP-Technology in all emerging markets. With the thermal storage systems, CSP-plants are able to produce dispatchable energy out of a volatile energy source, the sun. Thinking on cost reduction of the LCOE of the whole CSP-plant, thermal storage system plays also an important role.

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Nomenclature

A	Shell surface in m²
Bi	Biot-Number
CSP	Concentrated Solar Power
d	Diameter of the particular stone in m
HTF	Heat transfer fluid
HTTESS	High temperature thermal energy storage system
i	Shell index
n	Number of shells
r	Shell radius in m
T	Temperature in °C
TES	Thermal energy storage
V	Air velocity
α	Specific heat transfer coefficient in W/m²K
λ	Specific thermal conductivity factor in W/mK

Molten-salt TES-systems could be considered as current state-of-the art systems. Due to the high costs for the molten salt, one possibility to reduce the system costs could be the use of a cheap and local available storage material like rocks, gravel or sand [1]. To use these materials in a TES-system, a different design for the storage system must be considered, presented in [2].

In this paper the usage of a packed-bed storage system is analyzed, with a special focus on the size and the characteristics of the used storage material. With this new analysis the influence of the storage material on the temperature is evaluated, supporting the adaptation of the system.

1.1. Enolcon – HTTESS system

Enolcon is developing since 2011 a HTTESS including the overall system layout as well as the design of the storage vessel and the storage material itself. The overall concept including the modular design of the storage vessels is described in [2]. Additional a schematic layout is given in Fig. 1.

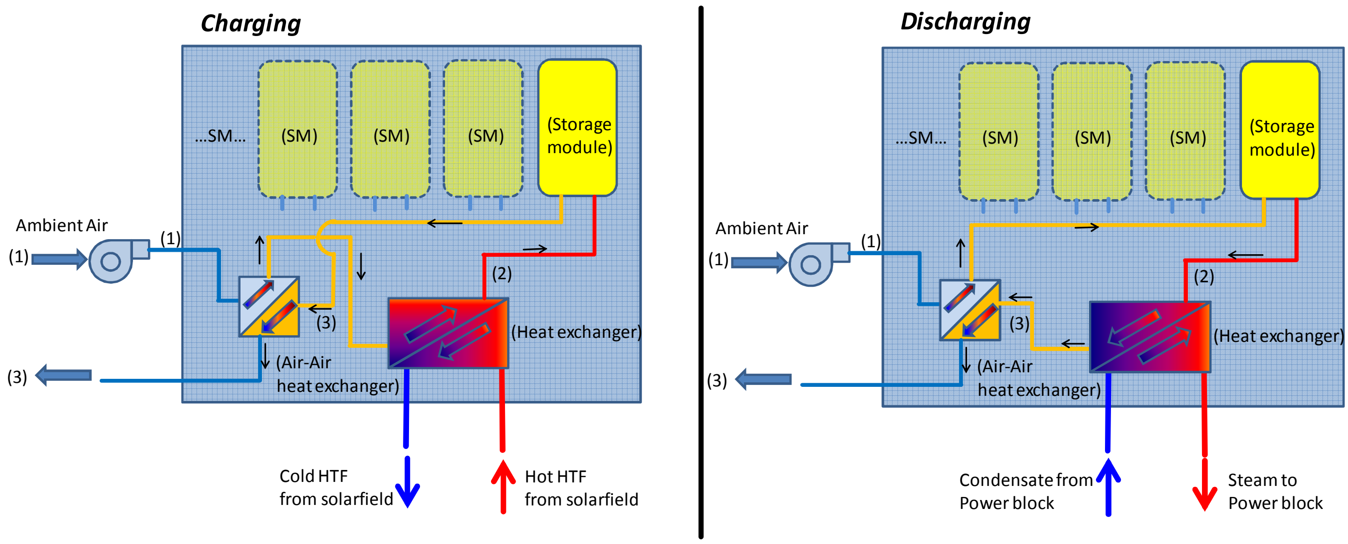

Fig. 1. Principal setup of the enolcon-HTTESS in charging (left) and discharging (right) mode

To charge the storage, cold air from the ambient is directed with a blower through an Air-Air heat exchanger to the charging heat exchanger. There the air is heated up using the heat from the solar field, transferred by the HTF. The hot air is directed to the storage vessel, where the heat is transferred to the storage material. After leaving the storage, the remaining heat is used in the Air-Air heat exchanger to heat up the ambient air. With this closed heat-circle and the open air-circle, the air blower could be placed outside the hot air system, avoiding huge requirements on the thermal resistant of the blower.

