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Numerical Simulation of Packed Bed Cubical Storage Unit Filled with Spherical Capsules of PCM

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Abstract : Modern life and increasing demand on the energy make the saving of available energy in the packed bed of PCM capsules very important to use in the other time. A numerical investigation is proposed for storage of thermal energy using packed bed of spherical capsules filled with phase change material PCM. The spherical capsules are arranged as layers in the cubic vessel that exposed to heat transfer fluid. The fourth order Runge-Kutta method is applied to solve the energy balance equation of heat transfer fluid and the energy conservation equation of spherical capsules of PCM is solved using finite differences method with heat capacity method for phase change of PCM. The effect of Reynolds number and diameter of capsulated sphere are studied. The results illustrate that at constant porosity of packed bed the small diameter of capsulated spheres gives shorter time for melting, where at D=50mm & t=196.5sec the melting fraction of PCM is 0.09, while at D=10mm & t=196.5sec the melting fraction of PCM is 1.00. The results of present study have been compared with other previous results and give a good agreement.

Key words*: Spherical capsules, PCM, Numerical simulation, Packed bed*

محاكاة عددية لوحدة خزن السرير المكتظ التكعيبية المملوءة بالكبسولات الكروية من بي سي أم

احمد كاظم الشرع

الملخص :ان الحياة الحديثة والطلب المتزايد على الطاقة يجعلان خزن الطاقة المتوفرة في السرير المكتض من كبسولات بي سي أم, مهم جدا للاستخدام في وقت اخر. تحقق عددي جديد اقترح لخزن الطاقة الحرارية باستخدام سرير مكتض من الكبسولات الكروية المملوءة بمواد متغيرة الطور بي سي أم. الكبسولات الكروية مرتبة كطبقات في الوعاء المكعب والتي تتعرض لمائع انتقال الحرارة. طبقت طريقة رونج-كتا من المرتبة الرابعة لحل معادلة موازنة الطاقة ومعادلة الحفظ لكبسولات بي سي أم الكروية باستخدام طريقة الفروقات المحددة مع طريقة السعة الحرارية للتغير الطوري للبي سي أم. درس تـأثير كل من عدد رينولدز و قطر الكبسولة الكروية. النتائج وضحت عند ثبوت مسامية السرير المكتض, فان الكبسولات الكروية ذات القطر الصغير تعطي وقت اقصر للانصهار حيث عند قطر50mm و زمن 196.5sec يكون كسر لانصهار للبي سي ام 0.09 بينما عند قطر 10mm و زمن 196.5sec يكون كسر لانصهار للبي سي ام 1.00. قورنت نتائج الدراسة الحالية مع نتائج اخرى سابقة واعطت تطابق جيد.

الكلمات المفتاحية: الكبسولات الكروية, بي سي أم, محاكاة عددية, سرير مكتض.

INTRODUCTION

The increasing demand, the pollution and raising the price of fossil fuels make the world thinking to replace it with available energy such as solar energy, geothermal energy, waste energy etc., which have been considered as one of the promising solutions. These energies can be stored at time and used in another time by availing the latent heat of melting or solidification for phase change of phase change materials (PCMs). The phase change materials are kept in the containers or capsules with different shapes: rectangular, cylindrical, and spherical etc. [1]. Many previous researches studied the applications of PCM, the development of storage energy using PCM, checking the arrangements of geometries of PCM containers and investigate and test various types of phase change materials PCMs [2, 3, 4, 5, 6, 7, 8, 9]. Takeda et al. [10] developed an experimental ventilation system that features direct heat exchange between ventilation air and granules containing a phase change material (PCM). The phase changes of PCM in single sphere were studied by [11, 12, 13], also single spherical shell was studied by Assis et al.[14]. Regin et al. [15] analyzed the behavior of storage the thermal latent heat in packed bed system. Spherical capsules filled with paraffin wax as PCM was used in the packed bed with a solar water heating system for both charging and discharging processes. in [16] investigated saving the energy in a concentrating solar power (CSP) plant to use in the operation of plant at other times when energy from the sun is not available by dispatching its storage energy. The research in [17] investigated numerically storage unit of packed bed from encapsulated spherical containers of PCM and compared a three different mathematical models for latent heat storage system, consisted of a cylindrical storage tank filled with encapsulated spherical containers of paraffin. in [18] analyzed theoretically a packed bed thermal energy storage with spherical capsules of phase change material (PCM) to enhance the performance of solar organic

