International Journal of Scientific & Engineering Research Volume 8, Issue 7, July-2017
ISSN 2229-5518

" Parametric effect on Stratification Coefficient of PCM-Packed Bed Latent Heat Storage System"

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Abstract

A latent heat storage system comprising of Phase Change Material (PCM) encapsulated in spherical capsules and stacked in a cylindrical vessel to form a packed bed. In the case of latent heat storage, the value of average stratification coefficient during charging process depends upon the important system and operating parameters. The system parameters that have been varied in this study include thermal conductivity of PCM (k_{pcm}), thermal conductivity of the capsule envelope (k_{env}) and diameter of the capsule (D_c) concerns the individual capsule performance while the void fraction of the bed (**ε**) concerns the bed performance. Operating parameters like mass flow rate, thermo physical properties of the Heat Transfer Fluid (HTF), inlet temperature of the bed and ambient temperature have not been varied in this study. Temperature profiles of the bed and air were determined and these values were utilized to calculate the value of average stratification coefficient of the system for charging as function of these parameters.

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Keywords

Diameter of capsule; phase change material; thermal conductivity of PCM material; thermal conductivity of capsule material; Void fraction.

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1. Introduction

Several analytical and experimental studies [Keumnam Cho and S.H. Choi [2]] have been undertaken by various investigators to understand the phenomenon of phase change in energy storage systems. The temperature of the PCM rises from the temperature few degrees below the phase change (or melting) temperature till the melting temperature; major portion of the energy is stored at this temperature and subsequently the temperature rises a few degrees above this temperature.

This happens in each individual PCM element or capsule in the case of encapsulated PCM systems. The temperature time history therefore dictates the amount and rate of temperature rise in each individual capsule.

Some of the studies analyze solidification and melting in various geometries. Typically, experimental investigations into single capsule dynamics involve a capsule suspended in a fluid, exposed to a working heat transfer fluid [K.A.R. Ismail et al. [3]].

[A. Felix Regin et al. [13]] have presented details of the following equations describing a packed bed are often referred to as Schumann model.

A series of experiments were carried out by [J.P. Bedecarrats et al. [14]] to investigate the effects of various parameters on the performance of encapsulated phase change energy storage during the charging and the discharging processes. They used spherical capsules containing water with nucleation agent as a phase change material (PCM) filled the thermal storage tank.

2. *Packed bed latent heat storage system*

In solar air heating systems the low density of air makes it impractical to store the heated air itself. It is therefore necessary to transfer the thermal energy from air to a denser medium. During charging mode, solar heated air is forced into the top of the container i.e. upper plenum and it then passes evenly down through the bed heating the storage and passes out through the lower plenum. Air is drawn off at the bottom and returned to the collectors. When energy is needed from storage, the airflow is reversed. Room air enters from bottom and flows to the top of the bed and is delivered into the building. After losing heat in the room again, room air comes to the bottom of the bed and the cycle is repeated.

2.1 *Fixed and Variable Parameters*

In order to investigate the temperature of the storage system for a given set of system and operating parameters, it is necessary to fix the appropriate Values or range of values of the relevant parameters for the storage system, these parameters can be categorized into fixed and variable parameters.

Table 1 Fixed Parameters of the system

Description	Parameter	Value
Height of the tank(m)	H_t	1.42
Diameter of the tank(m)	D_t	0.95
Inlet hot fluid temperature (^oC)	T_{fin}	56
Density of hot fluid(kg/m^3)	ρ_f	1.05
Density of PCM (kg/m^3)	ρ_{pcm}	912
Specific heat of the hot fluid(J/kg-K)	C_{pf}	1005
Specific heat of the PCM (J/kg-K)	C_{Ppcm}	2981
Time interval (hr.)	dt	0.02
Mass flow rate (kg/hr.)	m_f	800
Initial temperature of PCM (^oC)	T_{pcm}	40
Melting temperature of PCM (^oC)	T_m	48
Latent heat of fusion(J/kg)	L_f	147000
Ambient temperature (^oC)	T_{amb}	40

