NUMERICAL STUDY OF PACKED BED THERMAL STORAGE SYSTEMS WITH ENCAPSULATED PHASE CHANGE MATERIAL

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ABSTRACT

A numerical study is carried out to predict the transient response of a packed bed thermal storage system containing a phase change material (PCM) as a packing material. A vertical cylindrical heat storage packed bed containing PCM encapsulated in spherical pebbles with air as a working fluid is investigated. Three different PCMs in addition to rock grains are tested. The present problem is modeled using two dimensional axisymmertric time-dependent coupled partial differential equations for energy conservation of the working fluid and the PCM. The energy equation for the working fluid is transformed by finite difference approximation and solved by Alternating Direction Implicit scheme (ADI) while the PCM energy equations are solved using fully explicit schemes. The temperature distributions for both the working fluid and PCM and the liquid mass fraction of the PCM are predicted in radial and axial directions for both charging and recovery modes at different operating parameters.

The present predictions are compared with previous experimental data to check the validity of the present model. Also, the influence of the flowing fluid mass flow rate, inlet fluid temperature, heat storage volume and the PCM thermophysical properties are investigated. An enhancement in the thermal energy stored with a maximum value of about 500% is predicted when using beds containing PCMs instead of using rock grains.

KEYWORDS

Phase Change Materials-PCM-Thermal energy storage systems-Packed beds.

1. INTRODUCTION

In the field of power generation, storage of energy provides a way of adjusting the variations in the energy demand. Stored energy can be available at peak demand duration and it makes the process of energy production more economical. Among the different methods of thermal energy storage systems, the packed bed is favored for many applications such as solar thermal heating and cooling system. Packed bed offers a compact structure due to their relatively greater heat storage capacity as compared to systems that utilize energy transporting fluid as the storage medium. Also, due to the large surface area offered by packed beds for heat transfer between the energy transporting fluid and the bed particles, the process of energy transfer and storage becomes very efficient. A properly designed thermal storage system may significantly increase the overall system efficiency. Therefore, it is important for the designer to pay more attention to the thermal performance of the storage device in energy system design.

Recently, encapsulated PCM have received considerable attention as energy storage materials. The use of an encapsulated PCM is very appealing since it makes the utilization of latent heat storage capacity possible. Specially, in solar heating and cooling applications, paraffin wax can be used as a PCM where it exhibits good thermal properties as its melting temperature is suitable which can be reached easily and reduces the energy loss to the surroundings. Also, the storage capacity of the paraffin is relatively large as the latent heat of fusion-solidification is high and this produces compactness of the storage volume.

The dynamic response of sensible energy storage systems has been extensively studied and precise predictive models have been developed. A summary of sensible energy storage models for packed beds has been presented by Beasley and Clark [1]. The studies were classified into numerical in one dimension, two dimensions, analytic and experimental. Abdel Moniem et al. [2] developed a two-dimensional transient model which precisely predict the dynamic thermal response of rock grains packed beds. Three correlations were obtained to calculate the system charging duration, effectiveness and the storage efficiency as functions of the different operating and design parameters. El-Sharkawy et al.[3], introduced an experimental and numerical study to enhance the system by storing thermal energy in aluminum and cement coated aluminum wire mesh.