Rankine cycle ORC system of power generation by using its operation time demand to the night. The analysis based upon a finite difference technique for discharging and charging process. in [19] studied the behavior of storage latent thermal energy in a packed bed system. The model used the concentric-dispersion equations, except the phase change process of PCM inside the capsules was investigated by using enthalpy method. The results indicated that decrease the size of PCM capsule and inlet velocity of fluid, or increase the storage height, give in an increase in the charge efficiency (the ratio of storage energy to input and pump energy). in [20] employed the sodium thiosulphate pentahydrate as phase change material experimentally and which is stored in stainless steel capsules. The experimental design considered the following parameters: heat transfer fluid inlet temperature, flow rate and PCM capsule shape. The experimental data were analyzed applying Fuzzy Logic to find the optimal values of heat transfer fluid inlet temperature, flow rate and PCM capsule shapes. The authors in [21] developed mathematical model to test the effects of using phase change materials (PCM) in accumulation tank with fully mixed water. They considered spheres with a diameter of 40 mm in a packed bed system as an option to enhance energy storage density. The authors in [22] presented a numerical model for thermal energy storage (TES) system in a packed bed using phase change material (PCM). The storage system was to be used for a solar cooking application. The heat transfer fluid is sunflower oil during charging cycles. The packed bed thermal energy storage TES consists of capsulated spheres filled with erythritol, as PCM. The model uses for heat transfer the dual-phase mathematical equations while the phase change phenomena inside the PCM capsules is investigated by using the effective heat capacity method. in [23], analyzed a latent thermal energy storage system, which uses a sodium nitrate to fill capsulated spheres inside a cylindrical tank, for applications of concentrating solar power plant. They noticed that; the heat transfer rate is clearly increased when the capsule size is decreased because the surface to volume ratio; the completed melting time is shorter than the time of solidification due to the convection effects during melting process. in [24], presented experimentally and numerically heat transfer investigation of a packed bed of spherical capsules PCM. He found that the higher the inlet heat transfer fluid temperature gives a higher the time for completing charge. Also, the higher the mass flow rate of the heat transfer fluid leads to the shorter the time for completing charge. in [25] developed a numerical model to obtain the heat transfer characteristics of lab-scale energy storage system, which consists of encapsulated spherical capsules (molten salt) and air. in. [26] studied numerically the flow and heat transfer on a latent heat storage system based on a phase change material (PCM) in capsulated spherical shells. It is designed for passive cooling in air condition applications by cold accumulation through the solidification of PCM during the night and by cold discharging through the melting of PCM during the day. The aims of the present work are: studying the saving energy in packed bed of spherical capsules of PCM numerically using finite difference method, and investigating the effect of Reynolds number, diameter of spheres on the melting process.

Theoretical Analysis

The schematically figure of present model is presented in the Fig.1. The heat transfer fluid H.T.F enters to package bed (cubic vessel) which arranges with horizontal rows of spherical capsules filled with phase change material PCM, with uniform velocity w_{in} and uniform inlet temperature T_{in}. The cross section of vessel is square and the spherical capsules are sorted in cubic package. Each cubic cell has length L with sphere has diameter D. The PCM is kept in thin capsules that made from solid metal with high thermal conductivity such as copper (the thermal resistance of thin wall is negligible). The melting temperature of PCM T_m and the region of change from liquid to solid is $T_m - dT_m \ to \ T_m + dT_m$.

The energy conservation equation of PCM and energy balance equation of heat transfer fluid with the following assumptions;

1-The heat transfer fluid at any row has the same temperature T_f.
2-The temperature variation of spherical capsule of PCM is radial only.
3-Constant properties of H.T.F.
4-The free convection in the PCM is neglected.
5-The radiation between PCM spheres is negligible.
6-The density of PCM is constant.
7-The vessel is insulated from the side wall.

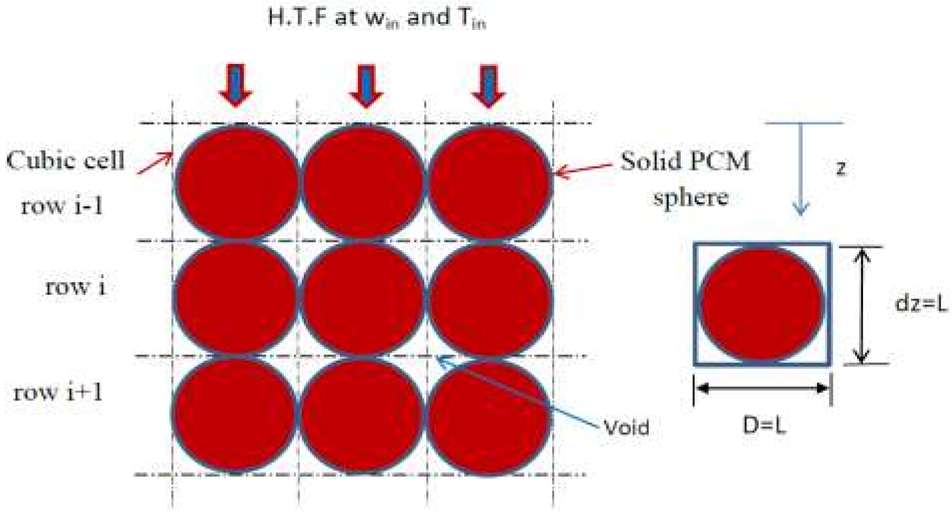

Fig.1 Schematic diagram of present model.

