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A pseudo-analytical model based on the enthalpy approach for the simulation of packed-bed rock thermal energy storage systems

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Abstract:

Packed-bed rock thermal energy storage with solids for heat storage is a cost-effective solution. Approaches to model thermal storage systems range from simplified models based on analytical solutions to the partial differential equations representing the system, to more advanced models based on the finite volume method, or even complex models based on computational fluid dynamics. Previous works presenting simulation models for packed-bed rock energy storage systems address single-phase heat transfer fluids (either liquid or gaseous), with or without a solid packed-bed. Such systems represent what is currently commercially available. However, for applications where the heat transfer media is in the two-phase or vapour state, it may offer advantages to use a packed-bed rock thermal energy storage system with phase change of the heat transfer fluid. In this work, we present a novel simulation approach to model packed-bed rock thermal energy storage systems based on the enthalpy approach, unlike the typically used temperature based approach. This approach allows the modelling of the packed-bed rock storage with phase change of the heat transfer fluid, in addition to the modelling of the charging of a packed-bed rock storage system using a liquid or gaseous heat transfer fluid. The presented model is based on an analytical solution to the partial differential equations representing the system. The model is validated using experimental results, with a mean absolute percentage deviation of 0.7 % and 1.1 %, for the charging of the packed-bed rock thermal energy storage with liquid and gaseous heat transfer fluids, respectively.

Keywords:

Analytical solution; packed-bed; thermal energy storage.

1. Introduction

Conventional two-tank storage systems are widely used for the thermal energy storage. Apart from that, single-phase thermocline systems are used. In these systems, the energy is stored by increasing the temperature of the heat transfer fluid, and/or packed-bed systems, where the heat transfer fluid transfer the heat to a bed of solid materials (sensible thermal storage) or phase-change materials (latent thermal storage) [1]. Thermal storages that use the latent heat from a phase changing heat transfer fluid (i.e., liquid-gas latent thermal storage) may offer additional storage capacity, because of the phase-change of the heat transfer fluid, and the addition of heat at an almost constant temperature. However, the final selection of the storage configuration should be based on the techno-economic feasibility of the storage system, considering the cost of thermal energy storage (in €/kWh) compared to the conventional thermal energy storage configuration. Such storage technology can be beneficial to use for applications where the heat transfer media is in the two-phase or vapour state (e.g., nuclear power plants, and linear Fresnel reflector based concentrated solar power plants).

Among the different ways of modelling thermal storage systems (e.g., computational fluid dynamics, finite volume or element methods, analytical solutions), analytical solutions provide a simplified, easy-to-implement, and low-computational-demanding method to predict the behaviour of packed-bed rock thermal energy storage systems. Existing analytical solutions consider different types of thermal storages and hypotheses. For instance, Riaz [2] provided analytical solutions for the step, impulse and ramp responses of a single-phase air thermal storage with solid packed-bed by considering both a two-phase model and a single-phase model. Here the concepts of two-phase model and single-phase model refer to whether the solid packed-bed is considered as an independent phase along with the heat transfer fluid (a two-phase model, see Eq. 1 and Eq. 2) or not (single-phase model). Spiga and Spiga [3] presented an analytical solution based on the two-phase model for a packed-bed thermal storage system with a varying inlet temperature. Bayón and Rojas [4] correlated a logistic cumulative distribution function parameter with the thermocline storage tank parameters and conditions of the working fluid using the numerical results obtained using the single-phase one-dimensional modelling approach. Typically, temperature approach, where the temperature profiles for the thermocline storage over different time periods is predicted, is used for the single tank thermocline storage, both with and without solids. As the enthalpy does not present derivative discontinuities in time and space during the phase change, contrary to the fluid temperature that remains constant during the phase change (assuming the fluid is a pure or azeotropic substance), an enthalpy approach predicts the enthalpy variations. Fortunato [5] presented an analytical solution for the modelling of a packed-bed of phase change materials, introducing the phase-change of the packed-bed into the standard analytical solution. Tumilowicz et al. [6] used the enthalpy approach to model thermocline systems with encapsulated phase-change materials thermal storage.