Several studies were carried out to investigate energy storage in PCMs in a variety of one dimensional geometries. The transient response of a PCM contained in a cylindrical annulus using the enthalpy method of Shamsunder and Sparrow [4] was achieved by Yiner et al. [5]. Green and Vliet [6] developed a numerical model and introduced experimental measurements for a PCM storage unit in a form of shell and tube heat exchanger. Wood et al. [7] examined encapsulated PCM beds of spheres for use as a thermal energy storage medium in a flowing water system. Different shapes of the packing material were used and it was found that spheres are attractive in terms of heat transfer surface area and packing density i.e. area to volume ratio. Beasley et al. [8] carried out experimental and numerical studies to investigate the transient thermal response of a PCM storage system. Phase change models were developed for both isothermal and non-isothermal melting behavior in one dimensional separate phases formulation. Michio and Masuda [9] used calcium chloride as a latent heat storage material in a vertical cylindrical heat storage container, with a single pipe for heat transfer purpose. Heat transfer rates during melting process were measured and it was found that the heat transfer from the pipe to the PCM is greatly affected by natural convection. Vafai and Sozen [10] presented a numerical study on transient behavior of a packed bed of encapsulated PCM with condensing fluid flow through it. Plumb [11] developed a simple one dimensional model based on the volume averaged equations for convective melting. It was found that for a large Peclet number the heat transfer is dominated by convection and the melting rate depends on Stefan number, liquid to solid density ratio, fluid velocity, and the initial solid fraction.

The aim of the present analysis is to provide a predictive computer code for the dynamic thermal response of a packed bed containing encapsulated PCM in spherical pebbles. Previous models of the dynamic thermal response of PCM storage systems have been limited to constant inlet fluid temperature and one dimensional analysis. So, the purpose of the present model is to allow for two dimensional analysis and time varying inlet fluid temperature to the PCM thermal storage system. Also, to provide engineers and designers with precise predictions for the bed performance characteristics represented by the stored energy, charging duration, bed efficiency, melting rate, recovery heat rate and fluid outlet temperature at different design and operating parameters.

2. GOVERNING EQUATIONS AND SYSTEM MODELING

The proposed system is a vertically positioned cylindrical packed bed with different phase change materials encapsulated in spherical pebbles with air as a working fluid as shown in Fig.(1). Based on the following assumptions:

1- two-dimensional axisymmetric case.
2- constant fluid properties.

3- constant PCM (solid and liquid phases) properties.

4-the capsule wall is made of very thin conductive material such that it has negligible heat capacity and thermal resistance, respectively.

The energy equations which govern the present system are as follows:

1- For the working fluid;

$$\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial x} = \frac{k_e^x}{\rho_f c_f}\frac{\partial^2 T_f}{\partial x^2} + \frac{k_e^r}{\rho_f c_f}\left(\frac{1}{r}\frac{\partial T_f}{\partial r} + \frac{\partial^2 T_f}{\partial r^2}\right) + \frac{h\alpha}{\rho_f c_f \varepsilon}(T_{PCM} - T_f) \tag{1}$$

where, $\alpha = n_p A_p = 6(1\text{-}\varepsilon)/d$

2- For the packing material

a- At solid phase (before melting);

$$\rho_{PCM} c_s (1-\varepsilon)\frac{\partial T_s}{\partial t} = h\alpha(T_f - T_s) \tag{2}$$

b- At two phase solid-liquid (during melting)

$$\rho_{PCM} h_{sl} (1-\varepsilon)\frac{\partial \phi}{\partial t} = h\alpha(T_f - T_m) \tag{3}$$

c- *At* ***liquid phase (after melting);***

$$\rho_{PCM} c_l (1-\varepsilon)\frac{\partial T_l}{\partial t} = h\alpha(T_f - T_l) \tag{4}$$

These governing equations include the effects of radial and axial thermal dispersion and are subjected to the following boundary and initial conditions:

2.1. Boundary Conditions

The present system, shown in Fig.(1), is analyzed as a two dimensional problem with insulated surface. Therefore,

at $r = R$;

$$\frac{\partial T_f}{\partial r} = 0 \text{ and } \frac{\partial T_{PCM}}{\partial r} = 0 \tag{5}$$

Also, at the bed center line (r=0) L'Hospital rule from Hornbeck [12] is applied and the second term of the right hand side of Eq.(1) $\frac{k_e^r}{\rho_f c_f}\left(\frac{1}{r}\frac{\partial T_f}{\partial r} + \frac{\partial^2 T_f}{\partial r^2}\right)$ becomes; $2\frac{k_e^r}{\rho_f c_f}\left(\frac{\partial^2 T_f}{\partial r^2}\right)$.