Using the above assumptions, the energy equation of spherical capsule of PCM is [19],

$$\rho_p c_p \frac{\partial T_p}{\partial t} = k_p \left[\frac{\partial^2 T_p}{\partial r^2} + \frac{2}{r}\frac{\partial T_p}{\partial r} \right] \tag{1}$$

Where c_p, k_p and according to heat capacity method [27] are:

$$c_p = \begin{cases} c_s & T_p < T_m - dT_m \\ \dfrac{c_s + c_l}{2} + \dfrac{H}{2dT_m} & T_m - dT_m \le T_p \le T_m + dT_m \\ c_l & T_p > T_m + dT_m \end{cases} \tag{2.a}$$

and

$$k_p = \begin{cases} k_s & T_p < T_m - dT_m \\ k_s + \dfrac{k_l - k_s}{2\delta T_m}\left[T_p - T_m + dT_m\right] & T_m + dT_m > T_p > T_m - dT_m \\ k_l & T_p > T_m + dT_m \end{cases} \tag{2.b}$$

Also, the energy balance equation of heat transfer fluid (for cubic unit) is,

The energy in – The energy out = The energy storage

$$w_{in}\, L^2\, \rho_f\, c_f\, T_f - \left[h_D\, \pi\, D^2\, (T_f - T_p) + w_{in}\, L^2\, \rho_f\, c_f\, (T_f + \frac{\partial T_f}{\partial z} dz) \right] = \rho_f\, (L^3 - \pi D^3/6)\, c_f \frac{\partial T_f}{\partial t} \tag{3a}$$

Then

$$h_D \pi\ D^2\ (T_p - T_f) - w_{in}\ L^2\ \rho_f\ c_f\ \frac{\partial T_f}{\partial z} dz = \rho_f\ (L^3 - \pi D^3/6)\ c_f\ \frac{\partial T_f}{\partial t} \qquad (3b)$$

The initial and boundary conditions are:
The initial conditions:

$$T_f = T_i \qquad at\ t = 0 \qquad and\ 0 < z < L_V$$

$$T_p = T_i \qquad at\ t = 0 \qquad and\ 0 < r < D/2$$

Where L_V: Vessel length (in the z-direction).
The boundary conditions
H.T.F. :

$$T_f = T_{in} \quad at\ \ z = 0$$

PCM,

$$\frac{\partial T_p}{\partial r} = 0 \qquad at \quad r = 0 \qquad \text{and} \qquad k_p \frac{\partial T_p}{\partial r} = h_D (T_f - T_P) \qquad at\ r = D/2$$

Applying the dimensionless form

$$R = \frac{r}{D},\quad Z = \frac{z}{D},\quad \tau = \frac{t\ \mu_f}{\rho_f\ D^2},\qquad \theta_f = \frac{T_f - T_m}{T_{in} - T_m},\quad \theta_p = \frac{T_p - T_m}{T_{in} - T_m},\qquad d\theta = \frac{dT_m}{T_{in} - T_m},$$

$$\mathrm{Re} = \frac{w_{in}\,\rho_f\ D}{\mu_f},\quad \mathrm{Pr}_f = \frac{\mu_f c_f}{k_f},\quad K = \frac{k_p}{k_f},\qquad K_l = \frac{k_{pl}}{k_f},\qquad K_s = \frac{k_{ps}}{k_f}$$

$$C = \frac{\rho_p\ c_p}{\rho_f\ c_f},\quad C_s = \frac{\rho_{ps}\ c_{ps}}{\rho_f\ c_f},\quad C_l = \frac{\rho_{pl}\ c_{pl}}{\rho_f\ c_f},\ Ste = \frac{c_f (T_{in} - T_m)}{H},\quad and\quad Nu = \frac{h_D\ D}{k_f}$$

Where Re, Pr_f, Ste and Nu are: Reynolds number, Prandtl number of heat transfer fluid, Stephan number and Nusselt number respectively.

