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Effect of Thermal Properties of Storage Material on Packed Bed Performance

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***Abstract*— For concentrated solar power plants, packed bed of rock represents a good alternative to two-tank molten-salt thermal energy storage system. In this study, a two-phase numerical model is developed and successfully validated with experimental data. A parametric study was carried out to assess the effect of thermal properties of storage material on the thermal behavior and performance of rock bed energy storage system. The results obtained show that the thermal capacity and conductivity of storage material have a great effect on thermocline zone, thermal stratification, stored energy during charging, recovered energy during discharging and on the efficiency of the storage system.**

Keywords—thermal storage, storage matérial, rock bed, thermal capacity, thermal conductivity.

I. INTRODUCTION

The integration of thermal energy storage system (TES) in concentrated solar power plants (CSP) is a crucial necessity to overcome the inherent characteristics of solar energy: it is intermittent and stochastic. It is therefore essential to develop an efficient TES systems, which are less costly and ecofriendly. The packed bed of rock using rocks as storage material and air as heat transfer fluid HTF represents the most suitable TES system for the solar air heaters [1-2]. It is environmentally friendly, it is based on the concept of direct storage in a single tank which considerably reduces the overall cost compared to indirect two-tank molten salt storage system, and it is usable at high temperature which optimizes its efficiency. In addition, heat transfer between HTF and storage material is direct therefore, the use of the heat exchanger is eliminated.

The thermal storage system works according to two modes: charging mode and discharging mode. During charging process, the hot air flows through the tank from the top to the bottom to heat the storage material. However, during discharging process, the flow direction is reversed: the cold air flows from the bottom to the top of the tank to recover the stored energy during the charging phase. The majority of studies on packed beds specially air/rock bed TES systems in the literature are focused on thermal charging process. While, the thermal performance depends on the success of the two process: charge and discharge. In particular, Yang and Garimella carried out a detailed studies to investigate the effect of the Reynolds number, tank height and particle size on the discharge efficiency of a molten-salt/rock bed TES system [3, 4]. The aim of this work is to investigate the effect of the thermal properties of the storage material on the thermal behavior and performance of the rock bed TES system during the two process of charge and discharge. To this end, a transient two-phase model was developed and validated with experimental data taken from literature.

II. MODELING

For modeling the thermal behavior of air/rock bed, a two-phase model has been developed. The major advantage of this model is that it allows to describe the heat transfer in the fluid and solid phases separately taking into account the heat exchange between the two phases.

The main assumptions of the numerical model are the following:

- The air is treated as an ideal gas.
- The flow of fluid through the rock bed is laminar.
- The temperature distribution in each rock is uniform (Bi << 1).
- The thermal properties of the fluid are temperature-dependent.
- No internal heat generation.
- The heat transfer by radiation is neglected.

The numerical model considers also the thermal losses, it is described by the following energy equations:

For fluid phase:

$$\frac{\partial}{\partial t}\left(\varepsilon\rho_f c_p T_f\right) + \nabla\left(\vec{v}\left(\rho_f c_p T_f\right)\right) = \nabla\left(\varepsilon k_f \nabla T_f\right) + h_f a\left(T_s - T_f\right) + U_w A_w\left(T_w - T_f\right) \quad (1)$$

For solid phase:

$$\frac{\partial}{\partial t}\left((1-\varepsilon)\rho_s c_s T_s\right) = \nabla\left((1-\varepsilon)k_s \nabla T_s\right) + h_f a\left(T_f - T_s\right) \quad (2)$$

Where T_f and T_s (K) are respectively the fluid and solid temperature, h_f (W/m^{2}K) is the convective heat transfer coefficient between the fluid and solid phases, *a* (m^2/m^3) is the surface area per unit volume and ε is the void fraction.

The detailed description of the numerical modeling and the initial and boundary conditions is performed in our previous work [5]. The numerical model was successfully validated against the two experimental data taken from the literature [6,7].

TABLE I. OPERATIONAL PARAMETERS OF STORAGE SYSTEM [5].