Therefore at the center line, Eq.(1) becomes;

$$\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial x} = \frac{k_e^x}{\rho_f c_f}\frac{\partial^2 T_f}{\partial x^2} + \frac{2k_e^R}{\rho_f c_f}\left(\frac{\partial^2 T_f}{\partial r^2}\right) + \frac{h\alpha}{\rho_f c_f \varepsilon}(T_{PCM} - T_f) \tag{6}$$

At the inlet of the packed bed, the fluid temperatures are assigned the value of the inlet fluid temperature. Also, the temperatures at the bed outlet are assigned values at the previous time. Therefore,

at $x = 0$; $T_f(0,r,t) = T_{in}(t)$ (7)

and at $x = H$; $T_f(H,r,t) = T_f(H,r,t-\Delta t)$ (8)

2.2. Initial Conditions

At the beginning of charging or discharging mode the system of the flowing fluid and the PCM is assumed to be in thermal equilibrium state with a uniform temperature. Also, the liquid mass fraction ϕ is assigned an initial value that depends on the mode (either charging or recovery). Therefore,

at $t = 0$; $\quad T_f(x,r,0) = T_{PCM}(x,r,0) = T_0 \quad$ (9-a)

and for charging; $\quad \phi(x,r,0) = 0.0 \quad$ (9-b)

and for recovery; $\quad \phi(x,r,0) = 1.0 \quad$ (9-c)

2.3. Bed Performance Characteristics

The time dependent bed performance characteristics can be represented by the charging duration, bed efficiency and the melting/solidification rates which are defined as follows:

i- Charging duration (τ): is defined as the time at which the bed reaches the state of thermal equilibrium.

ii- Bed efficiency (η): which is defined according to the mode of operation as;

a-for charging mode,

$$\eta_C(t) = \frac{q_{s,C}(t) + q_{s\text{-}l,C}(t) + q_{l,C}(t)}{\int_0^t m_f c_f [\overline{T}_{f,in}(t) - T_o]\, dt} \qquad (10\text{-a})$$

b-for Recovery mode,

$$\eta_R(t) = \frac{\int_0^t m_f c_f [\overline{T}_{f,out}(t) - \overline{T}_{f,in}(t)]\, dt}{q_{s,R}(t) + q_{s-l,R}(t) + q_{l,R}(t)} \qquad (10\text{-b})$$

where,

$q_{s,C}(t) = m_s(t)\, c_s\, (T_s(t) - T_0)$, $\quad q_{l,R}(t) = m_l(t) c_l\, (T_l(0) - T_m)$

$q_{s\text{-}l,C}(t) = m_l(t)\, h_{sl}$, $\quad q_{l\text{-}s,R}(t) = m_l(t)\, h_{sl}$

$q_{l,C}(t) = m_l(t) c_l\, (T_l(t) - T_m)$ and $\quad q_{s,R}(t) = m_s(t)\, c_s\, (T_m - Ts(t))$

iii-Melting/solidification rate (χ): which is defined as the temporal variation of the molten-solidified volume ratios:

for charging mode, $\chi_s = (V_l / V_{st})$ (11-a)

for recovery mode, $\chi_l = (V_s / V_{st}) = 1 - \chi_s$ (11-b)

3. METHOD OF SOLUTION

The governing equations for both the flowing fluid and PCM Eqs.(1) to (4) are approximated by using finite difference technique. The formulation utilizes a central difference approximation for the first and second derivatives. The simplicity of the PCM equations, Eqs.(2), (3) and (4) allows explicit statements for the PCM temperature and liquid fraction at the general node i,j, shown in Fig.(1), at the time $t+\Delta t$ (time iteration $n+1$) as;

a- For solid phase

$$Ts_{i,j}^{n+1} = \frac{1}{(1+\gamma_s \Delta t)}(Ts_{i,j}^{n} + \gamma_s \Delta t Tf_{i,j}^{n+1}) \qquad (12)$$