Table 3.2 Variable Parameters of the system

Description	Parameter	Range
Void fraction	ϵ	0.4-0.6
Diameter of the capsule (m)	D_c	0.05-0.15
Thermal conductivity of PCM (W/mK)	k_{env}	0.15-2.5
Thermal conductivity of capsule wall (W/mK)	k_{pcm}	0.5-0.9

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3. *System Model*

In the modeling, a well defined model of a cylindrical tank having spherical balls encapsulated with phase change material are arranged in a proper sequence i.e. a packed bed system is made. The size of the bed is fixed on the assumption that the bed absorbs maximum amount of energy delivered by the flowing air during charging process. The packing is such that the PCM balls are arranged in layers each having same number of balls, the number being determined on the basis of void fraction to be obtained.

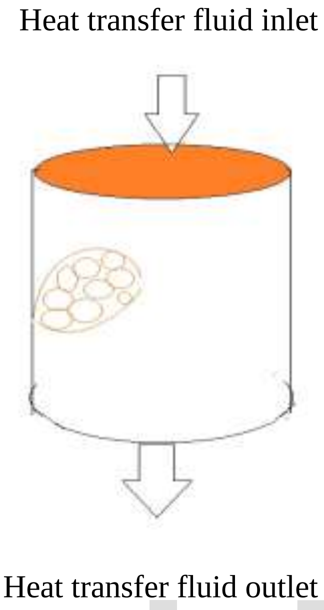

Fig 1 System model

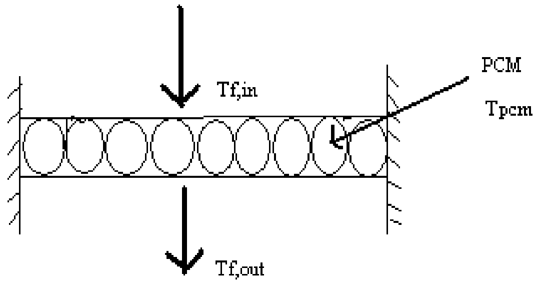

Fig.2 Energy balance over layer of spherical capsules in the tank

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The container has two passages one being bottom passage while the other is the top passage. Heat transfer fluid (HTF) air flows from top to bottom of the bed and heat transfer takes place from fluid to the PCM, consequently the temperature of the PCM rises and reaches its melting point and the process of melting takes place. Circulation of heat transfer fluid is maintained using a pump. The rate of heat transfer to or from the solid in a packed bed is a function of the physical properties of the air and capsule, the local temperature of the air and surface of the capsule, the mass flow rate of air, and the characteristics of the packed bed.

In the present study attempt has been made to determine the optimum value of parameters for the design and operation of a thermal energy storage system. The values of different system variables namely thermal conductivity of PCM and capsule envelope, the void fraction of bed and the diameter of ball have been optimized. Optimization process seeks to determine a set of values of the system parameters that yield the highest degree of stratification under given set of operating parameters and other system parameters.

The tank has been divided into equal layers, each layer has a number of capsules which is an integer and each layer has a height equal the diameter of a single capsule. Each layer has T_{fin} and T_{fout}, as the inlet and outlet temperature and the latter will be the inlet temperature of the next layer and so on for the whole tank, as shown in **Fig.2.**

The heat transfer fluid migrates from one layer to the next and transfers heat to the capsules.

To evaluate the PCM temperature histories during sensible heating of the PCM, it is assumed that the temperature of the PCM is homogenous, and the internal energy variation in the PCM is equal to the heat transfer with the capsule.

Now, the number of layers (N) in the system can be calculated from the total bed height H_t and capsule Diameter D_c as:

$$N = \frac{H_t}{D_c}$$

If in case the number of layers turns out to be in fraction, an approximate value lower than the actual value is used. The volume of the cylinder (V) is calculated as:

$$V = \left(\frac{\pi \times (D_t^2) \times H_t}{4} \right)$$

Where D_t is the diameter of the tank.