For the discharging mode, the ambient air is directed to the storage, is heated up and then transferred to the water-steam cycle of the power block. If the exit temperature of one module is below the required temperature, the air is directed to the next storage module, enabling a nearly constant temperature at the entrance of the steam boiler.

2. Theoretical Background

The size of the storage material is one important parameter within the design of the thermal storage system. To evaluate the influence of the material on the temperature behavior in the packed bed, a shell model is developed and simulated. This chapter is conducted by a comparison of the simulation results with the Biot-Number.

2.1. Modeling the heat transfer in grained material

In order to model the heat transfer behavior in a single, particular stone, the stone is considered as a set of several staggered shells, see also Fig. 2. For each shell, the temperature is considered as constant.

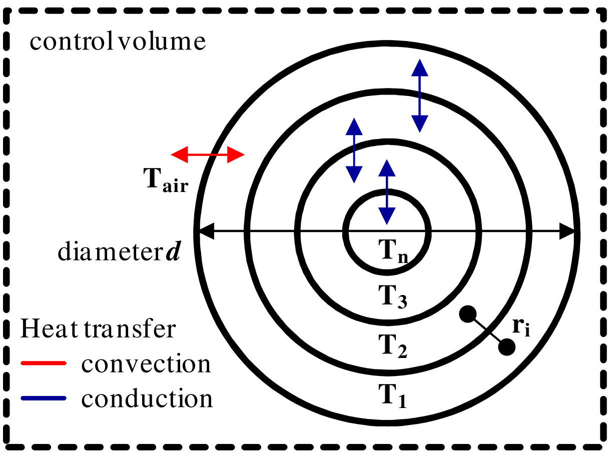

Fig.2. Used Shell-model for the simulation of the temperature behavior

With an increasing number of shells (n) the accuracy of the model is improved, on the other hand the computational time is also increased. Several simulations show, that for the used diameters (1-15 mm) an amount of $n = 20$ shells shows a very good accuracy with a suitable computational effort.

The heat transfer between the shells is calculated based on a set of parameters (shell surface, heat capacity, etc) and could be calculated based on heat convection between the first shell and the surrounding hot air and on heat conduction between the different layers. In order to model the heat transfer a differential equation for each shell could be formulated as

$$\dot{Q}_i = \frac{\lambda_i}{r_i} A_i (T_{i-1} - T_i) - \frac{\lambda_{i+1}}{r_i} A_{i+1} (T_i - T_{i+1}) \tag{1}$$

with the heat transfer via conduction depending on the temperature difference between each shells, the boundary area A_i between the shells and the radius r_i describing the distance between the two shell centers. The area A_i is getting smaller for the inner shells while the radius r_i is kept constant, depending on the diameter d of the stone

$$r_i = \frac{d}{2n} \tag{2}$$

For the first shell, the heat convection with the air must be taken into account, followed by another formulation of the differential equation as

$$\dot{Q}_1 = \alpha_{stone} A_1 (T_{air} - T_1) - \frac{\lambda_2}{r_i} A_2 (T_1 - T_2) \quad (3)$$

Also the inner shall need another formulation, based on (1):

$$\dot{Q}_n = \frac{\lambda_n}{r_i} A_n (T_{n-1} - T_n) \quad (4)$$

With this formulation (1)-(3), a detailed simulation of the temperature behavior within the complete stone could be performed, using a constant air temperature in order to neglect boundary influences.