In this paper we present an enthalpy approach to describe the phase-change of the heat transfer fluid for the liquid-gas packed-bed thermal storage. A simplified approach is used to model liquid-gas thermal storage systems with packed-bed based on an analytical solution. This is the first time the enthalpy approach is used for this application. The enthalpy approach allows an easy representation of phase-change phenomena of the heat transfer fluid in the packed-bed, which would not be feasible with a temperature-based approach, due to the discontinuity of the temperature during phase-change of the heat transfer fluid. While phase change in the packed-bed filler material (phase change material thermal energy storage) has been studied and different analytical solutions have been presented for modelling packed-bed thermal storages, to the best of our knowledge, there are no predictive models are available to represent liquid-gas packed-bed thermal storage systems. Although analytical solutions for thermal storage investigation present a number of limitations (e.g., that pressure drops and heat losses cannot be included), they are a quick computational solution when a high number of simulations are required (e.g., storage material screenings, analysis of multiple operating conditions, annual simulations), with acceptable accuracy for qualitative comparative analyses. As in any analytical solution, a number of hypotheses are assumed that allow simplifying the study of these systems. The models are validated using experimental data for the charging of the packed-bed rock thermal energy storage with liquid and gaseous heat transfer fluids.

Section 2 describes the traditional temperature based approach for the modelling of packed-bed rock thermal energy storage. Section 3 describes the proposed enthalpy based approach for the modelling of packed-bed rock thermal energy storage, Section 4 presents the model predictions for charging of the packed-bed rock thermal energy storage using liquid, gas and liquid-gas heat transfer fluids, and Section 5 discusses the conclusions and further research of the work.

2. Packed-bed thermal storage modelling: traditional approach

The most widely used approach to describe the behaviour of a thermal storage with packed-bed is the one presented by Schumman [7], also called a two-phase model, as it considers two different equations for each phase (the fluid phase and the solid phase). In this model the temperature of the fluid phase and the packed-bed are described by the following equations:

$$\varepsilon \rho_f c_{p,f} \frac{\delta T_f}{\delta t} + \varepsilon \rho_f c_{p,f} v_f \frac{\delta T_f}{\delta y} = \varepsilon k_f \frac{\delta^2 T_f}{\delta y^2} - h_{f,s,V}\left(T_f - T_s\right) \tag{1}$$

$$(1-\varepsilon)\rho_s c_{p,s} \frac{\delta T_s}{\delta t} = (1-\varepsilon) k_s \frac{\delta^2 T_s}{\delta y^2} - h_{f,s,V}\left(T_f - T_s\right) \tag{2}$$

where ε is the void fraction, ρ_f, $c_{p,f}$,and k_f are the density, isobaric specific heat capacity and thermal conductivity of the fluid, ρ_s , $c_{p,s}$,and k_s are the density, isobaric specific heat capacity and thermal conductivity of the solid phase, and $h_{f,s,V}$ is the volumetric heat transfer coefficient between the fluid and the solid phase. For Schumman's model, the boundary conditions (Dirichlet's conditions) during charging are expressed by the following equations:

$$T_f(H,t) = T_{in} \tag{3}$$

$$T_f(y,0) = T_0 \tag{4}$$

$$T_s(y,0) = T_0 \tag{5}$$

These boundary conditions imply that the temperature of the fluid at the inlet (located at the top of the storage) will be always the maximum and the initial temperature of both the stones and the fluid in the storage is equal to the ambient temperature.