Parameter	Value
T_{max}	893 K
T_{min}	293 K
G	0.225 kg/(m²s)
H	1.2 m
D	0.148 m
A	0.0172 m
ε	0.4
d_s	0.02 m
U_w	0.678 W/(m² K)

The stored energy over the storage height is calculated by

$$E_s = \int_0^H \rho_s c_s (1-\varepsilon)(T_s(y) - 293) A \, dy \qquad (3)$$

Where *A* (m²) is the surface area.

The efficiency of the storage system is defined as the ratio between the recovered energy during the discharging process and the input thermal energy during the charging process:

$$\eta = \frac{\int_0^{t_{discharge}} G c_p (T_{top} - T_{bottom}) dt}{\int_0^{t_{charge}} G c_p (T_{top} - T_{bottom}) dt} \qquad (4)$$

G (kg/sm²) is the mass flow rate per unit cross section.

III. RESULTS

A. *Thermal capacity*

The thermal capacity characterizes the amount of thermal energy stored in a material when the temperature rises. It is defined as the product of the specific heat (c_s) and the density (ρ_s). The choice of storage material is essentially based on this physical quantity which must be high enough to optimize the thermal performance of the storage system. Özkahraman et al. [8] have found that the thermal capacity of the storage material must be greater than 1MJ/m³K. In addition, the large values of the thermal capacity leads to a decrease in the storage volume, which optimizes the efficiency by reducing the cost of the storage system and the thermal losses [9, 10].

To characterize the influence of the thermal capacity of rocks on the performance of air/rock bed TES system, a comparative study of three different rocks: Gabbro, Quartzite and Sandstone was carried out. The selection of these rocks was based on their thermal and thermo-mechanical properties. The main characteristics of the selected rocks are illustrated in table I.

Table II. Characteristics of the selected rocks [11].

Rocks	c_p (320°C) (J/kgK)	ρc_p (320°C) (kJ/m³K)	λ_s (20°C) (W/mK)	Hardness (HV)
Gabbro	1021	2897	2.19	210.9
Quartzite	1065	2827	4.10	185.9
Sandstone	975	2497	2.34	173.6

To clearly show the effect of thermal capacity of storage material on the packed performance during the charge process, four hours of continuous charging has been simulated. Fig. 1 illustrates the evolution of the average temperature of the three rock beds during the charging process. It shows that the average temperature in the Sandstone bed increases rapidly than that obtained in the Quartzite and Gabbro beds. In addition, the axial temperature of the Sandstone bed at the end of the charge is higher than that of the Gabbro and Quartzite beds (Fig. 2). These results can be explained by the low thermal capacity of Sandstone compared to Quartzite and Gabbro.

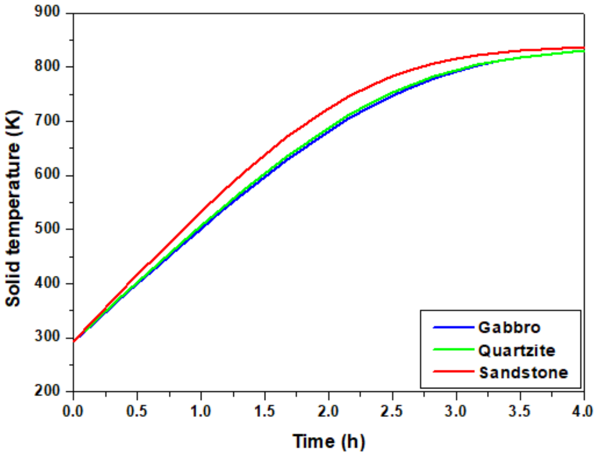

Fig. 1. Evolution of the average temperature of the three rock beds during the charging process : Gabbro, Quartzite and Sandstone.

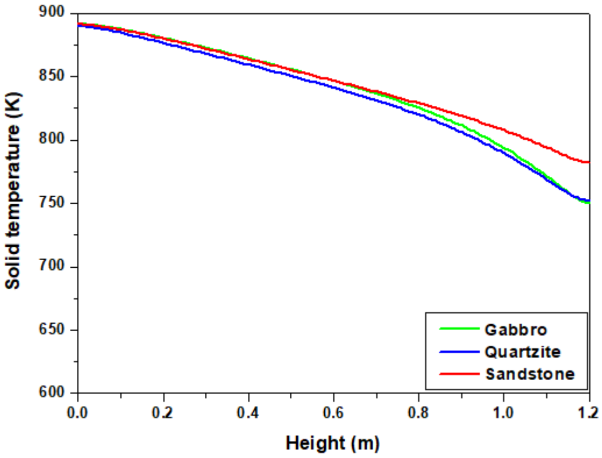

Fig. 2. Solid temperature profiles at the end of 4 hours of charging in the three beds: Gabbro, Quartzite and Sandstone.