2.2. Analysis for different sized storage material

Using the model presented in chapter 2.1, simulations for several sized materials are performed. The results are shown in Fig. 1. The temperature behavior depends strongly on the size of the stones. Small grained material (diameter of 2 mm) with a lower mass shows on the one hand a very fast temperature increase. On the other hand, there is nearly no deviation trough the different shells visible (the stone is heated up with an equal temperature distribution). With further increase of the diameter of the stones (8 mm and 15 mm) a slower dynamically behavior is observed and the difference between the temperature at the outer surface and the inner core is getting more and more relevant.

This effect is presented in the right part of Fig. 3. A temperature gradient of more than 15 K is observed over the whole stone.

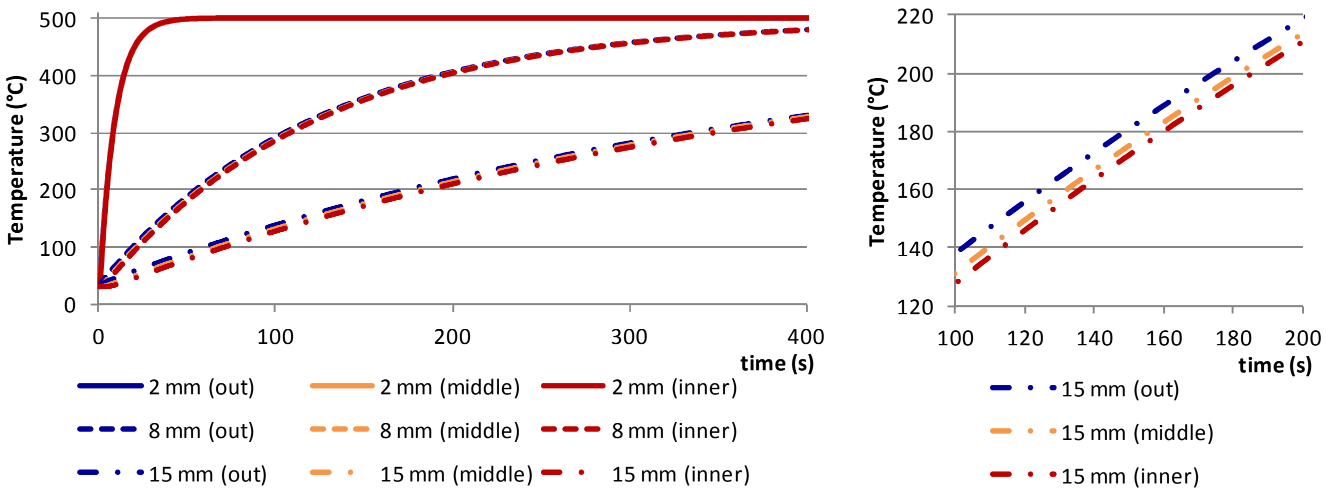

Fig.3. Modeled temperature behavior in different shells of a particular stone for three different radius (left), detailed view of the 15 mm radius (right)

The temperature behavior through the stones depends on two critical factors. First the thermal convection between the surface of the stones and the surrounding air and second the heat conduction within the stone. If the surfaces heats up very fast and the inner core of the stone remains cold (bad heat conduction or wide diameter), only a small amount of heat could be transferred to the stone.

2.3. Biot-Number

The results from the detailed dynamic simulation could be summarized in the relation between the inner heat conduction represented by λ and the outer heat convection represented by α_{stone}, with is depending on the air velocity around the stone with diameter *D*. This expression is called the Biot-Number and is defined as [3]:

$$Bi = \frac{\alpha_{stone}(v_{air})D}{2\lambda} \quad (4)$$

Based on detailed simulations and statistics, stones with a Biot-Numbers smaller than 0.1 show nearly no difference with between surrounding and inner temperature at any point of time, resulting in a very good heat storage ability.