Void fraction is the vacant space occupied by the HTF (air) within the cylinder. Now for one value of the void fraction (ε), one can calculate the volume occupied by the capsules. Using the number of layers (N), the volume occupied by one layer can be determined. This can yield the number of capsules (n) in a layer.

The value of fluid temperature at inlet is fixed. The amount of energy transferred can be calculated using the relation:

$$Q(t) = \left[\frac{T_{fin} - T_{pcm}}{R_f + R_{env}} \right]$$

Where,

$$R_f = \frac{1}{hS_c}$$

Where

S_c= Surface area of the capsule

$$S_c = 4 \pi r_e^2$$

$$h = \frac{hv * Dc}{6 * (1 - \varepsilon) * \alpha}$$

$$hv = 650 \left(\frac{G}{Dc} \right)^{0.7}$$

$$G = \left(\frac{m_f}{A} \right)$$

$$R_{env} = \frac{(1)}{4\pi k_{env}} \left[\frac{1}{r_i} - \frac{1}{r_e} \right]$$

$r_i = r_e - 0.002$, where 0.002m is the wall thickness and is taken to be constant.

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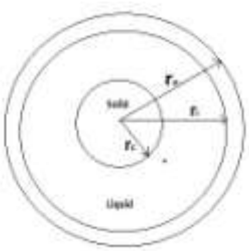

Fig 3. Energy balance over a spherical capsule

where

r_e= outer most radius

r_i= inner capsule wall radius

$r_{c=}$ radius of solid left

From energy balance across the capsule layer

$$m_f \times C_{pf}\,(T_{fin} - T_{fout}) = n\,Q\,(t)$$

$$T_{fout} = T_{fin} - \left[\frac{n.Q(t)}{m_f.c_{pf}}\right]$$

The inlet fluid temperature for the top most layers is fixed value while the subsequent layers, the calculation are made layer by layer.

The temperature history of PCM and HTF along the axial position of the tank have been calculated by taking energy balance on each layer and depending on the process either it is sensible solid heating process or liquefaction process.

For sensible heating, the rate of change of PCM temperature (dT_{pcm}/dt) is obtained for each capsule as:

$$\rho_{pcm} \times C_{Ppcm} \times V_{pcm} \times \left(\frac{dT_{pcm}}{dt}\right) = Q\,(t)$$

$$T_{pcm,new} = T_{pcm,old} + \left[\frac{Q\,(t) \times dt}{\rho_{pcm} \times C_{Ppcm} \times V_{pcm}}\right]$$

Where,

$$V_{pcm} = \left(\frac{4 \times \pi \times r_i^{\;3}}{3}\right)$$

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V_{pcm} is the volume of PCM inside a single capsule (m^3) from the above relation, and dt is the time interval.

$T_{pcm,\,old}$ is the initial temperature of PCM for each time step, the value for first time step is the initial value.

$T_{pcm,\,new}$ is the temperature of PCM at the end of each time step.

As the temperature of the capsule reaches the melting point of the phase change material latent heating starts and in this case heat exchanged by the spherical capsule is calculated with the help of the relation given below:

$$Q(t) = \left[\frac{T_{fin} - T_{pcm}}{R_f + R_{env} + R_C}\right]$$

$$R_c = \frac{1}{4\pi k_{env}}\left[\frac{1}{r_c} - \frac{1}{r_i}\right]$$

The mass of the material which undergoes the phase change process during time step can be calculated by the formula

$$Q = m \times L_f$$

Let the total mass of PCM material be M and the amount of mass melted be m (because the phase change), then the quantity of solid mass will be given by M-m.

Volume of the solid mass left is given by

$$V_1 = \left(\frac{\text{M - m}}{\rho_{\text{pcms}}} \right)$$

The new value of radius r_{c1} is therefore obtained from:

$$V_{pcm} = \left(\frac{4 \times \pi \times r_{c1}{}^3}{3} \right)$$

Once the value of r_{c1} is calculated, its value will be the r_c for the next iteration.