Fig. 3 illustrates the average energy stored as a function of the charging time for the three storage beds. It shows that the stored energy increases with the charge time for the three rocks. However, the Gabbro bed stores simultaneously more energy than the Quartzite and Sandstone beds. Therefore, the large thermal capacity of the storage material leads to an increase in the average stored energy in the tank.

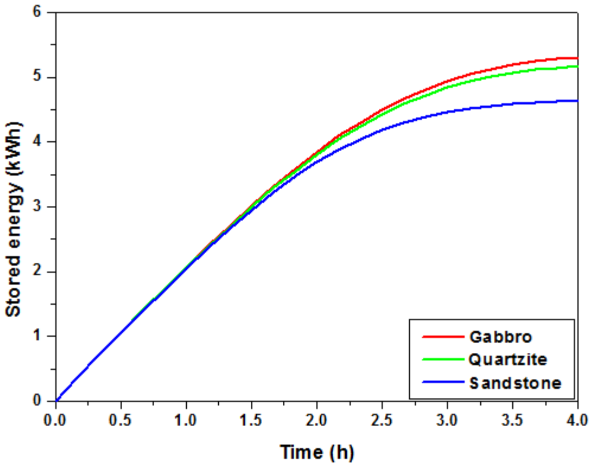

Fig. 3. Average energy stored as a function of the charging time in the three storage beds : Gabbro, Quartzite and Sandstone.

During the thermal discharge process, the cold air enters from the bottom of the tank with a temperature equal to 293K to restore the heat stored in the charging phase. Therefore, during the discharge, the temperature of the solid phase decreases with the time for the three rock beds, which can be seen in Fig. 4. It show also that at the end of the discharge, the temperature within the Gabbro bed is higher than that obtained in the other beds. This result can be explained by the high value of the energy stored in the Gabbro bed during charging in comparison with the Quartzite and Sandstone beds.

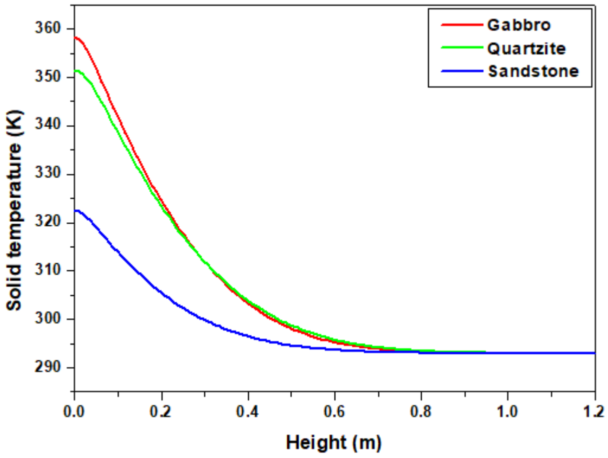

Fig. 4. Solid temperature profiles at the end of 4 hours of discharge in the three beds: Gabbro, Quartzite and Sandstone.

The outlet temperature of the fluid during the discharge process is the most important criterion for evaluating the performance of thermal storage in the rock bed. This temperature is used to assess the degree of success of discharge process. In fact, the thermal capacity of storage material has a significant influence on this parameter. Fig. 5 shows that the fluid outlet temperature during the discharge phase decreases as a function of time for the three rock beds. Also, it is higher for the Gabbro bed compared to the Quartzite and Sandstone beds.