For an exemplary stone, with a specific thermal conductivity factor λ of 2.5 W/mK the Biot-Number is analyzed for different air velocities. The resulting curve for Biot-number of 0.1 is shown in Fig. 4. For all values below this line, the temperature in the stone could be considered as constant and equal to the surface. The evaluation shows, that small grained material with diameters lower than 2 mm shows a significant advantage, because they can be used with higher air velocities. As the air velocity is directly related to the useful surface and the charging capacity, this results in a lower necessary surface necessary to achieve a defined charging (and discharging) capacity.

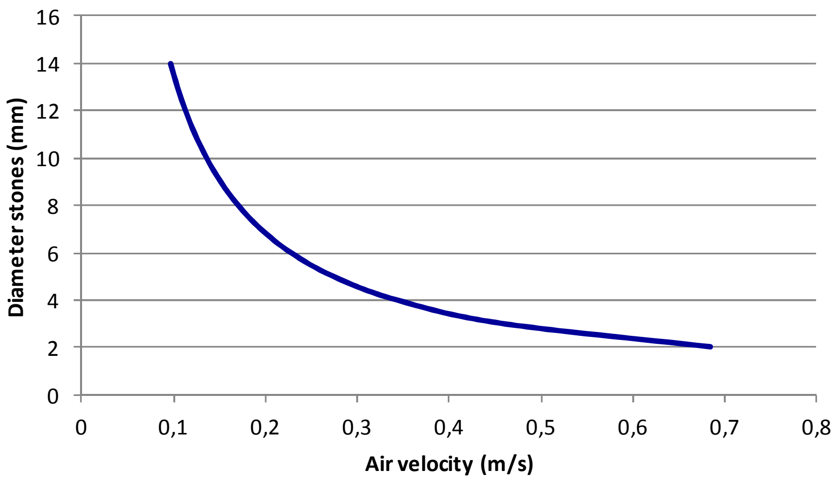

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Fig. 4. Calculated Biot-Number of 0.1 based on the air velocity and the stone diameter, using (4)

3. Experimental setup

Enolcon is operating several test facilities in order to validate the theoretical results, to approve new design concepts and to gain operational experience with the HTTESS [4]. Within this paper, the results of a single packed bed test facility are presented. Due to the design of the heating unit, a temperature range between 300 °C and 550 °C is possible with an air flow between 25 Nm³/h and 100 Nm³/h. The principle design of the test facility together with the measurement equipment is described in the following chapter.

3.1. Test facility

The test facility used in this paper is based on a single packed bed, with a length of 40 cm. The facility is equipped with several thermocouples, as shown in Fig. 5. There are three measurement levels over the total height of 45 cm. The thermocouples are placed in the middle of the packed bed (at a depth of 15 cm). An electrical air heater together with a blower (not shown in the figure) is used to generate the necessary thermal energy.

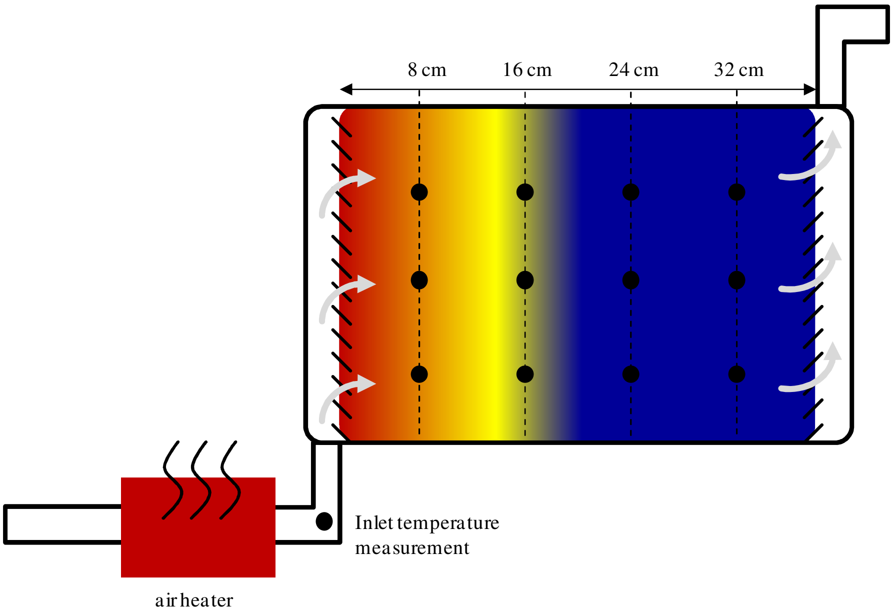

Fig. 5. Schematic layout of the test facility including the relevant measurement positions

