Assessment of the thermal energy storage on open-cell foam as a hierarchical thermal accumulator in a lumped-particle packed bed system: Charging and discharging

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ABSTRACT
Energy safety and climate change are challenges toward a sustainable futurity. The demand of global energy is growing, and depend on the fossil fuels. The Thermal Energy Storage (TES) systems have a potential importance regarding the energy consumption rate of the world. The thermal performance of the Molten Salt (MS) on open-cell foam includes TES can be splitted into three areas, such as sensible heat materials (solid and water), latent heat (Phase Change Materials (PCMs)) and thermochemical (endothermic chemical reversible reactions). The energy storage concept can be used to investigate heat transfer characteristics between the MS particles and fluid phase based on continuous solid phase model. These heat transfer characteristics are focused on the TES inside the MS particles and in fluid phase. The mathematical modelling developed based on two phase model, i.e., in modelled a governing equation for the MS particles (solids) that behave as a continuous medium and governing equation for the fluid phase. The governing equations of the two-phase model are coupled through solid-fluid heat transfer flow. Works developed to assess the results of the charging and discharging profiles as well as the charging time and discharging of the thermal storage on the lumped-particle packed bed. In addition, the use of some physical parameters as the effective thermal conductivity and fluid-solid heat transfer coefficient have been used to check the impact on the charging and discharging about thermal storage. A discussion of the results from the current work will be made with the results of other authors.

Keywords: Therma, Chargin, Discharging, Energy storage, Open-cell foam.

1 INTRODUCTION

Global warming and the serious environmental pollution caused by the use of fossil fuels are becoming crucial issues that constrain the sustainable development of human society. These problems are increasingly most aggravated and affect the energy sector, climate change and other issues environmental issues, experts and authorities agree that the development of use of new renewable energy sources have become vital to the development human sustainability (Yang et al., 2022) Thermal energy storage is considered a important subsystem for thermal solar power plants due to light fluctuations from the sun over time. Recently, energy storage technology Thermal energy has attracted worldwide interest due to its potential to contribute with environmental problems (Kratschmann and Dütschke, 2021).

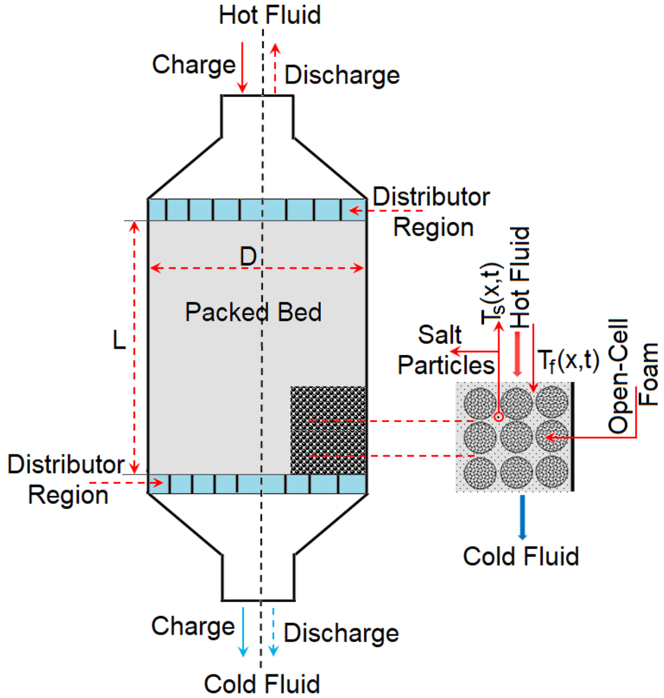
Thermal energy storage is an indispensable component when it comes to energy management issues considering the discontinuity of energy supply and demand (Gupta et al., 2022). Storage can be carried out in the form of sensible heat on solid or liquid materials, heat storage latent on specific phase change materials and also storage thermochemical through conversion of chemical processes (Arkar and Medved, 2005). the mixtures Nitrate salt binaries play an important role in energy storage due to its thermophysical properties. the energy storage thermal insulation plays an important role in some industrial applications such as such as solar thermal storage and waste heat recovery system (Ji et al., 2022).

