Dynamic Performance of Various Thermal Energy Storage Materials

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Abstract

The thermal effects of metal partitions inside Porous Thermal Energy Storage (PTES) have been investigated experimentally and theoretically. Four circular cross-sectional area matrices have been studied and comparison was made between them. These include; storage with Flat Plate partitions (FP), storage with Corrugated Plate partitions (CP), storage with Wire Mesh partitions (WM), and storage Without Partitions (WP). A numerical model has been developed to simulate dynamic thermal energy transfer within (PTES) to include the important thermal effects of the partitions within porous matrices. The developed numerical model is characterized by system of differential energy conservation equations, these equations are solved numerically by time marching implicit method. The theoretical analysis and computational scheme validity has been verified through comparisons with measured data from the experimental work conducted in this work. The investigation has been done for Reynolds number, $Re$, of $1270 < Re < 8050$. A convenient agreement was found between theoretical and experimental results for all of the tested matrices. The metal partitions were specified to have considerable effect on the thermal response for each type of the tested materials. From the comparison of different matrices concerning their ratio between pressure drop and heat transfer, it was found that the (CP) matrix has the highest performance. In this work, an improved transient method was presented for the calculation of the average heat transfer coefficient for porous flow channels along the axial direction with the thermal effects of the metal partitions. A correlation equation been developed for the J-factor have for each matrix material at the range of Reynold's number under investigation. The new (three) correlations predicting the J-factor are found to be in reasonable agreement with the limited published data. However, these correlations have been included the effect of the inside partitions, which have been ignored in all previous published data.

1. Introduction

Porous media have been used in many applications. Packed bed heat exchanger and regenerator, catalytic reactors, geothermal reservoirs near a flowing well, pebble bed nuclear reactors and natural circulation of fluids through underground rock formations are examples of applications of porous media. The features of the Rock-beds are non-toxic, cheap, non-flammable and available [1]. The main drawback it operates with a high pressure drops. the using of rock packed bed for Concentrated Solar Power (CSP) heat storage demonstrates hopeful results with simplified handling cost and economical use of materials of plant with a comparison of the conventional molten-salt energy storage [2]. In a (CSP) plant, which used molten-salt, around 24% decreasing in cost of thermal investment
could be reached by substituting a conventional two tank molten-salt storage with a rock-bed storage [3]. A several studies of using packed bed for thermal storage application are obtained in the literature, however most of these studies interested with a laboratory-type spherical particles [2]. The transient behavior of a packed-bed storage system with different fluids was investigated numerically by Cascetta et al. [4]. They conclude that air permit a considerable temperature range, in absence of ecological and technical problems. Zavattoni et al. [5] were performed CFD simulations with fluent code for predicting time-based behavior of high temperature rock bed TES system. They confirmed the important effect of the containing walls in so-called near-wall region. Mertens et al. [2] improved a mathematical model for the heat transfer in a rock-bed thermocline storage unit with air as a working fluid. The model has been validated with experimental data from literature and wall effect is neglected in this model. Mertens et al. [2] conclude that further work on the effects of thermo cyclic stress on wall and rock filler is required for improving the technology across commercial maturity. Kays and London [6] have noted that the increase of the surface area to volume ration is the most effective way to increase the heat exchanger performance. Packed porous matrix having large values of surface area to volume ratio. Because of the tortuosity effect in conjunction with high value of porosity (\(\varepsilon\)) of these materials, their pressure drop would be high. So, much of the past work concerning heat transfer in permeable packing has focused on average values of transport properties. However, the effect of the internal-partitions, bounding surfaces and end effects create local differences in the packing void fraction, which in turn influence local values of flow characteristics, and thus upon transport processes. Therefore, the objective of the present study is to investigate the transient response of permeable packing with including the effects of various internal metal-partitions that separates the matrix and placed parallel to the direction of flow.