The storage material is placed between two holders with several slant steel sheets holding the storage material at its position. This open constructions allows on the one hand a relatively smooth entrance of the air flow, on the other hand the thermal expansion of the storage material during the heat-up phase could be compensated with this construction. Compared to other packed bed concepts, the air flow is directed horizontal through the packed bed. The storage vessel itself is isolated against the ambient.

3.2. Storage material

In order to evaluate the influence of the used storage material and the graining size, three different storage materials are used in this paper:

- **Silica sand:** locally available, ordinary silica sand with a maximum graining size of 0.5 mm (diameter) and an average gaining size of 0.2 mm. The packing density is quite high, compared to the two other materials considered.
- **Basalt gravel:** locally available gravel based on basalt with a graining size between 2 and 4 mm (diameter). The packing density is lower than the silica sand and comparable to the quartz gravel
- **Ordinary (quartz) gravel:** locally available gravel with a higher amount of quartz with a graining size of between 1 and 2 mm (diameter). Packing density is comparable to the basalt gravel.

During the initial test runs, every storage material was cleaned and afterwards dried during the first test runs.

4. Results

The principal behavior of the temperature within the packed bed is shown in Fig. 6. As already described in chapter 3, the temperature is measured along the length and the height of the packed bed. In the left part of Fig. 6 an average of the measurements along the height is shown. There are several small deviations in the temperature behavior along the height, as shown in the right part of the figure, but they are relatively small, so that the temperature distribution over the height could be considered as uniform.

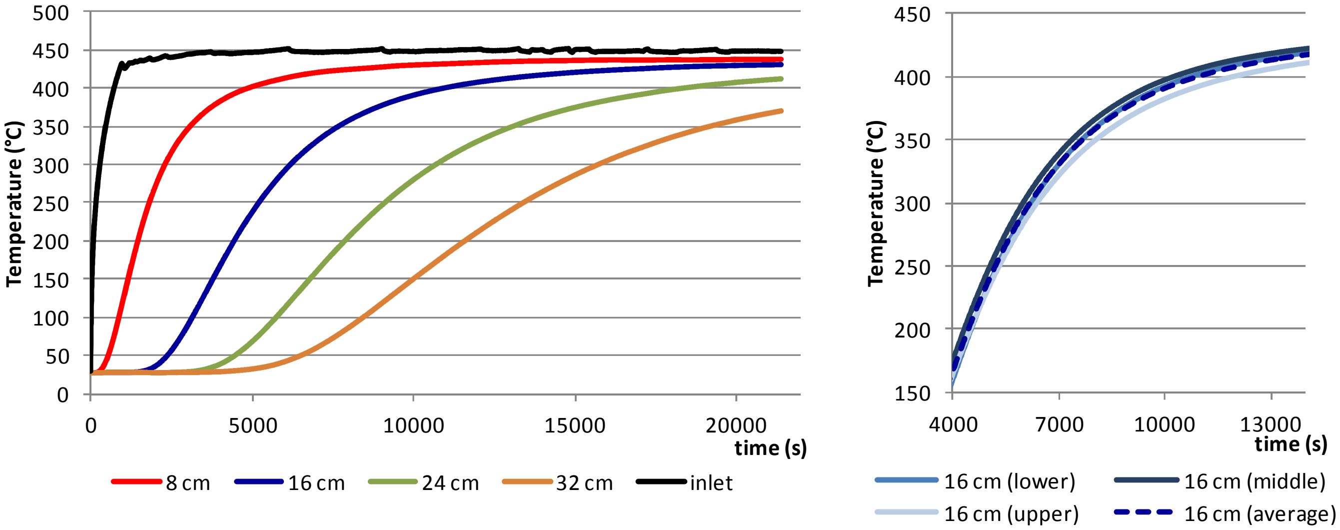

Fig. 6. Principal behavior of the temperature trough the packed-bed (*quartz gravel with 2 mm, air flow: 35 Nm³/h*)