Also ε: porosity of packed bed, which is defined as

$$\varepsilon = \frac{Pore\ volume}{Bulk\ volume} = \frac{Bulk\,volume - Solid\ volume}{Bulk\,volume} = 1 - \frac{\pi D^3/6}{L^3}$$

Using non-dimensional form, the governing equations become:

PCM

where

$$C = \begin{cases} C_s & \theta_p < \theta_m - d\theta_m \\ \dfrac{C_s + C_l}{2} + \dfrac{C_s}{2\ Ste\ d\theta_m} & \theta_m - d\theta_m \le \theta_p \le \theta_m + d\theta_m \\ C_l & \theta_p > \theta_m + d\theta_m \end{cases} \qquad (5.a)$$

and

$$\frac{\partial \theta_p}{\partial \tau} = \frac{K}{C\ \mathrm{Pr}_f} \left(\frac{\partial^2 \theta_p}{\partial R^2} + \frac{2}{R} \frac{\partial \theta_p}{\partial R} \right) \qquad (4)$$

$$K = \begin{cases} K_s & \theta_p < \theta_m - d\theta_m \\ K_s + \dfrac{K_l - K_s}{2 d\theta_m} [\theta_p - d\theta_m] & \theta_m - d\theta_m \le \theta_p \le \theta_m + d\theta_m \\ K_l & \theta_p > \theta_m + d\theta_m \quad (7b), \end{cases} \qquad (5.b)$$

where

$$d\theta_m = \frac{dT_m}{T_{in} - T_m}$$

H.T.F

$$\frac{\partial \theta_f}{\partial \tau} = -\frac{\text{Re}}{\varepsilon}\frac{\partial \theta_f}{\partial Z} - \frac{6\ Nu\ (1-\varepsilon)}{\varepsilon\ \text{Pr}_f}(\theta_f - \theta_p) \qquad (6)$$

Where Nu is the Nusselt number of packed bed with porosity ε [28]

$$Nu = f_\varepsilon\ Nu_{D,over\ sphere} \qquad (7)$$

where

$$f_\varepsilon = 1 + 1.5(1-\varepsilon)$$

$$Nu_{D,over\ sphere} = 0.664\text{Re}^{1/2}\ \text{Pr}_f^{1/3}$$

$$for \quad 0.7 < \text{Pr}_f < 60 \quad and \quad 1 \le \text{Re} \le 10^6$$

The initial and boundary condition in the dimensionless form are
The initial conditions:

$$\theta_f = \theta_i \qquad at\ \tau = 0 \qquad and\ 0 < Z < N_{row}$$

$$\theta_p = \theta_i \qquad at\ \tau = 0 \qquad and\ 0 < R < 0.5$$

Where N_{row}: number of rows.
The boundary conditions
H.T.F

$$\theta_f = 1.0 \qquad at\ Z = 0$$

PCM,

$$\frac{\partial \theta_p}{\partial R} = 0 \quad at\ R = 0 \quad \text{and} \quad K\frac{\partial \theta_p}{\partial R} = Nu(\theta_f - \theta_P) \quad at\ R = 0.5$$

Numerical Analysis

The governing equation of PCM Eq.4 is solved numerically and simultaneously with Eq.3 using finite difference method (Fig.2) with explicit method for time, central difference for second order derivative and forward difference for first order derivative as shown below;

$$\frac{\theta_p^{n+1} - \theta_p^n}{\Delta\tau} = \frac{K}{C\ \text{Pr}_f}\left(\frac{\theta_{p,j+1}^n + \theta_{p,j-1}^n - 2\theta_{p,j}^n}{\Delta R^2} + \frac{2}{R_i}\frac{\theta_{p,j-1}^n - \theta_{p,j}^n}{\Delta R}\right) \qquad (8)$$

Where

$$\Delta R = \frac{0.5}{Nj - 1} \qquad and \qquad \Delta\tau = \frac{\tau}{Nt}$$

Where Nj: number of nodes in the R-direction, Nt: number of time steps.

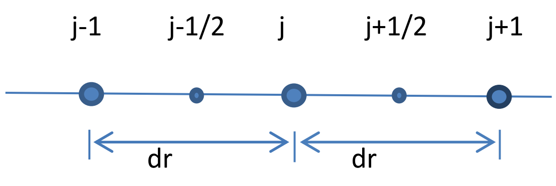

Fig.2 Nodal displacement in the r-direction of spherical capsule of PCM.

By rearrangement Eq.8 can be obtained,

$$\theta_{p,j}^{n+1} = a_j\, \theta_{p,j}^{n} + a_{j+1}\, \theta_{p,j+1}^{n} + a_{j-1}\, \theta_{p,j-1}^{n} \qquad (9)$$

where

$$a_j = 1 + \frac{K\,\Delta\tau}{C\,\Pr_f}\left(\frac{-2}{\Delta R^2} - \frac{2}{R_j\,\Delta R}\right), \quad a_{j+1} = \frac{K\,\Delta\tau}{C\,\Pr_f}\left(\frac{2}{\Delta R^2} + \frac{2}{R_j\,\Delta R}\right) \quad and \quad a_{j-1} = \frac{K\,\Delta\tau}{C\,\Pr_f}\left(\frac{1}{\Delta R^2}\right)$$