2. Numerical Model
In this work, a separate phase, two-dimensional theoretical model for dynamic response of permeable packing is developed. The analysis considers the effects of the internal partitions inside matrix. The transient energy balance for solid phase of the packing may be represented as [7]:

\[
\rho_s C_s \frac{\partial T_s}{\partial t} = K_s \frac{\partial^2 T_s}{\partial x^2} + h_b \epsilon \left[ T_f - T_s \right] \tag{1}
\]

The transient energy balance for metal-partitions that divided the packing in the direction of flow can be written as:

\[
\rho_w C_w \frac{\partial T_w}{\partial t} = K_w \frac{\partial^2 T_w}{\partial x^2} + h_w \epsilon A \left[ T_f - T_w \right] + U A_0 \left[ T_a - T_w \right] \tag{2}
\]

The dynamic energy balance for fluid phase of the packing for a general interior node may be represented as,

\[
\rho_f C_f \frac{\partial T_f}{\partial t} + \rho_f c \frac{\partial T_f}{\partial x} = K_f \epsilon \frac{\partial^2 T_f}{\partial x^2} + h_b \epsilon \left[ T_i - T_f \right] \tag{3}
\]

However, for outermost fluid nodes (where \(i=m\)), the term should be added to above equation to include the effect of convection between fluid and metal-partition wall. Figure 1 show grid scheme for the model.
The resulting equation for the partition wall at the general node as follows [7]:

\[
\frac{\rho \cdot C_v \Delta}{\Delta t} [T_{w}(j,t+1) - T_{w}(j,t)] = \frac{k_w}{(\Delta x)^2} [T_{w}(j+1,t+1) - 2T_w(j,t+1) + T_{w}(j-1,t+1)] + h_w A [T_f(j,t+1) - T_w(j,t+1)]
\]

(4)

The boundary condition assumed for the partition wall equation is that of insulated boundaries at \(i=1\) and \(j=n\).

The solid phase equation is [7]:

\[
\frac{\rho_c \cdot C_s [1 - \varepsilon]}{\Delta t} [T_s(i,j,t+1) - T_s(i,j,t)] = h_p A [T_f(i,j,t+1) - T_s(i,j,t+1)]
\]

(5)

At the general interior node, the fluid equation may be represented by:

\[
\frac{\rho_f \cdot C_p \Delta}{\Delta t} [T_f(i,j,t+1) - T_f(i,j,t)] + \frac{\rho_f \cdot C_p \cdot U}{2 \Delta x} \frac{K_r}{(\Delta x)^2} [T_f(i,j+1,t+1) - 2T_f(i,j,t+1) + T_f(i,j-1,t+1)]
\]

\[
= \frac{K_r}{(\Delta x)^2} [T_f(i,j+1,t+1) - 2T_f(i,j,t+1) + T_f(i,j-1,t+1)]
\]

(6)

The above equation does not apply at center-line where \(i=1\) or at inlet where \(j=1\). For \(i=1\), the condition of symmetry at the center line implies that:

\[
T_f(i+1,j) = T_f(i-1,j)
\]

For \(j=1\), the term \(T_f(i,j-1,t+1)\) in equation (6) becomes \(T_f(j,0,t+1)\), which is equal to the given inlet fluid temperature for time step \(t+1\).

The solid phase equation could be solved explicitly for \(T_s(i,j,t+1)\), which is then substituted into equation (6). This reduces the original equations in the unknown \(T_w, T_s,\) and \(T_f\) to a set of linear equations at each time step for the partitions and fluid temperatures.

The solid-fluid heat transfer coefficient, \(h_p\), has been widely studied in packed and fluidized beds, the correlation chosen for this study was that produced by Cascetta et al. [4]:

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**Figure 1.** Model grid scheme.
To have a reliable prediction of the thermal energy transport between partition-wall and the flowing fluid, heat transfer coefficient for the plate \( h_w \), is expressed in the form of a dimensionless Plate Nusselt number \( N_u_w \). Martin and Nilles,\[8\] suggest the following equation:

\[
N_u_w = 0.19 \, Re^{0.75} \, Pr^{-0.42}
\]

This Equation shall be used in this work to calculate the plate Nusselt number. The solution of the above equations will be done using time marching implicit method. The iteration accuracy has been selected as:

\[
T_{t+1} - T_t = 0.0001
\]

3. Experimental Work

The validity of the improved time marching implicit model, the computational routine verified through comparisons with measured data from the experimental work conducted in this study. All types of matrices have been packed with the same container and filled with same packing, with air as the working fluid. Both container and partitions were made from steel with specific heat of 502 J/kg\(^\circ\)C, thermal conductivity of 45.3 W/m\(^\circ\)C and 7833 kg/m\(^3\) density.