The heat is transferred trough the solid bed and the storage material is heated up. The time behavior of the temperature shows a very characteristic behavior. During the first phase, the temperature gradient is very high, followed by a phase with a slower increase of the temperature. With further charging time, the temperature almost reaches the input temperature. This principal behavior is true for all measurements along the packed-bed, although the gradients get smoother via the length of the packed bed.

After reaching a higher temperature (around 150 °C and more), the air flow leaving the storage module is directed to a second (discharged) module in order to heat this module up (see also Fig. 1.). With this modular concept, no heat is wasted, even if the boundary layer between the hot and the cold storage material is wide.

In a second experiment, the behavior of different storage materials is analyzed, comparing the results of quartz gravel and silica sand. The results are shown in Fig. 7, for both experiments the same amount of energy was stored in the system.

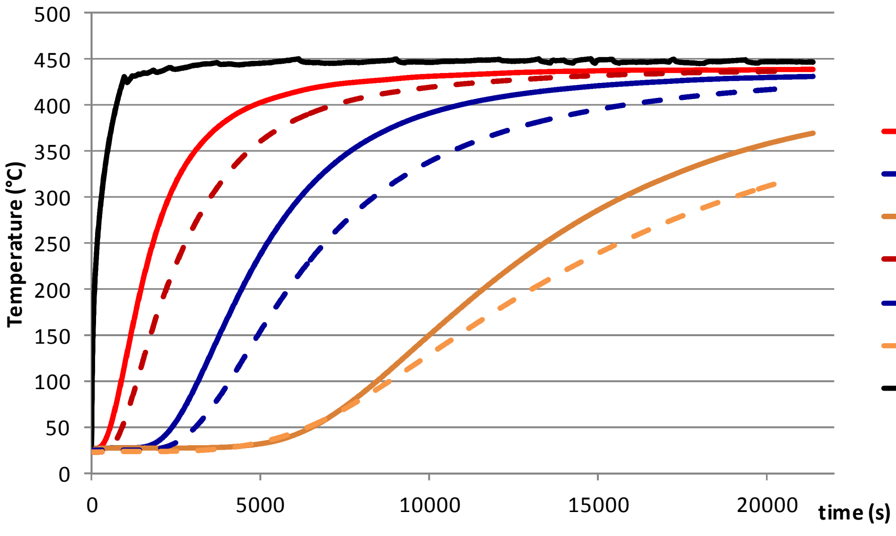

Fig. 7. Comparison of the temperature behavior through the packed-bed (*quartz gravel with 2 mm, silica sand < 1 mm, air flow: 35 Nm³/h)*

As the packing density of sand is higher than the density of quartz gravel, the dynamic behavior of the sand-packed bed is obviously slower, due to the higher mass that must be heated up. But nevertheless, the overall behavior is comparable, with a very sharp gradient at the beginning of the charging and a relatively sharp border between the hot and the cold storage material.

The storage system itself could also handle higher temperatures, as shown in Fig. 8. Here an exemplary test run with an inlet temperature of 530 °C is shown. As storage material, basalt gravel is used, showing a very similar behavior as the quartz gravel. As the air flow is slightly reduced, the dynamic behavior is slower compared to the experimental setup shown in Fig. 7.