This process is repeated till r_c equals to zero.

At this point of time, the system starts heating up again and it follows the same system as equations, discussed above for sensible heating. The calculations proceeds till the end of the charging period.

3.1 Stratification Coefficient

Wu and Bannnerot (1987) defined an index for degree of stratification called stratification coefficient based on a mean square deviation of temperatures in the storage from the mean storage temperature

$$ST_{WU} = \frac{1}{m_{store}} \sum\nolimits_n m_n \left[T_{bn} - T_{avg} \right]^2$$

4. *Result and discussion*

The results of mathematical simulation of the system have been discussed in the system. The effect of system parameters, namely, capsule size, void fraction of capsule bed and thermal conductivities of PCM and the capsule material on the performance parameter has been investigated. Temperature profiles of the bed and air were determined and these values were utilized to calculate the value of average stratification coefficient of the system for charging as function of these parameters.

4.1 Temperature distribution in bed

Fig 4 shows that the entire bed has an initial temperature (at t=0 hr) of 40^{o}C, all capsules being at this initial temperature. It is found that for the high thermal conductivity of capsule material the transfer of heat from hot HTF to the capsule will be faster that result in quick rise of temperature; more than half of the capsules have attained a melting point temperature of 48^{o}C just in short time interval of 0.50 hour while at the end of 1.0 hour, the temperature of all the capsules in the bed are at the same temperature because most of the heat transfer goes into the phase change (melting) process and does not result in temperature rise. This is due to the fact for low value of thermal conductivity of PCM the heat transfer between the PCM shells will be much lower. Also for the low value of void fraction the flow of HTF will be slowly acting in downward direction due to which the top layers will be heated much faster than the lower layer. Therefore as indicated in the Fig that at the end of 5 hour, a fraction of PCM mass of the top layers has been already melted and its temperature begins to rise beyond melting temperature. At the end of 8hour, almost the entire bed has attained the maximum temperature of 56^{o}C which is the inlet temperature of hot HTF.

Mathematical simulation has been used to yield the average temperature of each element of storage system considered, during charging at a given instant of time. It is found that the higher void fraction results in low value of heat transfer coefficient due to low average velocity of air through the voids for given mass flow rate. As the value of void fraction increases, the HTF will flow slowly in

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downward direction due to which the temperature of the bottom layers increases much faster as compared to low value of void fraction which is indicated in Fig 5.