For packed-bed rock thermal energy storage systems, the contribution to heat transfer by conduction in both the fluid and stones is very small compared to the contribution by convection. Because of this, it is possible to eliminate the conduction term (or consider null conductivity) [3]. If this is done, analytical solutions can be found for the representation of the temperature profiles of the fluid $T_f(y,t)$ and the packed-bed $T_s(y,t)$. These analytical solutions, such as the ones proposed by Riaz [2] or Spiga and Spiga [3], consider constant thermo-physical properties for both the fluid and the packed-bed (i.e., properties non-dependent on temperature). In the solution provided by Spiga and Spiga [3], Eqs. (1) and Eq. (2) are simplified by neglecting heat transfer by diffusion, and transforming the independent variables y and t as $Y = \left(yh_{f,s,V}\right)/\left(\varepsilon\rho_f c_{p,f} v_f\right)$ and $\tau = \left(th_{f,s,V}\right)/\left((1-\varepsilon)\rho_s c_{p,s}\right)$, which are dimensionless spatial co-ordinate and dimensionless time respectively. With this simplification, the phases' equations become

$$z\frac{\delta T_f}{\delta\tau} + \frac{\delta T_f}{\delta Y} = \left(T_s - T_f\right) \tag{6}$$

$$\frac{\delta T_s}{\delta\tau} = \left(T_f - T_s\right) \tag{7}$$

where z is a non-dimensional variable which is defined as $z = \left(\varepsilon\rho_f c_{p,f}\right)/\left((1-\varepsilon)\rho_s c_{p,s}\right)$.

Now, introducing the non-dimensional temperature, $\theta = (T - T_0)/(T_{in} - T_0)$, Eq. 6 and Eq. 7 can be written as follows:

$$z\frac{\delta\theta_f}{\delta\tau} + \frac{\delta\theta_f}{\delta Y} = \left(\theta_s - \theta_f\right) \tag{8}$$

$$\frac{\delta\theta_s}{\delta\tau} = \left(\theta_f - \theta_s\right) \tag{9}$$

The above equations (Eq. 8 and Eq. 9) can be used to determine the temperature profiles along the packed-bed over a period of time. The final solution of the temperature profiles of the thermal energy storage for a fluid step response can be given by the following equations [3]:

$$\theta_f(Y,\tau) = U(\tau - zY)\exp(-Y)\cdot\left\{exp[-(\tau - zY)]\cdot I_0\left[2Y^{1/2}(\tau - zY)^{1/2}\right] + \int_0^{\tau - zY}\exp(-\mu)\cdot I_0\left(2Y^{1/2}\mu^{1/2}\right)d\mu\right\} \tag{10}$$

$$\theta_s(Y,\tau) = U(\tau - zY)\exp(-Y)\cdot\left\{\int_0^{\tau - zY}\exp(-\mu)\cdot I_0\left(2Y^{1/2}\mu^{1/2}\right)d\mu\right\} \tag{11}$$

where U is the Heaviside function and I_0 is the Bessel function.

The obtained solutions are non-dimensional magnitudes of the fluid and the solid phase temperatures, $\theta_f(Y,\tau)$ and $\theta_s(Y,\tau)$, respectively.

3. Packed-bed thermal storage modelling: enthalpy-based approach

Similarly to the approaches followed in the analytical solutions presented for phase change materials storage system, an enthalpy approach is adopted to represent both the fluid and the solid phases in Schumman's model. The enthalpy approach is appropriate because the enthalpy does not present derivative discontinuities in time and space during the phase change, contrary to the fluid temperature that remains constant during the phase change (assuming the fluid is a pure or azeotropic substance). By considering that the specific enthalpy of the fluid/solid in the single phase can be obtained as the product of the difference of temperature of the fluid and a reference state, and its isobaric specific heat capacity, and the reference specific enthalpy of both phases is considered null at 273.15 K, the specific enthalpies of the fluid and solid phases can be written as $h_f = c_{p,f}\left(T_f - 273.15\right)$ and $h_s = c_{p,s}(T_s - 273.15)$. By introducing these new variables in Eq. 1 and Eq. 2, neglecting diffusion, and multiplying all terms by $c_{p,f}$, the following is obtained:

$$\varepsilon\rho_f c_{p,f}\frac{\delta h_f}{\delta t} + \varepsilon\rho_f c_{p,f} v_f\frac{\delta h_f}{\delta y} = -h_{f,s,V}\left(h_f - h_{s,0}\right) \tag{12}$$

$$(1-\varepsilon)\rho_s c_{p,f}\frac{\delta h_s}{\delta t} = h_{f,s,V}\left(h_f - h_{s,0}\right) \tag{13}$$

where $h_{s,0} = h_s c_{p,f}/c_{p,s}$. These two equations (Eq. 12 and Eq. 13) resemble the initial Schuman's equations with the difference that the variable temperature T is replaced by enthalpy h, and the specific heat capacity of the solid phase $c_{p,s}$ is replaced by that of the fluid $c_{p,f}$ in the non-dimensional variables, described in Eq. 6 and Eq. 7.

In addition to allowing for the modelling of the charging of a packed-bed rock thermal energy storage system using a liquid or gaseous heat transfer fluid in contact with solids, this approach allows the modelling of the packed-bed rock storage with phase change of the heat transfer fluid. Modelling a liquid-gas storage includes significant complexities, because when the heat transfer fluid evaporates, its specific volume increases, and so does the volumetric flow rate. Additionally, the thermo-physical properties of the fluid change drastically during phase-change, affecting the heat transfer coefficient to the solid bed. In order to use the proposed enthalpy-based approach for the liquid-gas storage, we consider a thermal storage with solid packed-bed with a charging loop that keeps the inlet fluid temperature (T_{in}) constant. The volumetric flow rate of the heat transfer fluid is kept constant for simplicity, resulting in a constant fluid speed inside the bed. As the specific volume of the fluid will increase as it undergoes phase change, it is assumed that there is empty space above the fluid inlet or in an expansion tank. Fig. 1 shows a schematic diagram of the proposed packed-bed rock thermal energy storage with a charging loop. Although it has been indicated that the Schumann's model in which the analytical solution of Spiga and Spiga [3] is based, is only valid for gases [8] and no fluid phase change is considered [9], it has also been found that experimental data with packed-beds and liquid heat transfer fluids are well approximated by this model [9]. Therefore, in this work we assume that the Schumann's model can be applicable to the entire fluid region. By doing this, the analytical solutions provided by Spiga and Spiga [3] for the non-dimensional temperatures can be transformed to calculate the enthalpy of each of the phases, keeping in mind the change of specific heat capacities and the reduction of the solid phase enthalpy. Once the enthalpy of both phases is obtained from the analytical solution of the Eq. 12 and Eq. 13, the temperature of the solid phase can be obtained by using the following expression:

$$T_s = h_s / c_{p,s} + 273.15 \tag{14}$$

and the temperature of the fluid phase can be calculated, depending on the phase of the fluid as

$$T_f = \begin{cases} T(p_f, h_f)_l;\ h_f < h_{sat,l} \\ T_{sat};\ h_f \in [h_{sat,l}, h_{sat,v}] \\ T(p_f, h_f)_v;\ h_f > h_{sat,v} \end{cases} \tag{15}$$

Here T_{sat} is the saturation temperature of the fluid at a specific pressure, and $h_{sat,l}$ and $h_{sat,v}$ are the enthalpies of the saturated liquid and saturated vapour, respectively.

As already mentioned, this model presents a number of limitations due to the hypotheses used during its derivation. The assumed hypotheses are the following:

- The volumetric flow of fluid is assumed to remain constant for the liquid and gas. This implies that the speed of the fluid through the packed-bed remains constant. In order to keep the volume flow rate and the fluid velocity constant with the height while the fluid evaporates, the tank diameter needs to increase. In an alternative implementation of this type of thermal storage, changes in speed and volume flow rate should be considered as the fluid is heated up.
- While the thermo-physical properties of the heat transfer fluid are dependent on temperature, it is generally acceptable to consider them as constant values in the single phase. However, when phase change occurs it is necessary to account for their variation. Since the analytical solution is derived by considering them as constant values, the way to consider their variation is in this work by using constant values for each of the fluid states (i.e., liquid, vapour, two-phase). During phase-change, a weighted average of the values in the saturated liquid and vapour states are considered, e.g., $c_{p,f} = c_{p,f,liq} \cdot (1 - x) + c_{p,f,gas} \cdot x$, where x is the quality.
- The heat transfer coefficient during phase change is initially assumed to be a weighted average of the heat transfer coefficients in the saturated liquid and vapour states $\left(h_{f,s,V} = h_{f,s,V,liq} \cdot (1 - x) + h_{f,s,V,gas} \cdot x\right)$. Heat transfer correlations for a boiling heat transfer fluid in a packed-bed are not widely available in the open literature, and the most used correlations have been developed either for the liquid or the gas state of the heat transfer fluid [8]. Although the evolution of the heat transfer coefficient during boiling may depend on multiple factors and its prediction requires further research [10], assuming a constant weighted average between the heat transfer coefficients in saturated liquid and saturated gas conditions may be an initial good approximation to the boiling phenomena, based on the heat transfer evolution with vapour quality reported by Nobel [11]. Such approach is employed in the present work.
- In the analytical solution, no wall losses are included (i.e., perfect insulation of the thermal storage is assumed).

Based on these assumptions, the predictions of this model can be assumed to represent with sufficient accuracy thermal storage systems where wall loses are negligible, the heat transfer fluid is a pure or azeotropic substance, and pressure and volume flow do not increase due to the transition from liquid to gas. The model has been implemented as a code in Matlab, for its easy implementation in existing simulation codes.

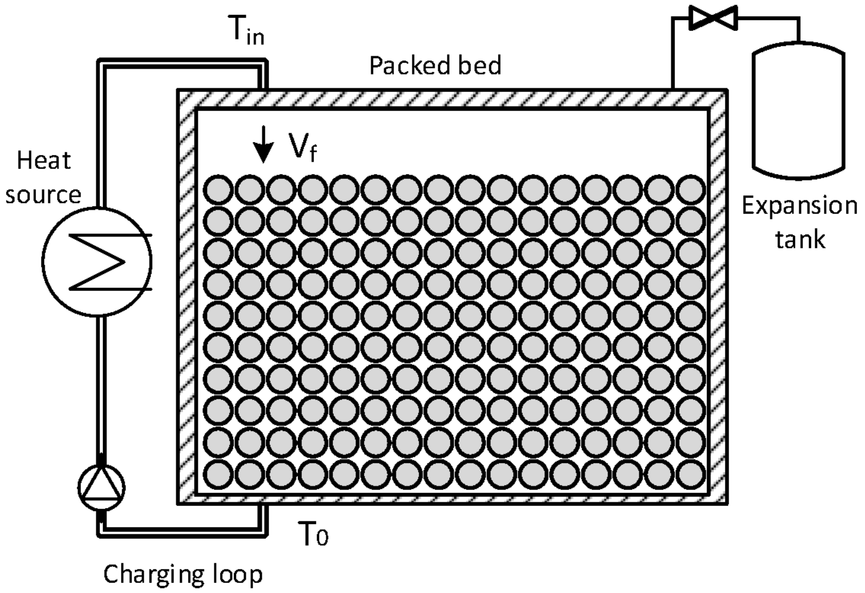

Fig. 1. Schematic diagram of a liquid-gas thermal storage with solid packed-bed.

4. Model predictions

In this section, the developed model is validated against experimental data from the open literature, covering different heat transfer fluids and fluid phases.

4.1. Validation in the single phase: packed-bed storage using thermal oil as working fluid

Experimental data from a prototype packed-bed using thermal oil (Therminol 66) as the heat transfer fluid and silica pebbles as the solid phase from the work presented by Esence et al. [12] is used for validation. The geometrical data of the setup and operating conditions used for the validation are given in Table 1. Fig. 2 shows the comparison of predicted temperature profiles for the liquid and solid phases, and the experimental data of operation for a charging cycle starting from a fully discharge bed with initial temperature of 85 °C. As can be observed, there is a very good agreement, with mean absolute percentage deviation of 0.7 %, between the experimental data and model predictions.