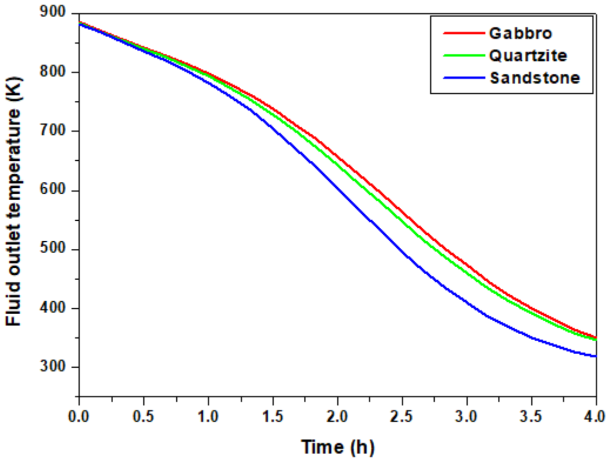

Fig. 5. Evolution in time of fluid temperature at the outlet during the discharge phase for the rocks: Gabbro, Quartzite and Sandstone.

In addition, the thermal capacity of the storage material influences the efficiency of the tank. Fig. 6 shows that the efficiency of the Gabbro bed is greater than that of the quartzite and Sandstone beds. Summarizing, a high thermal capacity of storage material optimizes the performance of the air/rock bed TES system.

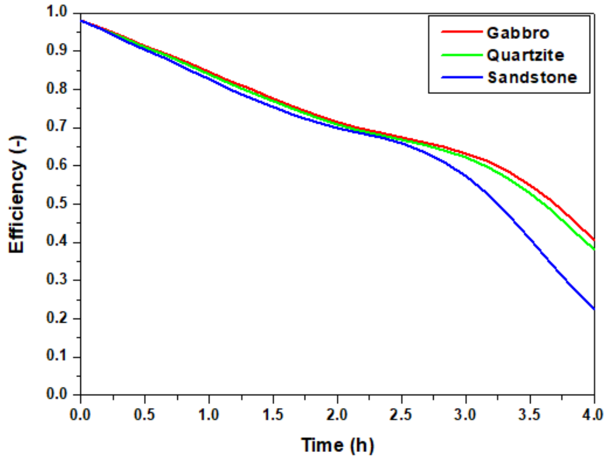

Fig. 6. Evolution in time of efficiency of the three rock beds : Gabbro, Quartzite and Sandstone.

B. Thermal conductivity

Thermal conductivity is also an important parameter that must be taken into account when choosing the storage material. In general, the thermal conductivities of natural rocks varies between 0.2 and 10W/mK at ambient temperature [12, 13]. Usually, natural rocks with high quartz content have higher thermal conductivities [11].

The thermal conductivity of the storage material influences directly on the heat diffusion in the rock bed which also influences on the thickness of the thermocline zone during the charging and discharging process. To highlight the effect of this parameter on the performance of the tank, two storage materials with very close thermal capacities and very different thermal conductivities were chosen: Aluminum and Gabbro. The thermal conductivity at ambient temperature for Aluminum and Gabbro are respectively 204 W/mK [14] and 2.19 W/mK.

The solid temperature profiles within the Aluminum and Gabbro beds after 1200s and 4800s of the charge are plotted in Fig. 7. It shows that the thermocline zone formed in the Aluminum bed is wider than that in Gabbro bed. Also, the temperature at the top of the Gabbro bed is higher and very close to the air inlet temperature. While, the temperature at the bottom of the Aluminum bed is higher compared to the Gabbro bed. As a result, the Aluminum bed stores more energy at the bottom. However, in the Gabbro bed the energy stored at the top is much higher, which has a positive influence on the performance of the storage system.

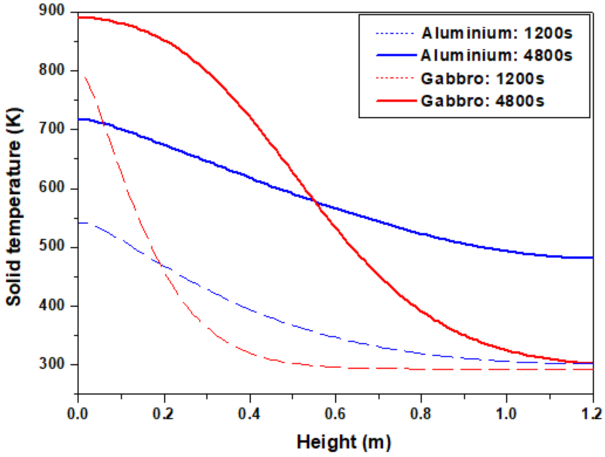

Fig. 7. Solid temperature profiles of the Aluminum and Gabbro beds during the charging.