b- For the two phase solid-liquid

$$\phi_{i,j}^{n+1} = \frac{1}{(1+\gamma_{sl}\Delta t)}(Ts_{i,j}^{n} + \gamma_{sl}\Delta t \phi_{i,j}^{n+1}) \tag{13}$$

c- For the liquid phase

$$Ts_{i,j}^{n+1} = \frac{1}{(1+\gamma_{l}\Delta t)}(Ts_{i,j}^{n} + \gamma_{l}\Delta t Tf_{i,j}^{n+1}) \tag{14}$$

where, $\phi = \dfrac{\text{mass of liquid in the PCM}}{\text{total mass of the PCM}}$

$$\gamma_s = \frac{h\alpha}{(1-\varepsilon)\rho_{PCM}c_s}, \ \gamma_{sl} = \frac{h\alpha}{(1-\varepsilon)\rho_{PCM}h_{sl}} \ \text{and} \ \gamma_l = \frac{h\alpha}{(1-\varepsilon)\rho_{PCM}c_l}$$

Substituting Eqs.(12), (13) and (14) into the finite difference form of Eq.(1), yields the following general expression for the fluid temperature at the general node i,j;

$$\Psi_1 Tf_{i,j}^{n+1} + \Psi_2 Tf_{i,j+1}^{n+1} + \Psi_3 Tf_{i,j-1}^{n+1} + \Psi_4 Tf_{i+1,j}^{n+1} + \Psi_5 Tf_{i-1,j}^{n+1} = \frac{1}{\Delta t} Tf_{i,j}^{n} + \Psi_6 Ts_{i,j}^{n} \tag{15}$$

where;

$$\Psi_1 = \frac{1}{\Delta t} + \frac{2k_e^x}{\rho_f c_f (\Delta x)^2} + \frac{2k_e^r}{\rho_f c_f (\Delta r)^2} + \frac{h\alpha}{\rho_f c_f \varepsilon}\left(1 - \frac{\gamma\Delta t}{1+\gamma\Delta t}\right) \tag{16-a}$$

$$\Psi_2 = \frac{u}{2\Delta x} - \frac{k_e^x}{\rho_f c_f (\Delta x)^2} \tag{16-b}$$

$$\Psi_3 = -\left(\frac{u}{2\Delta x} + \frac{k_e^x}{\rho_f c_f (\Delta x)^2}\right) \tag{16-c}$$

$$\Psi_4 = -\frac{k_e^r}{\rho_f c_f}\left(\frac{1}{2r\Delta r} + \frac{1}{(\Delta r)^2}\right) \tag{16-d}$$

$$\Psi_5 = \frac{k_e^r}{\rho_f c_f}\left(\frac{1}{2r\Delta r} - \frac{1}{(\Delta r)^2}\right) \tag{16-e}$$

$$\Psi_6 = \frac{h\alpha}{\rho_f c_f \varepsilon}\left(\frac{1}{1+\gamma\Delta t}\right) \tag{16-f}$$

where, γ is taken (γ_s or $\gamma_{s\text{-}l}$ or γ_l) according to the phase of the PCM.

In fact, most of the previous models for the transient response of packed beds have assumed the void fraction, velocity and transport coefficient to be uniform throughout the cross section of the packing. Khan and Beasley [13] found that the mean void fraction for a packed bed is a function of the bed to particle diameter ratio D/d. Therefore, the correlation of Beavers et al. [14] was used in the present analysis as;

a) for D/d <28;

$$\varepsilon = 0.4272 - 4.516\text{x}10^{-3}\ (D/d) + 7.881\text{x}10^{-5}\ (D/d)^2 \tag{17-a}$$

b) for D/d ≥ 28; it is assumed that the mean void fraction is independent of the bed-to-particle diameter ratio and has a constant value as,