The first boundary condition (R=0) at j=2 gives

$$\theta_{p,2}^{n+1} = a_2\, \theta_{p,2}^{n} + a_3\, \theta_{p,3}^{n} \qquad (10)$$

Where

$$a_2 = 1 + \frac{K\,\Delta\tau}{C\,\Pr_f}\left(\frac{-1}{\Delta R^2} - \frac{2}{R_j\,\Delta R}\right) \quad and \quad a_3 = \frac{K\,\Delta\tau}{C\,\Pr_f}\left(\frac{1}{\Delta R^2} + \frac{2}{R_j\,\Delta R}\right)$$

and

$$\theta_{p,1}^{n+1} = a_i\, \theta_{p,2}^{n+1}$$

The second boundary condition (R=0.5) at j=Nj gives

$$\theta_{p,Nj}^{n} = \left[\theta_{p,Nj-1}^{n} + \frac{Nu\,\Delta R}{K}\,\theta_{f,i}^{n}\right] \Big/ \left(1 + Nu\,\Delta R / K\right) \qquad (11)$$

Where i the number of row

For heat transfer fluid it can be assumed that the storage energy at the small control volume is negligible; therefore Eq.6 becomes [15],

$$\frac{d\theta_f}{dZ} = \frac{-6(1-\varepsilon)\,Nu}{\mathrm{Re}\Pr_f}(\theta_f - \theta_p) = f(Z,\theta_f) \qquad (12)$$

This equation is ordinary differential equation O.D.E which can be solved using fourth order Runge-Kutta method [29]

$$\theta_{f,i+1} = \theta_{f,i} + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \qquad (13)$$

where

$$k_1 = dZ\ f(Z_i,\, \theta_{f,i})$$

$$k_2 = dZ\ f(Z_i + \frac{1}{2}dZ,\, \theta_{f,i} + \frac{1}{2}k_1)$$

$$k_3 = dZ\ f(Z_i + \frac{1}{2}dZ,\, \theta_{f,i} + \frac{1}{2}k_2)$$

$$k_4 = dZ\ f(Z_i + dZ,\, \theta_{f,i} + k_3)$$

To stability the solution, all coefficients in the Eq. 9 must be positive. Where a negative coefficient gives a high temperature at any point, or produces a lower subsequent temperature at that point. Therefore the numerical procedure becomes instability, which makes temperatures to oscillate, or physical behavior is unreasonable, therefore, a zero value of coefficients the minimum acceptable. The coefficient of $\theta_{p.j}^{n}$ must be equal to or greater than zero, therefore, $\Delta\tau$ can be determined as follow:-

To solve the equation (9) must be:

$$a_j = 1 + \frac{K\,\Delta\tau}{C\,\Pr_f}\left(\frac{-2}{\Delta R^2} - \frac{2}{R_j\,\Delta R}\right) \geq 0$$

and

$$\Delta\tau \le \frac{C\ \mathrm{Pr}_f}{K\left[\frac{2}{\Delta R^2}+\frac{2}{R_j\ \Delta R}\right]}$$

The equations (9, 10, 11 and 13) are solved instantaneously using FORTRAN program with following steps:

1- Input the dimensions of geometry.
2- Input the total time for process, Re, melting temperature of PCM, initial temperature of domain, inlet temperature of H.T.F.
3- Input the properties of H.T.F and PCM.
4- Calculate the steps of axial and radial direction.
5- Calculate the time step.
6- Calculate the temperature of H.T.F at axial position (Eq.13).
7- Calculate the temperature of PCM (Eqs. 9, 10 and 11).
8- Repeat the steps 6&7 until to reach the final length of packed bed at the certain time.
9- Add a time step to the old time and repeat the steps 6, 7 and 8.
10- Print the results.

The Results and Discussion

The present study is validated with experimental part of the work of Reddy et al. [20]. He used the water as H.T.F and sodium thiosulphate pentahydrate $Na_2S_2O_35H_2O$ as PCM in capsules which has three shapes: square, cylindrical and spherical. Those capsules were filled in the tank has capacity 10 Liter. The melting temperature of PCM is 48 °C and heat of fusion 210kJ/kg. The spherical packed bed is applied with sphere diameter 50mm. Fig.3 shows this comparison which gives a good agreement where the maximum error 8.5%, that makes this work is valid.