The fluid temperature at the outlet during charging is defined as the minimum temperature reached by the fluid after heating the storage materials. During the charging process, the temperature of the fluid leaving the Gabbro bed remains close to the minimum temperature of the tank (293K). Whereas, for the Aluminum bed, it increases rapidly with the charging time (Fig.8).

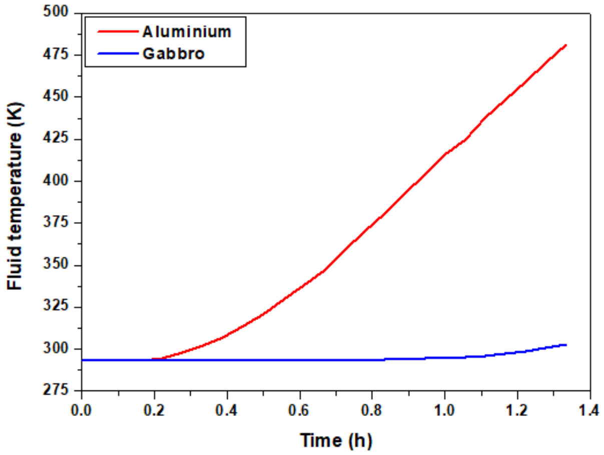

Fig. 8. Evolution in time of fluid outlet temperature during the charging process for the Aluminum and Gabbro beds.

The result of fig. 8 influences directly on the heat flux evacuated during charging which corresponds to the heat flux at the exit of the tank. Fig. 9 shows that the heat flux evacuated increases rapidly for the Aluminum bed as a function of charging time. However, for the Gabbro bed, it is equivalent to its minimum value and it remains almost constant during the charging period. This result means that the Aluminum bed has not absorbed the majority of the heat supplied by air like the Gabbro bed.

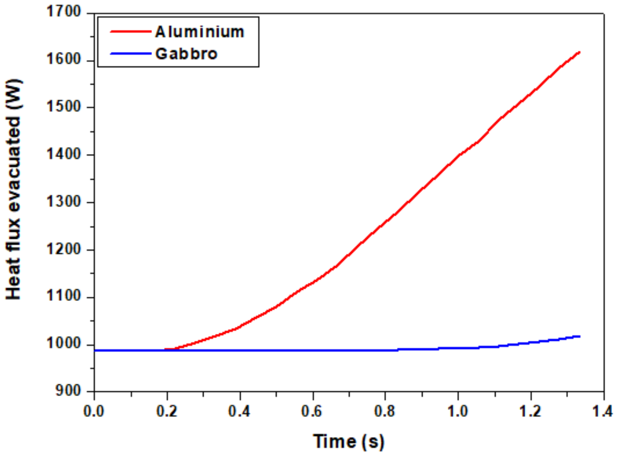

Fig. 9. Evolution in time of heat flux evacuated during the charging process for the Aluminum and Gabbro beds.

The temperature profiles of Aluminum and Gabbro beds during the discharge process are illustrated in Fig. 10. As can be seen, the variation of the solid temperature in the aluminum bed is smaller in comparison with the Gabbro bed. The thermocline zone formed within the Aluminum bed is wider than that formed in the Gabbro bed. Therefore, using the storage material with high thermal conductivities induces a reduction of the degree of thermal stratification in the storage bed.

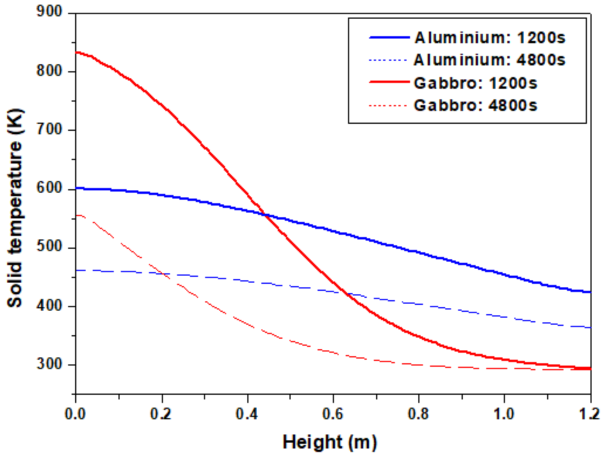

Fig. 10. Solid temperature profiles in the Aluminum and Gabbro beds during discharge process.