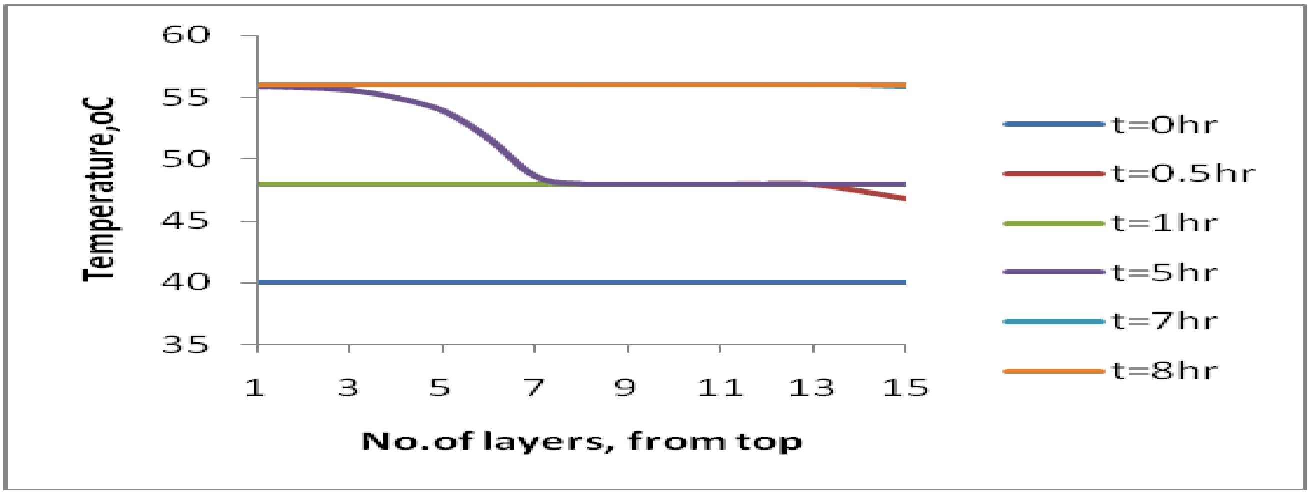

Fig 4. Temperature of PCM along the height of the tank as function of time for ε=0.4, kpcm=0.5 W/m-K, kenv=2.5 W/m-K, dc=0.09m

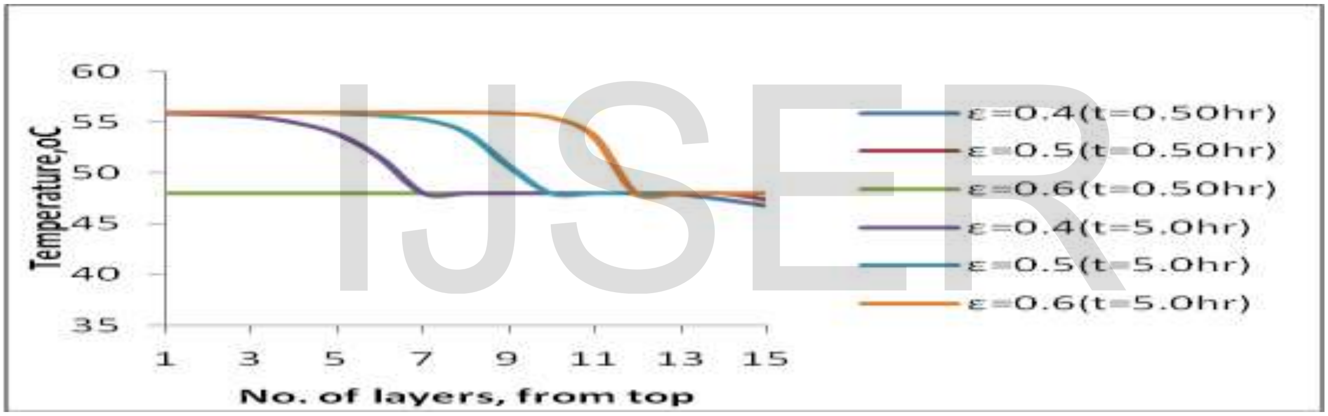

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Fig.5 Temperature of PCM along the height of the tank as function of time for kpcm=0.5 W/m-K, kenv=2.5 W/m-K, dc=0.09m