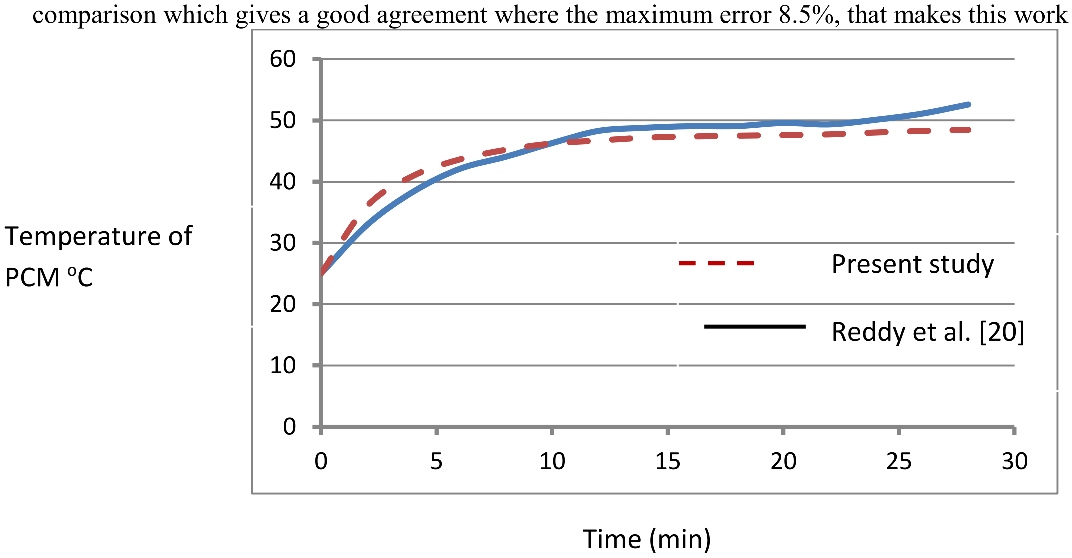

Fig.3 Comparison of present study and work of .in [20] at flow rate 4Liter/min.

The energy of heat transfer fluid (sensible energy) will be converted to a sensible energy and the bigger part to a latent energy for PCM, therefore it suitable to use the melting fraction of PCM as measurement to saving energy. The results of present study are presented as dimensionless temperature of PCM and melting fraction of PCM. The heat transfer fluid is water at 300K with Pr_f=5.83. The dimensionless temperatures of melting temperature of PCM, inlet temperature of H.T.F, initial temperature of all domains and $d\theta_m$ are: 0, 1, -0.2522 and 0.01789 respectively. The cells of packed bed are cubic with sphere at the center of cubic, where the length of cubic L is equal to the diameter of sphere D, therefore the porosity is constant and equal to 0.476. The PCM is paraffin wax with properties as shown in table1. The diameter of sphere is 10mm and the number of row is 50.

Table.1 Properties of paraffin wax (PCM) [5].

Melting temperature ºC	32 - 32.1
Heat of fusion H J/kg	251000
Specific heat capacity cp J/kg.K	3260 (liquid) 1920 (solid)
Thermal conductivity k W/m.K	0.224 (liquid) 0.514 (solid)
Density ρ kg/m3	830 (liquid) 830 (solid)

Fig.4 illustrates the variation of non-dimensional temperature θ_p with non-dimensional time τ at different radial local R of capsule sphere R=0.0667, 0.2334 and 0.4 where the non-dimensional axial location Z equal to 25. The dimensionless inlet temperature of H.T.F and initial temperature of all domains are: 1, -0.2522 respectively. It can be seen that the temperature is stayed constant at the period of phase change (latent heat change) where θ_p near the zero, also at region near the center of sphere R=0.0667 the process of phase change is longer (more time), than the region near the outer surface of sphere R=0.4, due to transfer the heat from outer surface to the center gradually by the conduction.

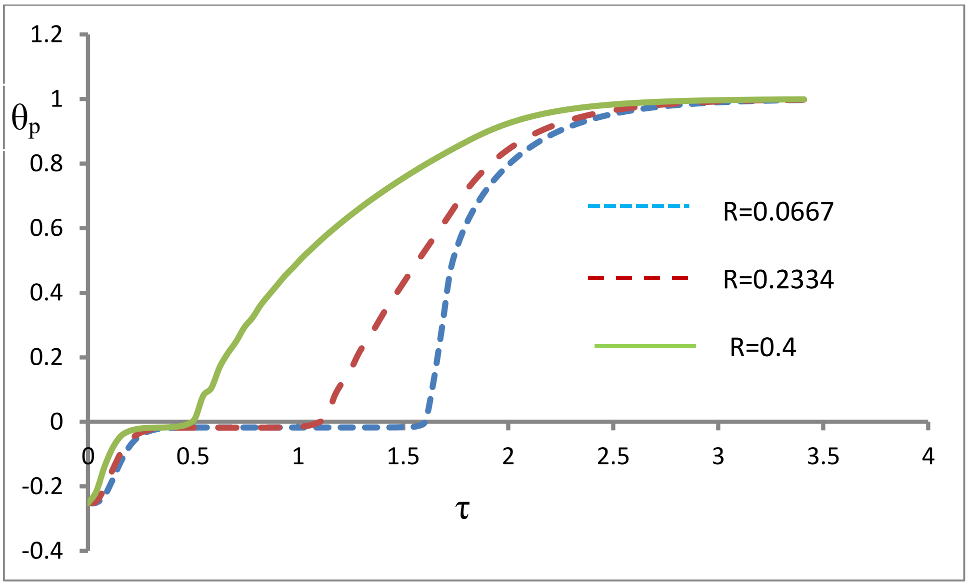

Fig.4 Plot of non-dimensional temperature of PCM θ_p with non-dimensional time τ at Re=1000 and different R.