$$\varepsilon = 0.3625 \tag{17-b}$$

A correlation for the radial velocity profile in the packed bed of uniform spheres based on the measurements of Newell and Standish [15] was adopted and used in the present model. The effective thermal conductivity in both axial and radial directions, for the present low range of flow velocities, was calculated using the following equation obtained from Cheng[16]:

$$\frac{k_{ei,j}^{X,r}}{k_f} = [1-\sqrt{1-\varepsilon}] + \frac{2\sqrt{1-\varepsilon}}{1-\lambda\beta}\left[\frac{(1-\lambda)\beta}{(1-\lambda\beta)^2}\ln\frac{1}{\lambda\beta} - \frac{\beta+1}{2} - \frac{\beta-1}{1-\lambda\beta}\right] \tag{18}$$

where, $\beta = 1.25\left(\frac{1-\varepsilon}{\varepsilon}\right)^{10/9}$ and $\lambda = \frac{k_f}{(1-\phi_{i,j})k_s + \phi_{i,j}k_l}$

Moreover, in the present model the heat transfer coefficient between the PCM spherical pebbles and the flowing fluid is calculated from [1] as:

$$Nu_d = 2.0 + C_1\ Re_o^{1/2}\,Pr^{1/3} + C_2\,Re_o\,Pr^{1/2} \tag{19}$$

where,

C_1, C_2 are constants having the values of 2.03 and 0.049 respectively, [8].

Re_o is Reynolds number based on the particle diameter and the superficial flow velocity and it is given by; $Re_o = u_o d/\nu$

u_o the superficial flow velocity and is given by; $u_o = u\,\varepsilon$

Substitution of Eqs.(16) through (19) into the difference equation, Eq.(15), yields a system of simultaneous linear equations for the fluid temperatures.

The Alternating Direction Implicit (ADI) method is applied to solve this system of linear equations at each time step which is solved radially at one half of the time step, $\Delta t/2$, and axially at the full time step, Δt. Therefore, the system of linear equations is decomposed into two tridiagonal systems of linear equations due to the application of the ADI method. These tridiagonal systems of equations are solved by using Gauss elimination method.

4. STABILITY AND ACCURACY OF THE NUMERICAL SCHEME

Several combinations for radial, axial increments and time steps are checked to find the optimum combination that assures the stability and convergence of the present model. Equal radial and axial increments greater than the particle diameter $\{\Delta x = \Delta r \geq d(1+2\varepsilon)\}$ are found to yield sufficiently accurate solutions.

The consistency and reliability of the present predictions are evaluated by comparing the present predictions with the experimental data of [8] as shown in Fig. (2) and the comparison shows fair agreement.

5. RESULTS AND DISCUSSIONS

Encapsulated bed pebbles filled with three different PCMs labeled PCM1, PCM2 and PCM3 in addition to solid rock grains are used as a thermal storage materials in the present model. Table (1) illustrates the thermophysical properties of the tested thermal storage materials.

Table (1): Thermophysical Properties of the Heat Storage Materials [17]

Property \ Energy Storage Material	PCM1 Paraffin wax	PCM2 $C_{14}H_{28}O_2$	PCM3 $NaSO_4.10H_2O$	Rock Grains
Melting point, T_{mp}, °C	51.6	53.8	32	-
Latent heat of fusion, kJ/kg	197.9	198.5	225.0	-
Thermal conductivity $k_s \simeq k_l$, W/mK	0.24	0.1	2.25	0.88
Solid specific heat c_s Liquid specific heat c_l, kJ/kg K	8.39 2.09	1.59 2.26	1.76 3.30	0.77
Density $\rho_s \simeq \rho_l$, kg/m^3	812	860	1460	2486