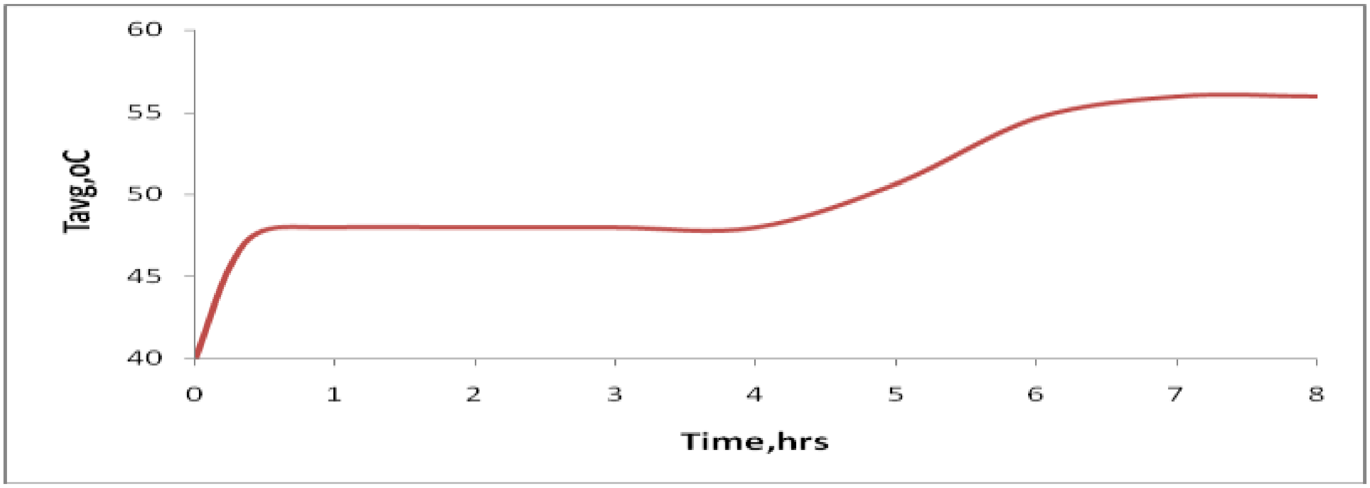

Fig. 6 Variation of average temperature of PCM with time for ε=0.4, kpcm=0.5 W/m-K, kenv=2.5 W/m-K, dc=0.09m

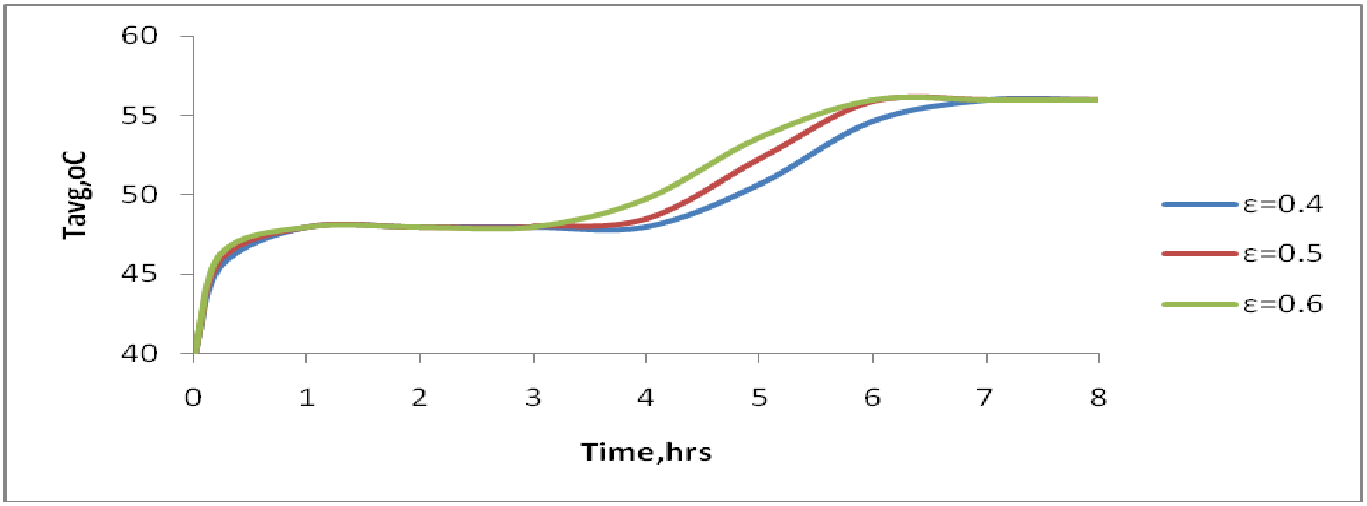

Fig.7 Variation of average temperature of PCM with time for kpcm=0.5 W/m-K, kenv=2.5 W/m-K, dc=0.09m

Fig 6 shows the variation of average temperature of bed as a function of time instant. It can be seen that the entire bed has an initial temperature (at t=0 hr) of 40°C, all capsules being at this initial temperature. It is found that for the high thermal conductivity of capsule material the transfer of heat from hot HTF to the capsule will be faster that result in quick rise of temperature As the time is increased the profile of average temperature rises and remains constant to 48°C up to t=4 hour. Also for the low value of void fraction the flow of HTF will be slowly acting in downward direction due to which the top layers will be heated much faster than the lower layer. Therefore at the end of t=4 hr the profile of average temperature again rises and reaches to the maximum value of 56°C and remain constant at the end of 8 hour.