The variation of melting fraction MF {the ratio of liquid PCM to total PCM (liquid + solid)} with non-dimensional time τ at different non-dimensional axial distance Z of rows, Z=5, 25 and 50 is shown in Fig.5. The figure indicates that the melting process (latent heat) for the rows that are nearest to the entrance of H.T.F such as Z=5 is faster than the rows that far away from the entry (Z=50). Where the energy is converted to sensible heat after the completion of phase change process from solid to liquid as shown in Fig.4.

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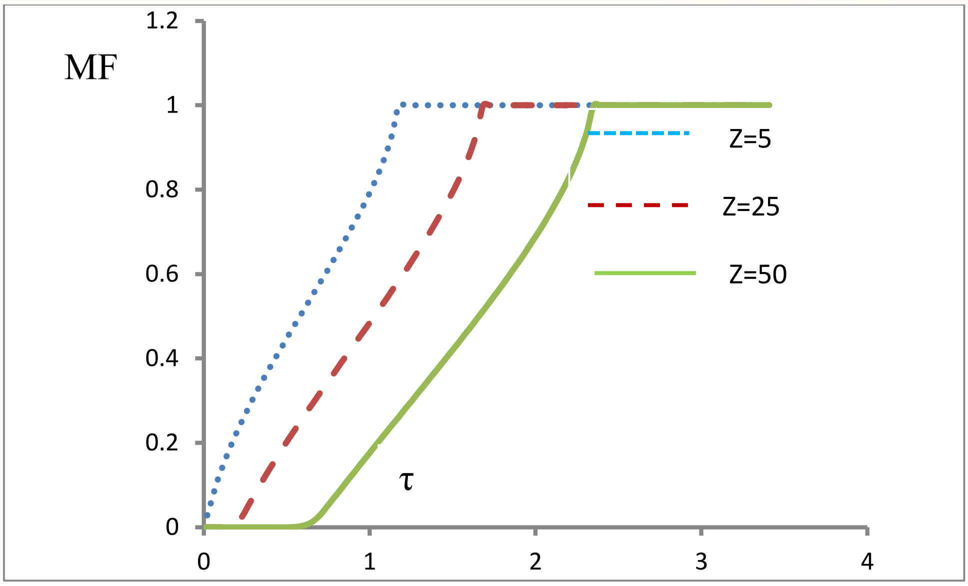

Fig.5 The variation of melting fraction MF with non-dimensional time τ at Re=1000 and different rows.

Fig.6 indicates the variation of melting fraction MF with non-dimensional time τ at different Reynolds number, Re=500, 1000 and 2000 and Z=25. The effect of Reynolds number is very clear where the process of melting increases with increasing Reynolds number due to increase the convection heat transfer on the outer surface of spheres (Eq.7). Also, effect of the increasing of the Re after certain limit such as Re=1000 to 2000 becomes smaller, because limitation thermal resistance of conduction inside sphere compare to convection in the outer of sphere.