The thermal conductivity of the storage material also influences the temperature of the fluid at the exit during the discharge process. Fig. 11 shows that the outlet fluid temperature during the discharge for the Aluminum bed is higher compared to the Gabbro bed.

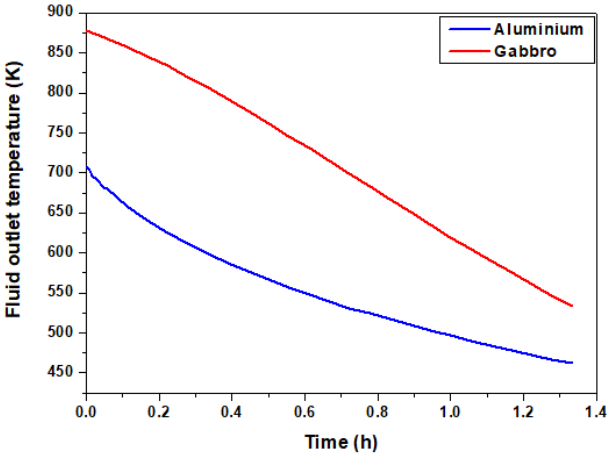

Fig. 11. Evolution of the fluid outlet temperature during discharge for the Aluminum and Gabbro beds.

Fig. 12 shows the evolution in time of the efficiency of the two storage beds. As can be seen, the efficiency of the Gabbro bed is more important compared to Aluminum bed. Therefore, using the storage material with high thermal conductivity decreases the efficiency of the storage system.

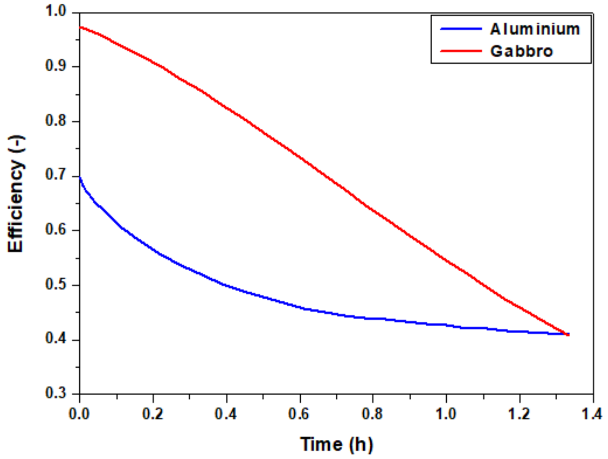

Fig. 12. Evolution in time of the efficiency of the Aluminum and Gabbro beds.

To conclude, the thermal conductivity of the storage material significantly influences the thermal performance of the storage system. The results obtained showed that the stored energy, the outlet fluid temperature during discharge and the efficiency of the storage system strongly decreases with high thermal conductivity values.

IV. CONCLUSION

The two-phase heat transfer model was developed allows to study the thermal storage in packed bed of rock TES system during the charging and discharging process. The numerical model was successfully validated against the experimental data taken from the literature. A detailed study was carried out to investigate the effect of the thermal properties of storage material. The main results obtained in this work are:

- The natural rocks have shown that they are the most suitable storage material for thermal storage in packed bed using air as HTF. The thermal capacity of the rocks must be high enough to optimize the performance of the TES system and to reduce the storage volume.
- The thermal conductivity of the storage material have a great effect on the performance of the packed bed TES system. The use of storage materials with low thermal conductivity limits the diffusion of heat in the bed, which influences the degree of thermal stratification and the thickness of the thermocline zone.
- According to this study and those of Tiskatine et al. 2017 [11], Gabbro rock presents the most suitable thermal storage material for air /rock bed TES systems.

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