4.2. Validation in the single phase: packed-bed storage using air as working fluid

Experimental data from a prototype packed-bed using air as the working fluid and alumina pebbles as the solid phase from the work presented by Messai et al. [13] is used for validation. The geometrical data of the setup and operating conditions used for the validation are given in Table 1. Fig. 3 shows the comparison of predicted temperature profiles for the solid phase at three different heights, and the experimental data. In general, a good agreement, with the maximum mean absolute percentage deviation of 1.1 % for the temperature profile at the bottom of the tank, can be observed, although the increase in temperature of the model results seems sharper with time than that of the experimental data.

4.3. Prediction during phase change

Given the lack of experimental data for validation of packed-beds with fluid phase change, in this section we present predicted temperature profiles of the fluid and solid phases for a hypothetical case in which water is used as working fluid and the pebbles are made of alumina, see Fig. 4. The conditions for the simulations are presented in Table 1. As it can be observed, there is a sharp increase in temperature of the fluid phase. This is because the water is considered initially at ambient temperature of 25 °C, and the inlet fluid temperature is above its saturation temperature. As for the solid phase temperature profile, it can be seen that its temperature increases during the phase change of the water. At the end of the simulation time duration, the water at the bottom of the tank is still in the two-phase, and therefore, the temperature of the water is the saturation temperature. Fig 5 shows the temperature profiles of the fluid and solid phases with higher volume flow rate of the heat transfer fluid than that of the case in the Fig. 4. As expected, the temperature of the solids at the bottom of the tank increases at much faster rate than that of the slow injection of the heat transfer fluid.

Table 1. Parameters used for the validation and simulation.

Variable	Packed-bed storage using thermal oil (Fig. 2)	Packed-bed storage using air (Fig. 3)	Packed-bed storage with phase change (Fig. 4)
Inside diameter of the tank (D_{in})	1 m	0.18 m	0.1 m
Height of the packed-bed (H)	3 m	0.32 m	0.68 m
Diameter of the solid particle in packed-bed (d_s)	A mixture of 3 cm silica gravel and 3 mm silica sand in a mass proportion of 20 % of sand/80 % of gravel	0.00435 m	0.018 m
Packed-bed porosity (ε)	0.27	0.4	0.42
Heat transfer fluid inlet temperature (T_{in})	150 °C	120 °C	120 °C
Ambient temperature (T_{amb})	25 °C	25 °C	25 °C
Fluid pressure (p_{fluid})	1.01325 bar	1.01325 bar	1.01325 bar
Fluid	Therminol 66	air	Water

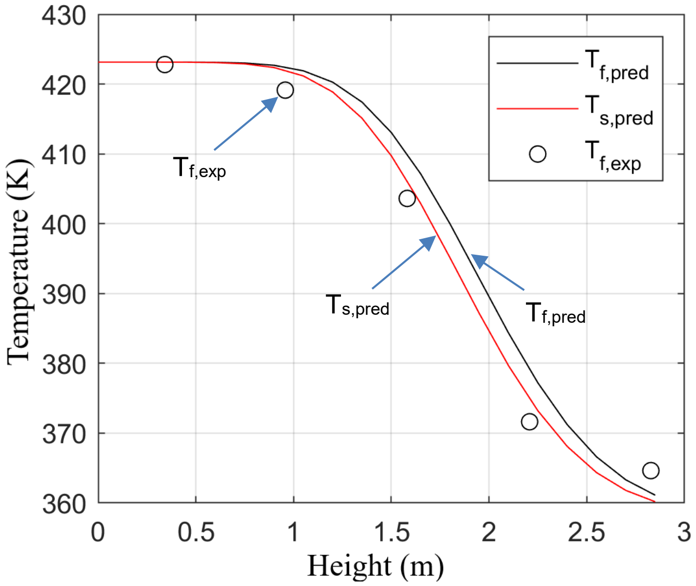

Fig. 2. Validation of the model with experimental data from a case of a thermal storage using Therminol 66 as a working fluid [12].