The effect of the bed aspect ratio (AR) on the storage performance of a fixed storage volume was previously investigated by the authors, [2] for a rock bed and no significant effect was found. Therefore, a bed of an aspect ratio of unity (AR=1) and 0.25 m diameter (D) with encapsulated pebbles of 12.6 mm diameter is considered as a reference for comparison in the present predictions. The predicted transient temperature for PCM1 at inlet fluid temperature of 65 °C at the bed center (x/H=0.5 and r/R=0.0) at different fluid mass flow rates is shown in Fig.(3). Figure (4) shows the effect of fluid mass flow rate on the transient temperature at the center of the bed with T_{in}= 65 °C, for different PCMs and rock grains within a range of fluid mass flow rate from 0.005 up to 0.04 kg/s. A longer charging duration is recorded for PCM2 which has the highest melting point. The charging duration is affected by the thermal potential (the difference between the fluid inlet temperature and PCM melting point) rather than the latent heat of fusion. Constant temperatures charging durations corresponding to the phase change temperatures of the PCMs are noticed for the bed containing different PCMs. It is obvious that, the charging duration with phase change is larger than that for sensible heat charging. This is attributed to the higher latent to sensible heat ratio for PCMs.

The axial transient temperature distributions at the bed center-line for the three different PCMs and rock grains are illustrated in Fig. (5). Two constant temperature regions (melting and thermal equilibrium regions), corresponding to both the melting point and the fluid inlet temperatures respectively, are noticed for all PCMs.

Isotherms within a bed of PCM1 with AR =1 at fluid inlet temperature of 65 °C and fluid mass flow rate of 0.01 kg/s at different times (t=0.25, 0.5, 0.75 and 1.0 hour) are shown in Fig. (6). It is noticed that, the radial variation in the PCM temperature and the melting front follow the fluid flow velocity profile through the bed with a propagation in the melt region. Also, the outer bed wall isotherms accumulation ensure that, a conduction mode heat transfer is dominant in this region as the fluid velocity vanishes.

The variation of the fluid exit temperature with time during charging process is shown Fig. (7). It is shown that, due to the large heat capacity of the beds with the different PCMs, the loss in both energy and availability (in terms of the exit fluid temperature) is much less compared with the case of single phase rock grains bed. Also, the energy stored within the reference bed (AR=1, D=0.25 m, d=12.6 mm) for different PCMs and for rock grains is shown in Fig.(8). The present predictions result in estimating the thermal capacity limits for three common PCMs and rock grains to help for economical selection of the packing material to assure storage capacity requirement with low material cost. For storage capacity per unit volume (Q_{st}/V_{st}) greater than 51.8 MJ/m^3 (636kJ/ 0.01227m^3) with fluid inlet temperature of

70 ^{o}C, all the tested PCMs exhibit good appealing for more energy storage. Also the weight for all the different PCMs is less than that of the rock bed and this is another advantage for PCMs packed beds energy storage systems.

The flowing fluid exit temperature from the bed at recovery mode versus time for different tested materials is depicted in Fig.(9). It is clear that all PCMs gives wide recovery durations with constant temperatures corresponding to the phase change temperatures while the rock grain bed recovers energy with a sharply decreasing temperature.

Figure (10) shows the rate of heat recovered from beds of PCM1, with a fixed ratio of fluid mass flow rate to bed storage volume (m_f/V_{st}) of 0.814 and bed aspect ratio of unity, with different bed diameters at different mass flow rates. Constant rates of heat recovery with different values, depending on the bed diameter, are predicted for wide recovery durations. These constant heat recovery rates enhance the availability and the second law efficiency of the storage system.

The transient variation of the molten volume fraction for different PCMs at different inlet fluid temperatures is illustrated in Fig.(11). Higher melting rate is noticed for higher inlet fluid temperature and a higher melting rate is noticed for the case of PCM3 which has the lowest melting point (32 ^{o}C). The temporal variation of the bed thermal efficiency for charging at different inlet fluid temperature for different PCMs is shown in Fig.(12). Three discrete trends of thermal efficiency are noticed corresponding to the three states of the PCMs during the charging process. The first duration corresponds to the solid phase where higher thermal efficiency is noticed with a sharp decreasing trend. The second duration corresponds to the two phase solid-liquid charging process and the third one is corresponding to the liquid phase heat transfer process where lower thermal efficiency is depicted due to the elevated bed temperature.