Various methods of thermal energy storage can be found in international literature. Currently, the packed bed of agglomerated particles has been an innovative method for thermal energy storage. For a system of packed bed thermal storage of agglomerated particles, a large amount of heat transfer surface area can be contained in a small volume and the uneven heat flow that exists in the voids of the packed bed increases the transport through turbulent mixing (Yang et al., 2020). The effect of several parameters, including the filler particle size, particle density, particle porosity, thermal capacity of the particles, thermal conductivity of the particles as well as the thermophysical properties of the fluid phase, can affect the heat flow between the solid and 5 fluid in the packed bed. The novelty of this work is focused on a new mathematical model developed based on a new configuration of a bed system packed with agglomerated particles. The mathematical formulation includes the balances simultaneous energy transfers taking into account the temperature in the solid phase and the temperature in the fluid phase (Wang et al., 2020).

2 PROBLEM DESCRIPTION

A physical model represents a physical construct whose physical phenomena of this physical model can be modeled by applying a mathematical model. Mathematical modeling is an established tool in science to study prediction of complex phenomena from physical models. Different aspects of mathematical models are considered as challenging issues for solving such mathematical models to interpret the results and predict the responses of the physical model. A simplified physical configuration of the physical model was used to develop the mathematical model and can be seen in Figure 1 as follows.

Figure 1. Physical working model for a packed bed system of agglomerated particles.



Achieving solutions to the environmental problems we face today requires potential actions. In this sense, thermal energy storage is one of the most efficient and effective options. Thermochemical energy storage offers an attractive prospect thanks to its high storage density and low heat losses. Equation (1) shows a reaction scheme with loading and unloading of heat.

$$Salt*(\alpha+\beta)H_2O_{(s)}+Q_{solar}\underset{\text{Descarregamento}}{\overset{\text{Carregamento}}{\rightleftharpoons}}Salt*\alpha H_2O_{(s)}+\beta H_2O_{(g)} \quad (1)$$

2.1 METHODOLOGY

Mathematical modeling of fluid-solid heat transfer in a packed bed system of agglomerated particles (see Figure 1) is a complicated matter where a fluid phase and a solid phase (salt particles) are considered. For this study, the continuous solid phase model was adopted. In this model, it is assumed that the salt particles behave as a continuous medium. To develop the mathematical model, some assumptions were adopted as follows: (2) The temperature variation along the axial direction is considered for the gaseous and solid phases, (3) The temperature variation along the radial direction is considered negligible, (4) The property of salt is constant and can be estimated at an average temperature, (5) Heat transfer by radiation is negligible, (6) Internal heat generation is not considered, (7) The volume change of the fluid and salt particle caused on the basis of temperature change is ignored, (8) the packed bed system of agglomerated particles is composed of identical salt particles, and (9) the porosity throughout was considered to be uniform. Based on the above assumptions, a transient continuous solid phase mathematical model is developed based on gaseous and solid phases (salt particles). As temperature indicates thermal energy storage in a substance, therefore, energy balance equations in packed bed system of agglomerated particles are developed based on gas phase temperature and salt particle temperature as follows (Dias and Silva, 2020).

- Energy balance for the solid phase;

$$(1-\varphi)\,\rho_s\,C_{p,s}\frac{\partial T_s}{\partial t} = (1-\varphi)\,\lambda_s\frac{\partial^2 T_s}{\partial x^2} + h_{sf}\,a_{sf}\left(T_f - T_s\right) \tag{2}$$

- The initial and boundary conditions for Equation (2) are defined as:

$$T_s\big|_{t=0} = T_{s,0} \tag{3}$$

$$T_s\big|_{x=0^+} = T_{s,ent.} \tag{4}$$

$$\lambda_s\frac{\partial T_s}{\partial z}\bigg|_{z=L} = h_{sg,eff}\left(T_{s,\infty} - T_s\big|_{z=L}\right) \tag{5}$$

- Energy balance for the gas phase

$$\rho_f\,C_{p,f}\left(\varphi\frac{\partial T_f}{\partial t} + u_f\frac{\partial T_f}{\partial x}\right) = \lambda_{f,eff}\frac{\partial^2 T_f}{\partial x^2} + h_{sf}\,a_{sf}\left(T_f - T_s\right) \tag{6}$$

- The initial and boundary conditions for Equation (6) are defined as:

$$T_g\big|_{t=0} = T_{g,0} \tag{7}$$

$$\lambda_f\frac{\partial T_f}{\partial z}\bigg|_{x=0^+} = \rho_f\,C_{P,f}\,u_f\left(T_g\big|_{x=0^+} - T_{f,ent.}\right) \tag{8}$$

$$\lambda_f\frac{\partial T_g}{\partial z}\bigg|_{z=L} = h_{gs,eff}\left(T_{f,said.} - T_f\big|_{z=L}\right) \tag{9}$$