A total of (four) matrices have been constructed and comparison was made between them. These include; storage with Flat Plate partitions (FP), storage with Corrugated Plate partitions (CP), storage with Wire Mesh partitions (WM), and storage Without Partitions (WP). All matrices have the same axial length of 80 cm. The internal diameter of matrix is (20.2)cm. Figure 2 shows the cross-sectional area of matrices under investigation.

![Figure 2. Cross-sectional area of matrices under investigation.](image)

The corrugated plates were manufactured locally by bending to generate periodical sinusoidal shaped walls. Stasiek et .al \[9\] determined that the average amount of the ratio of pitch - amplitude for wavy wall must be from (3) to (3.5), where this award a high heat transfer rate with little pressure drop. Thus, for all series of tests, the sinusoid pitch to amplitude ratio is kept at (3.589) for the present study.

The gravel-plate packing is prepared using clean gravel with a relatively smooth surface packed between two steel mesh grids on each side of energy storage. A sieve analysis (grading) is performed on the gravel. The selected gravel size is passing sieve (1 in) and retained on sieve (0.75 in). To determine the characteristics of the gravel particles which comprise the packing, a representative sample is prepared. ASTM C 702 \[10\] method has been employed to obtain the representative sample. ASTM C 127 \[2\] method employed to obtain the solid density and the void fraction for all type of the matrices. The gravel particles (average equivalent spherical diameter) \( D_p \), is obtained after determining the mass of 250 representative particles. The average equivalent diameter is found to be (2.19 cm). The average void was found to be 0.384. The accuracy in these measurements is ±0.04. Temperatures throughout the packing are monitored by 24 thermocouples type k to measure partitions,
fluid and packing material temperatures at different positions. A micro-inclined manometer has been used to measure the pressure drop across the porous media.

4. Results

Figure 3 shows a comparison of measured and computed values of fluid temperatures at the partition, container boundary and voids near the solid packing (at central difference between partition and container boundary). It is clear that the temperatures at partition are significantly higher than those at the packing for much of the transient response. In figure 3 it is clear that the corrugation of the partition are strongly influencing the thermal response, that is the fluid temperatures near-partition are significantly higher than those at packing during most of time. Also, this figure shows that the produced through the current modal are logical for all kinds of the matrices under investigation. However, it might also be mentioned that there are some inconsistency between the experimental data and numerical results.

![Figure 3](image_url)

**Figure 3.** Comparison between experimental and numerical thermal response of PTES with various partitions. (a) Without Partitions, WP matrix; (b) Flat Plate, FP matrix; (c) Corrugated Plate, CP matrix; (d) Wire Mesh, WM matrix.

In the present study, it has been found there is a little difference between experimental results and numerical calculation. This difference is due to the chosen equations of the heat transfer, and there is no suitable equation for each matrix. So, a step-change transient technique has been developed to determine heat transfer coefficient for porous material regenerators. The selecting criteria of heat transfer coefficient were the preferable converge between the experimental results and that calculated
by numerical model. This method for calculating the J–factor used by Couteir and Fasber [11] to improve a new experimental (empirical) equation for the (volumetric) heat transfer coefficient of a solar energy system. Figure 4 shows the J-factor predictions for the matrices under investigation.

This figure compares the data obtained by Gabor [12] and Paul and Saina [13] with the predictions of this work. It is seen from this Figure that the data of Gabor [12] over-estimates the J-factor predictions while the data of Paul and Saina [13] under-estimate the J-factor predictions of the present work. The large scatter depicted in figure 4 may be explained by the influence of the type of the boundary shape and various internal partitions.