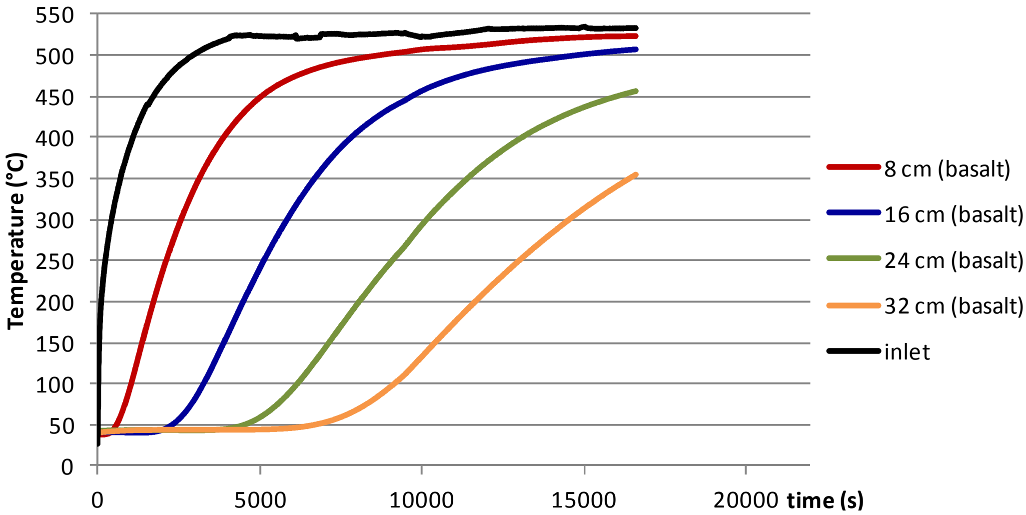

Fig. 8. Temperature behavior trough the packed-bed for 530 °C inlet temperature *(basalt gravel with 4 mm, air flow: 25 Nm³/h)*

In order to evaluate the influence of the air velocity on the storage system, several test runs were performed using a wide range of air velocities. In order to enable the heating device for this wide range, the air is only heated up to 320 °C. Nevertheless, the shown results are also valid for higher temperature ranges.

In order to show the behavior through the layer, the border section between the hot and the cold storage material, the so called "thermocline" is analyzed. With this thermocline the boundary layer between the already hot storage material and the still cold material is described. A sharp thermocline indicates a good charging behavior. This thermocline is modeled by a linear ramp via the length of the layer that is shifted through the storage with a certain speed. The modeling approach is described hereafter using a moving triangle with a fixed slope.

Figure 9 shows the behavior of the thermocline for two different air velocities and the 2 mm quartz gravel storage material. In order to model the behavior of the thermocline moving through the packed bed, a simplified model is used. The model consists of a triangle with a defined slope, representing the gradient of the thermocline. Depending on the used charging capacity (represented by the superficial velocity through the packed bed), this triangle moves with a defined speed through the packed bed. Both parameters are kept constant for every experiment.

In order to determine the correct parameters, a parameter identification algorithm was used ("gray model identification").

The results of the modeled behavior of the thermocline is shown in Figure 9 with a continuous line, the shown dots represent measured values that are used to verify the modeled behavior. The results of the parameter identification method are shown in table 1.