2.2 TRANSFORMED EQUATIONS

It is possible to transform the system of PDEs into a system of ODEs Using the boundary conditions of each PDEs. Equation (2) was transformed into an ODE using boundary conditions (4) and (5) and the ODE can be written as follows.

$$B_1 \frac{dT_s(t)}{dt} = B_2 B_4 \left[T_{s,\infty} - T_s(L,t) \right] - B_2 V_s T_s(0,T) + B_3 \left[T_f(t) - T_s(t) \right] \quad (10)$$

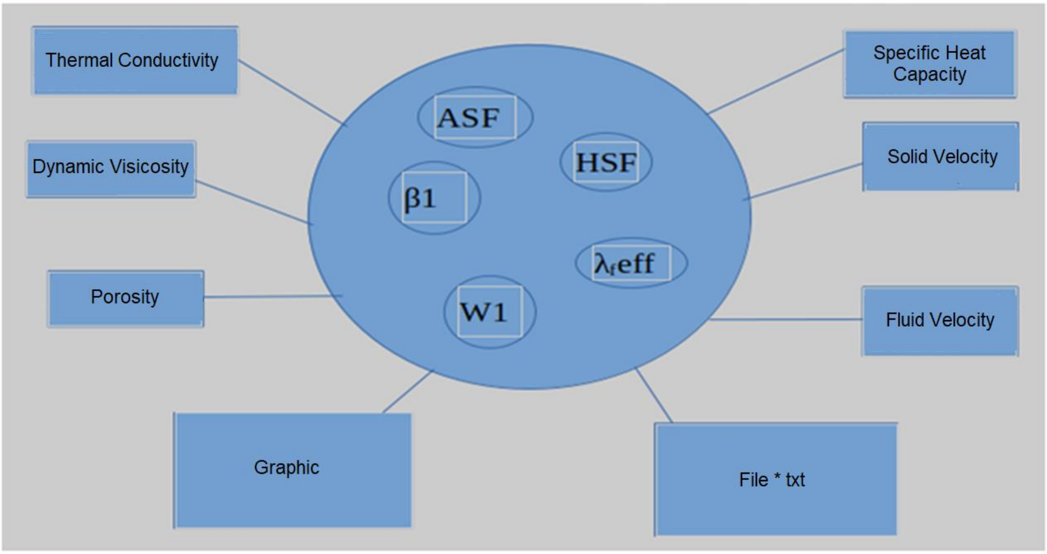
Equation (6) was transformed into an ODE using boundary conditions (8) and (9) and the ODE can be written as follows.

$$w_1 \frac{dT_f(t)}{dt} = w_2 \left[T_f(0,t) - T_f(L,t) \right] + \lambda_{f,eff} B_3 \left[T_{f,\infty} - T_f[L,t] \right] - \lambda_{f,eff} V_f T_f(0,t) + B_3 \left[T_s(t) - T_f(t) \right] \quad (11)$$

2.3 COMPUTATIONAL MODELING

A simulator code was developed in the Python programming language and an SQLite database has been used. The fundamental characteristics of the SQLite database are the implementation of a graphical interface for simulation and graphical analysis of the results of the variation of physical parameters for thermal storage. Figure 3 shows a simplified flowchart of program data.

Figure 2. Schematic diagram of the data flow.



3 RESULTS AND DISCUSSIONS

The forecast results are obtained from a set of input parameters to feed the computational algorithm developed for this work. The values of the input parameters are required for calculating the prediction curves and these values are shown in Table 1. The parameters in Table 1 are considered the initial parameters to feed the computer code.