The present model is also modified to deal with the effect of time varying fluid inlet temperature on the performance characteristic of a packed bed containing PCMs as storage materials. Figure (13) shows the transient temperature variation at the bed center for different PCMs and rock grains with the time varying inlet fluid temperature, according to {$T_{in}=T_o+T_{max}\,Sin(\pi\ t/12)$, where t in hours}. It is noticed that the rock grains single phase heat transfer mode follows exactly the inlet fluid temperature whereas the phase change heat transfer deviates from the inlet fluid temperature with each PCM following its own trajectory according to its phase change temperature. Also it can be recommended that the charging process must be ended when the bed reaches its maximum temperature.

Figure (14) shows the energy stored in the different materials for a time varying inlet fluid temperature. It is shown that, the time varying thermal response of PCMs is more favorable compared with that of the rock bed. Also, the stored energy loss in case of PCM3 is the lowest compared with PCM2 and PCM1, this may be due to its lower melting point.

CONCLUSIONS

1- The presence of PCMs always enhances the energy storage in packed beds.
2- The present predictions result in estimating the thermal capacity limits for three common PCMs and rock grains to help for economical selection of the packing materials to assure storage capacity requirement with low material cost.
3-For relatively high storage capacity greater than 51.8 kJ/m^3 all the used PCMs exhibit good appealing for more energy storage. Also the weight for all the different PCMs is less than that of the rock grains bed and this is another advantage for the usage of PCMs in energy storage systems.

4- The charging duration is affected by themophysical properties of the packing materials. A longer charging duration is recorded for the PCM with the highest melting point.

5-Constant rates of heat recovery at constant temperatures are predicted in most of the recovery duration for the beds with PCMs. This enhances the second law efficiency and the availability of the stored energy.

6- In the case of the time varying inlet fluid temperature, the bed temperature for the rock grains storage system follows exactly the fluid inlet temperature whereas for the bed with PCMs it deviates from the inlet fluid temperature according to its melting point.

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NOMENCLATURE

SI system of units is used for the whole parameters within the present paper.

A_p	PCM pebble surface area
AR	bed aspect ratio, (AR=H/D)
c	specific heat
C_1 , C_2	constant in equation (16)
D	bed diameter
d	PCM pebble diameter
H	bed height
h	convective heat transfer coefficient
h_{sl}	latent heat of melting/solidification
k	thermal conductivity
m_f	fluid mass flow rate
n_p	number of PCM pebbles per unit volume of the bed
PCM	phase change material
R	outer radius of the bed
r	radial coordinate
T	temperature
t	time
u	fluid velocity through the bed
V	volume
x	axial coordinate

Subscripts:

C	at charging mode
e	effective value
f	for working fluid
i,j	nodal point numbers
in	at bed inlet
l	liquid
m	melting temperature
o	superficial value
out	at bed exit
PCM	phase change material
R	at recovery mode
s	for solid phase
sl	solid-liquid
st	storage
0	initial value

Superscripts:

n	previous time
n+1	current time
r	for radial direction
x	for axial direction
—	average value

Greek letters:

α	interphase surface area per unit bed volume
β	variable in Eq. (18)
Δ	incremental step
ε	average void fraction
ϕ	PCM liquid mass fraction
Ψ_1 - Ψ_6	coefficients in Eq.(13) and given by Eqs.(14)
γ	variable in Eq. (12)
η	storage efficiency
λ	thermal conductivity ratio
ν	kinematic viscosity
ρ	density
τ	charging duration
χ	molten volume ratio

Dimensionless terms:

AR	aspect ratio (H/D)
Nu_d	Nusselt number (hd/k_f)
Pr	Prandtl number ($\mu c_p/k_f$)
Re_o	superficial Reynolds number ($u_o d/\nu$)