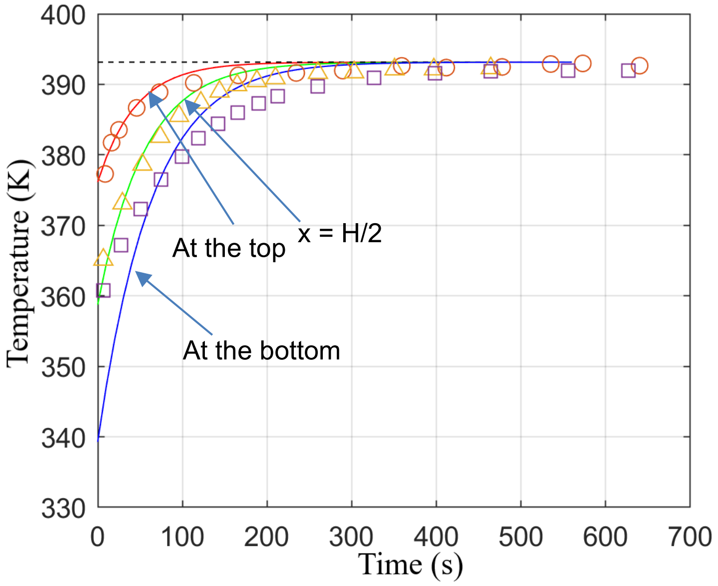

Fig. 3. Validation of the model with experimental data from a case of a thermal storage using air as a working fluid [13].

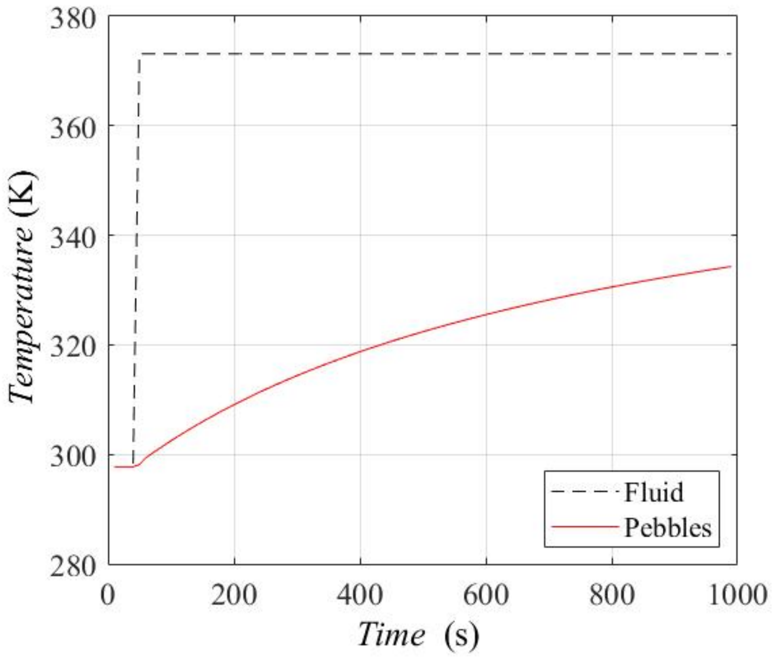

Fig. 4. Prediction of the temperature profiles at the bottom of the tank for a case of a thermal storage using water as a working fluid undergoing phase change and alumina pebbles (with volumetric flow rate 0.00005 m^3/s*).*