Compactness factor is one of the important results for the objective of the current study. Figure 5 is a presentation of (J/f) ratio as a function of the (Re) Reynolds number. The (FP) matrix shows the highest position in this figure. This means that this matrix has the highest performance.
5. Conclusions
Various types of internal metal partitions that are interposed between gravel packages have been analyzed. Three different partition configurations are supposed to be used in PTES have been studied and comparison was made between them. Within the limitations of mathematical analysis and experimental testing adopted in the present work, a good agreement found between numerical analysis and experimental results and can be used to calculate the matrix and thermal response of metal plate. The existence of the metal plate surfaces introduces difference in fluid temperatures through matrix. The temperature in the regions of near partition is clearly different than those at the center. For each type of the tested matrices, the metal plate has a different thermal response. Therefore, a careful attention to the internal partitions effect is necessary to allow for a correct prediction of behavior of the permeable packing. The comparison of different heat transfer packing showed a large potential to improve performance, concerning their ratio between pressure drop and heat transfer. It was found that the (FP) matrix has the highest performance (J/f ratio. It has been found that the suggested (FP) package greatly improves the performance. Due to lack of the heat transfer coefficient data for porous matrices with including the thermal effect of the inserted partitions, the primary goal of this work was the determination of the average heat transfer coefficient for such matrices. In the present study, (three) new correlations for the j-factor were developed to predict the temperature distribution during a range of Reynolds number. Considerable spreads in the obtained J-factor data for the different configuration of the matrices have been found. It should be noted that all the heat transfer correlations that have been predicted by other authors lack the thermal effect of the inserted metal plates, which was employed in the present simulation.

6. Nomenclatures
\[ a: \] Volumetric solid contact area.
\[ A_i: \] Inner container wall surface area.
\[ A_o: \] Outer container wall surface area.
\[ C_f: \] Specific heat (fluid phase).
\[ C_s: \] Specific heat (solid phase).
\[ C_w: \] Specific heat (partition wall).
\[ h_{fs}: \] Heat transfer coefficient (solid- fluid).
\[ h_w: \] Heat transfer coefficient (partition wall).
\[ i: \] Position index (radial).
\[ j: \] Position index (axial).
\[ K_f: \] Thermal conductivity of the fluid phase.
\[ K_s: \] Thermal conductivity of the solid phase.
\[ K_w: \] Thermal conductivity of the partition wall.
\[ m: \] Number of transverse nodes.
\[ n: \] Number of axial nodes.
\[ Nu_w: \] Partition wall Nusselt number.
\[ Pr: \] Prandtl number.
\[ Re: \] Reynold’s number.
\[ t: \] Time.
\[ T_f: \] Fluid temperature.
\[ T_a: \] Ambient temperature.
\[ T_s: \] Solid temperature.
\[ T_w: \] Temperature of partition wall.
\[ u: \] Velocity of fluid.
\[ U: \] Heat transfer coefficient (overall).
\[ X: \] Axial direction coordinate.
Void fraction.

\( \varepsilon \): Void fraction.

\( \rho_f \): Density of the fluid phase.

\( \rho_s \): Density of the solid phase.

\( \rho_w \): Density of the partition wall.

7. References

[1] Alva G, L Liu, X Huang and Fang G 2017 *Renewable and Sustainable Energy Reviews* **68** 693.

[2] Mertens M, Alobaid F, Frigge L and Epple B 2014 *Solar Energy* **110** 830-842.

[3] C. Libby 2010, *Solar Thermocline Storage Systems*-Preliminary Design Study, Electric Power Research Institute, Report no. 1019581 Palo Alto CA USA p188.

[4] Cascetta M, Cau G, Puddu P, and Serra F. 2014 *Energy Procedia* **45** 598.

[5] Zavattoni S, Barbato M, Pedretti A, Zanganeh G and Steinfeld A 2014 *Energy Procedia* **46** 124.

[6] Kays W M and London A L 1984 *Compact Heat Exchangers* 2nd edition p335 (New York, USA: McGraw Hill Co.).

[7] Ghanim K and Alhamdo M 2013 *Proc. of 7th. International Conference on Energy Sustainability* (Minneapolis, MN, USA: ASME) p 01.

[8] Martin H and Nilles M 1993 *Chem. Ing. Techn* **65**,1468.

[9] Stasiek, J., Collins M.W., Ciofalo M. and Chew P.E. 1996 *Int. J.Heat Mass Transfer* **39** 149.

[10] ASTM 2004 *Annual Book of ASTM Standards* USA American Society for Testing & Materials section 2 E-11.

[11] Coutier J P and Farber E A 1982 *Solar Energy* **29** 451.

[12] Gabor J D 1982 *Handbook of Heat Transfer* 2nd ed. Chapter 20 (New York, McGraw – Hill).

[13] Paul B and Saina J S 2004 *Renewable Energy* **29** 1836.