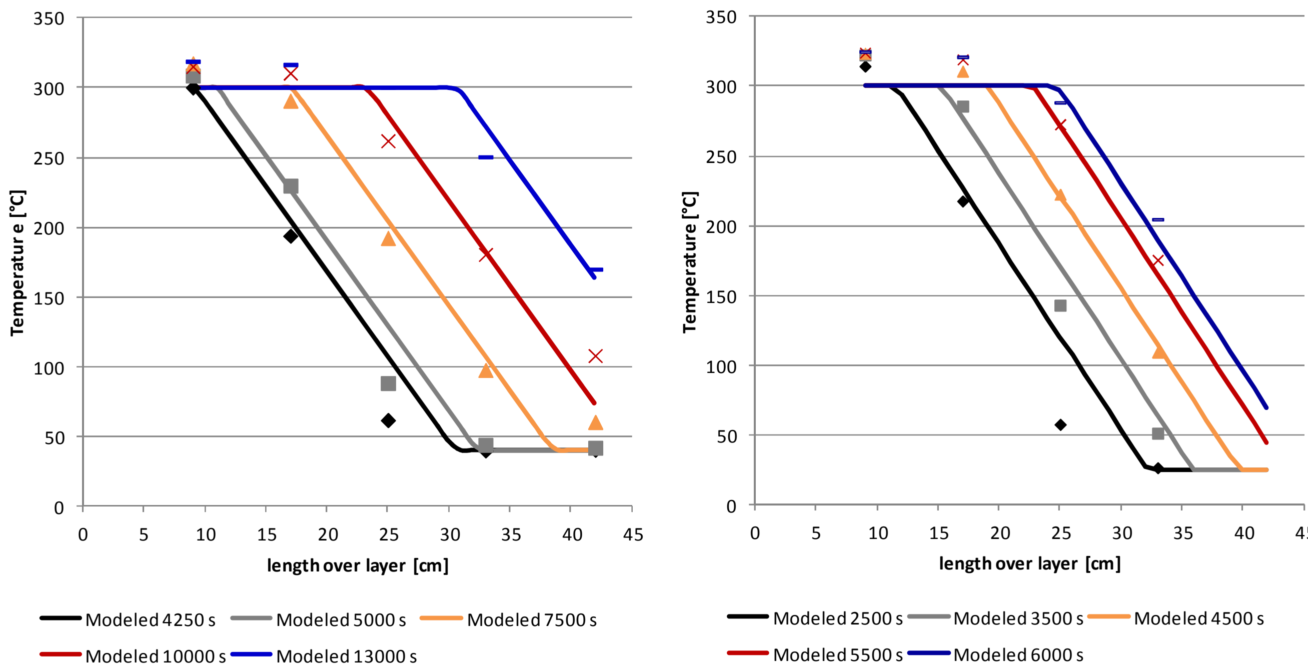

Fig. 9. Modeled thermocline through the packed bed *(quartz gravel, superficial velocity 0.12 m/s (left), 0.31 m/s (right))*

The results for three different air velocities are summarized in the following table 1. Especially the assumed gradient of the thermocline is not influenced by the air velocity. The speed of the thermocline through the layer is of course depending on the air velocity, which is direct proportional to the used thermal power.

Table 1. Summarized results for the analysis of the thermocline behavior

Superficial velocity (@300 °C) in m/s	Specific gradient of thermocline (K/mK)	Absoult gradient of thermocline (K/m)	Speed of thermocline (cm/h)
0.12	4.67	1215	8.9
0.16	4.72	1230	12.8
0.31	4.86	1260	19.4

Based on the evaluation made in chapter 2, the temperature distribution within the storage material could be considered as equal at all regarded superficial velocities. The experimental results show the same results. For every used velocity, the gradient of the thermocline remains in the same range, indicating the same heat storage behavior of the used material.

Together with the speed of the thermocline, this modeling approach enables a first design of the storage vessels and the packed bed, simulating the temperature behavior via the length of the packed bed.

5. Summary and Conclusion

Thermal energy storage systems are a key element for every solar thermal application, especially concerning the global need of reducing the LCOE of the CSP technology. Besides the “state-of-the-art” molten-salt storage system, other promising concepts are ready to enter the market.

In this paper, a packed-bed system is analyzed, using small grained material like silica sand, quartz gravel or basalt to store the thermal energy. The temperature range of such a system is quite huge; temperatures of up to 550 °C are possible without influencing the general charging behavior.

The theoretical and experimental results show, that especially small grained material offers a very good heat storage potential, as the temperature distribution within the stone is very fast and therefore the thermal energy could enter (and leave) the material very fast during charging (and discharging). Therefore a very sharp behavior of the thermocline could be observed.

Based on the experimental results, a simplified model for the temperature behavior through the packed bed was developed. With this model the design of the packed bed and the different parameters (like the superficial velocity) is easily possible and the storage system could be adapted to different boundary conditions.

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