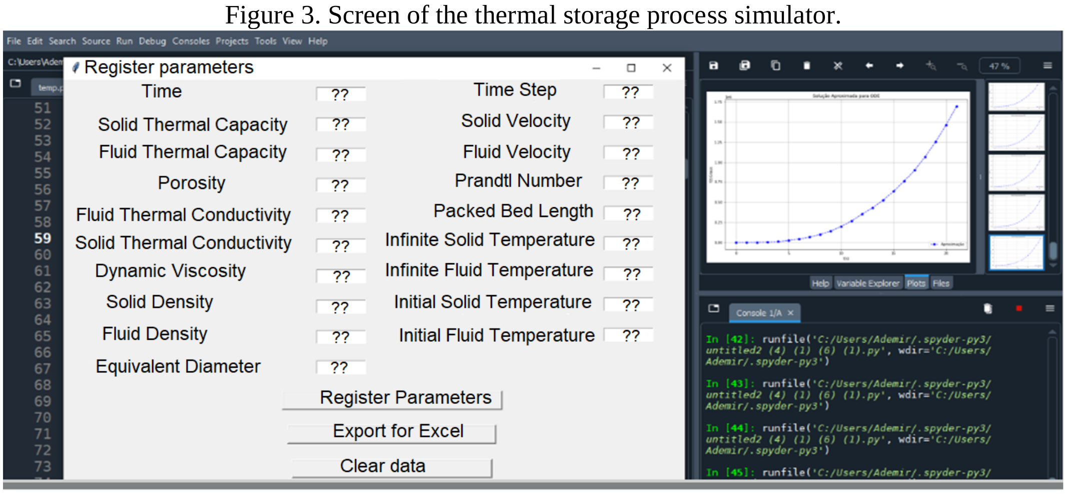
Table 1. Physical parameters used to obtain the simulation results.

Parameters		Values
Thermal conductivity of the solid (λ_s),	W/(m K)	2.0
Thermal conductivity of the fluid (λ_f),	W/(m K)	1,5
Solid heat capacity (cps),	K_j/(Kg-K)	0.8
Fluid thermal capacity ($C_{p,f}$),	K_j/(Kg-K)	0.4
Viscosity (μ),	Pa-s	0.001
Porosity (φ)		0.5
Solid velocity (V_s),	m/s	0.1
Fluid velocity (V_f),	m/s	0.02
Initial fluid temperature ($T_{s,0}$),	°C	100
Solid initial temperature ($T_{f,0}$),	°C	120
Diameter of the part (d_p),	mm	2
Density of the solid (ρ_s),	Kg / m^3	2750
Fluid density (ρ_f),	Kg / m3	1000
Effective thermal conductivity (λ_{feff}),	W/(m K)	0.2
Temperature of the solid at infinity ($T_{s,\text{¥}}$),	°C	27
Fluid temperature at infinity ($T_{f,\text{¥}}$),	°C	30
Fixed bed length (L),	m	1,0
Time (t),	sec.	10
volume specific surface area (A_{SF}),	m^2	-
coefficient of convective heat transfer between two phases (h_{SF})		-

4 SIMULATOR FOR THE DEVELOPED MATHEMATICAL MODEL

Figure 3 shows simplified setup for a process simulator. This setup was used to solve the mathematical model developed based on partial differential equations system and, therefore, the screen of this simulator can be seen in Figure 3 as follows.

Figure 3. Screen of the thermal storage process simulator.



As can be seen in Figure 4, the thermal charging profile regarding to the solid phase achieves a stable state after reaching 9 sec charging time. The temperature of the solid phase had reached a stable state around 312 °C. On the other hand, Figure 5 reports the thermal discharging in relation to the solid phase and, therefore, its stable state is achieved around 9 sec charging time.

In order to investigate the thermal charging profile of the gas phase on the open-cell foam using the simulator from Figure 3, Eq. (11) was used with its respective coefficients. Figure 6 shows the thermal charging profile along of the charging time. As the diffusion effect on the salt particles is very little, then the gas phase temperature is very near of the solid phase temperature. In this case, the energy storage between the two phases is very small. Figure 7 reports the thermal discharging profile of the gas phase, on the porous medium of the open-cell foam, as a function of the charging time. As can be seen in this figure, the gas phase temperature increases and after decreasing along the charging time. This effect can be attributed to the high porosity of the open-cell foam (Xu et al., 2012).

Figure 4. Charging profile of the temperature in the solid phase.

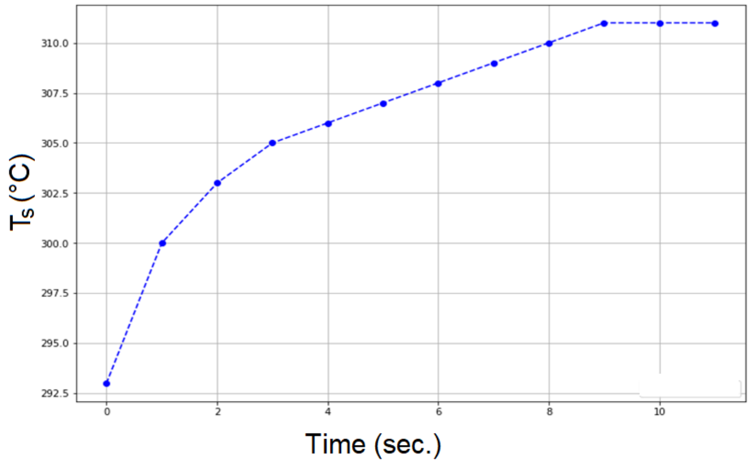


Figure 5. Discharging profile of the temperature in the solid phase.