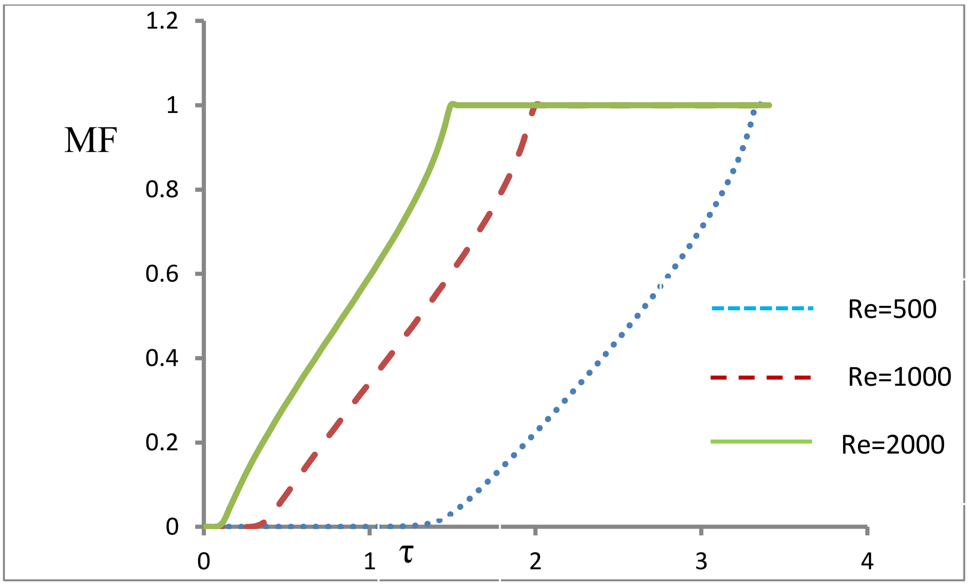

Fig.6 The variation of melting fraction MF with non-dimensional time τ at different Reynolds number and Z=25.

From the definition of non-dimensional time $\tau = \dfrac{t\ \mu_f}{\rho_f\ D^2}$, the variation of sphere diameter leads to variation of non-dimensional time, therefore it can be use the real time t (sec) to present the effect of sphere diameter on melting fraction with time. Fig.7 shows the variation of melting fraction MF with real time t at different diameter of sphere D, D=10, 15.625, 25 and 50mm and at constant axial distance (mid of axial distance Z) and the porosity of packed bed (ε=0.476). This figure shows that the increasing of diameter of sphere leads to increase the time for melting because increasing the thermal resistance of conduction with increasing the diameter of sphere.

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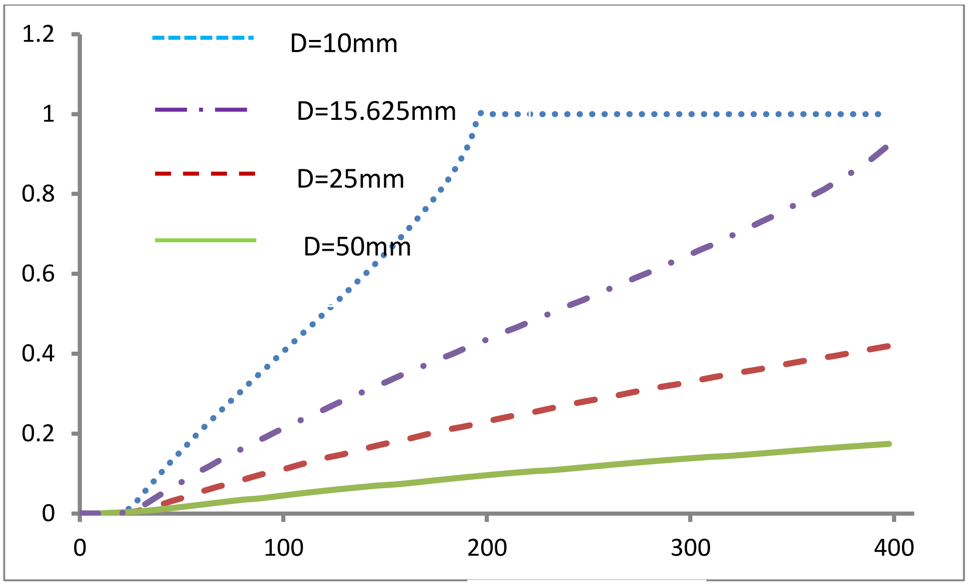
MF



Real time (t) sec

Fig.7 The variation of melting fraction MF with real time at Re=1000 and different diameter of sphere D.

Conclusions

The converted sensible energy of H.T.F to the packed bed which consists from spherical capsules of phase change material PCM is studied numerically by solving the energy balance equation of H.T.F applying the fourth order Runge-Kutta method and the energy equation of PCM using finite difference method. The parameters that affect melting process are investigated such as Reynolds number and diameter of sphere. The main conclusions are: the increasing of Reynolds number fasting the melting process, also the increasing of sphere diameter makes the melting process slow and have more time to complete the melting process, where at D=50mm & t=196.5sec the melting fraction of PCM is 0.09, while at D=10mm & t=196.5sec the melting fraction of PCM is 1.00; therefore it can be recommended to use smallest diameter of spherical capsules in the design of packed bed at constant porosity of packed bed.

Nomenclature

c specific heat J/kgK
D diameter of sphere m
h heat transfer coefficient W/m^2K
H heat diffusion of PCM J/kg
k thermal conductivity W/mK
L length of cubic cell m
r radial coordinate of sphere m
t time sec
T temperature $^{\circ}C$
w velocity in z-direction m/s
z axial coordinate in the direction of flow m

Greek symbols

α thermal diffusivity m^2/s
μ viscosity $kg/m\ s$
ρ density kg/m^3

Subscripts

f fluid
i initial, local in the z-direction
in inlet
l liquid state of PCM

m melting
p phase change material
ps solid state of PCM
pl liquid state of PCM
s solid
z z-direction

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