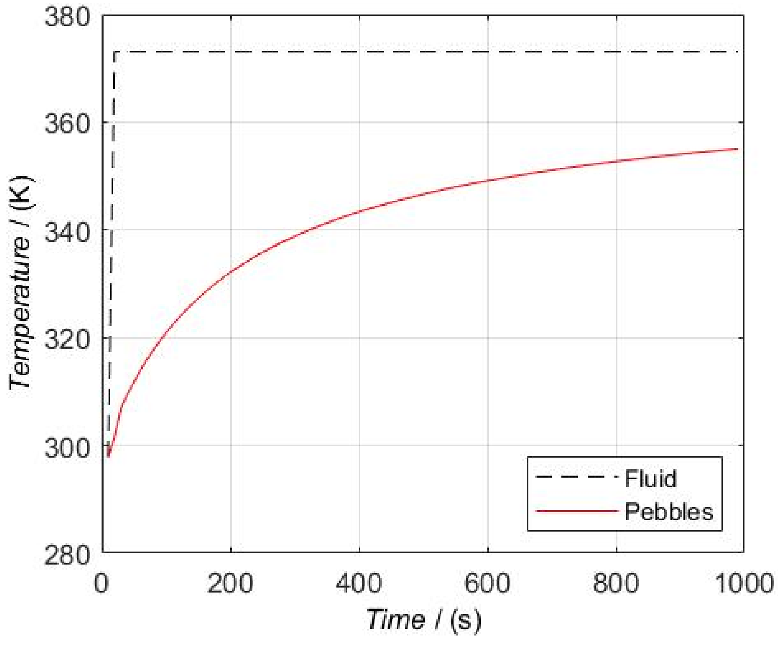

Fig. 5. Prediction of the temperature profiles at the bottom of the tank for a case of a thermal storage using water as a working fluid undergoing phase change and alumina pebbles (with volumetric flow rate 0.00020 m^3/s*).*

4. Conclusions and further research works

In this work, a novel analytical simulation approach to model packed-bed rock thermal energy storage systems based on the enthalpy approach, unlike the typically used temperature based approach, was presented. In addition to allowing for the modelling of the charging of a packed-bed rock thermal energy storage system using a liquid or gaseous heat transfer fluid in contact with solids, this approach allows the modelling of the packed-bed rock storage with phase change of the heat transfer fluid. The following observations are made:

- The developed model is based on a number of hypotheses that enables to obtain an analytical solution to the problem of packed-beds where the heat transfer fluid changes phase.

- Despite the assumed hypotheses, the model can represent with sufficient predictive performance experimental data of fluid and/or solid temperature of liquid packed-bed thermal storage and air packed-bed thermal storages.
- The developed model provides a simple way with short computational time to predict the temperature profile of liquid-to-gas packed-beds, possibly making it suitable for preliminary evaluations and optimization of the configuration parameters and heat transfer fluids of packed-bed thermal storages with phase-change.

The research presented in this paper is directed towards the need of development of detailed transient heat transfer models to predict the temperature time evolution along the bed for liquid-gas heat transfer fluid based packed-bed rock thermal energy storage systems considering changes in speed and volume flow rate, variations in the thermo-physical properties of the heat transfer fluid for each fluid states (liquid, vapour, two-phase) and wall losses. Moreover, there is a need to determine the actual heat transfer coefficient during phase change and to do a validation with experimental data of the model for the case where the heat transfer fluid undergoes phase change. Currently, no such experimental data are available.

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Nomenclature

c_p	specific heat (J/(kg·K))
d_s	particle diameter in packed-bed (m)
H	height of packed-bed (m)
h	specific enthalpy (J/kg)
$h_{f,s,V}$	volumetric heat transfer coefficient between the fluid and the solid phase (W/(m^3·K))
k	thermal conductivity (W/(m·K))
p	pressure (bar)
t	time (s)
T	temperature (k)
v	velocity (m/s)
x	quality (-)
y	coordinate along storage tank height (m)

Greek symbols

ε	Packed-bed porosity (-)
ρ	density (kg/m^3)

Subscripts and superscripts

amb	ambient
f	fluid
s	solid

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