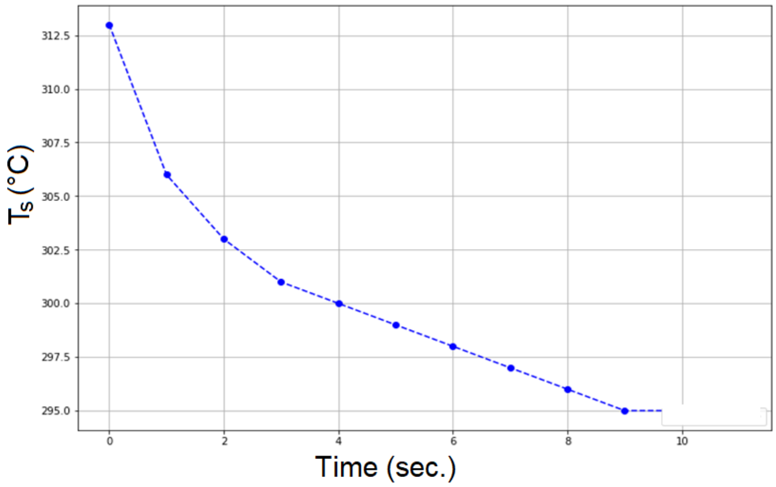


Figure 6. Charging profile of the temperature in the fluid phase.

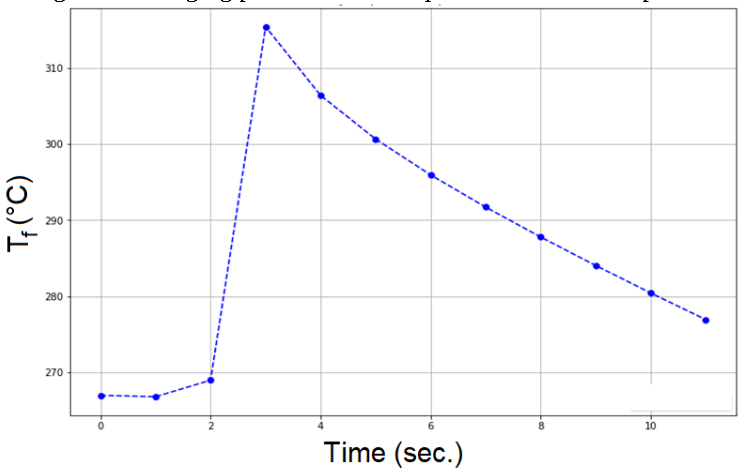
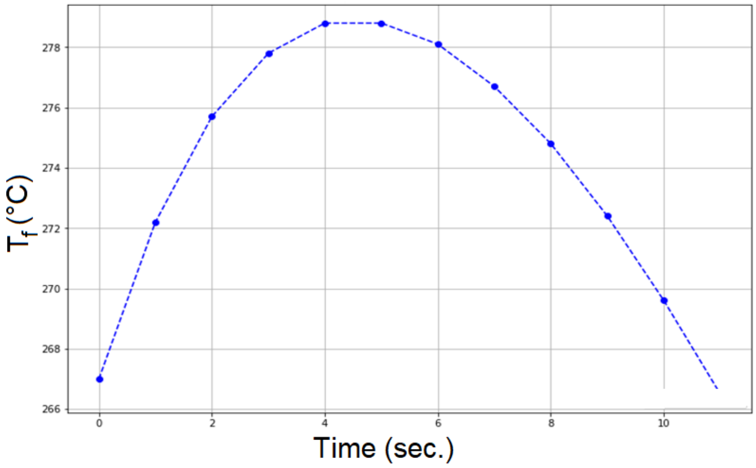


Figure 7. Discharging profile of the temperature in the fluid phase



5 CONCLUSIONS

Conducted in the context of thermal energy, this research resorted to the methodology of energy storage using mathematical models. The storage methodology allows the loading and unloading of thermal energy in a packed bed system of agglomerated particles. From the loading and unloading of energy it is possible to know the displacement of thermodynamic equilibrium. In this context, it is possible to draw the following conclusions:

1. Harnessing thermal energy is essential to drive various processes;
2. The process of harnessing thermal energy is considered a potential process for the environment.

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