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Initially the effect of void fraction is very low, as the time is increased corresponding to the increase in void fraction the temperature profile will rise which is indicated in Fig 7. It can be seen that the entire bed has an initial temperature (at t=0 hr) of 40°C, all capsules being at this initial temperature. As the time is increased the profile of average temperature rises and remains constant at 48°C up to t=3 hour. Also for the high value of void fraction the flow of HTF will be slowly acting in downward direction due to which the bottom layers will be get heated much faster than the lower value of void fraction. Therefore at the end of t=4 hr the profile of average temperature again rises and reaches to the maximum value of 56°C and remain constant at the end of 8 hour for all values of void fraction.

4.2 Stratification coefficient

Fig 8 shows the variation of stratification coefficient of bed as a function of time instant. It can be seen that the stratification coefficient first increases and then falls down to nearby zero at about t=0.5 hours. The stratification coefficient increases because of a larger variation in temperature caused by faster increase in the sensible heating temperature. Once the process of phase change starts, the temperature of the entire bed becomes nearby the same bringing down the stratification coefficient to nearby zero value; the stratification coefficient sees another fast increase when the sensible heating starts again.

The profile of stratification coefficient is depending upon the PCM temperature profile and average PCM temperature profile. For higher void fraction value of ε=0.6, the plot of stratification coefficient begin to rise faster because of high heat transfer coefficient as compared to lower void fraction, the higher void fraction plot yielding higher value. The lower void fraction plot showing late rise and falling to zero value later as compared to that for a lower void fraction plot indicated in Fig. 9.

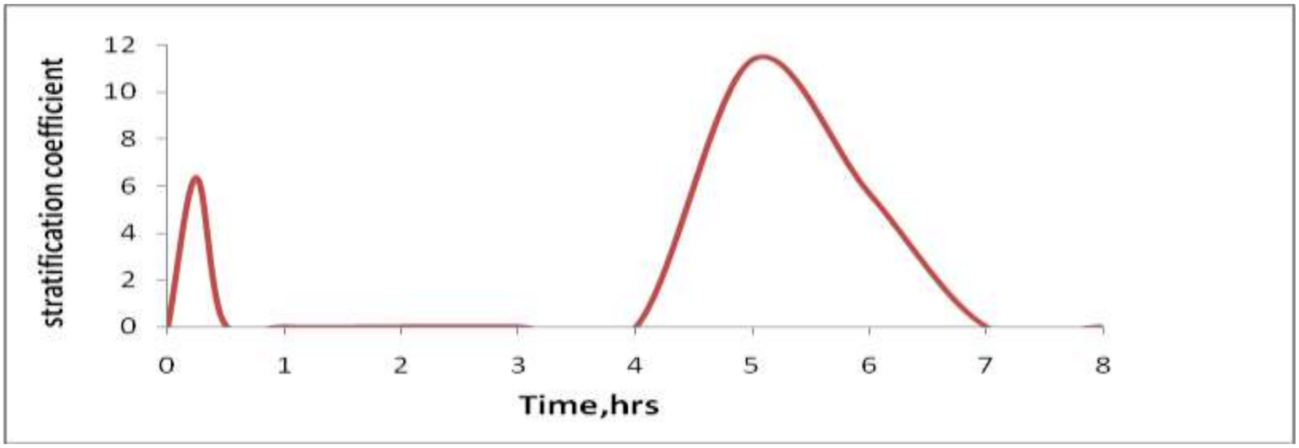

Fig.8 Variation of stratification coefficient value with time for ε=0.4, kpcm=0.5W/m-K, kenv=2.5 W/m-K, dc=0.09m

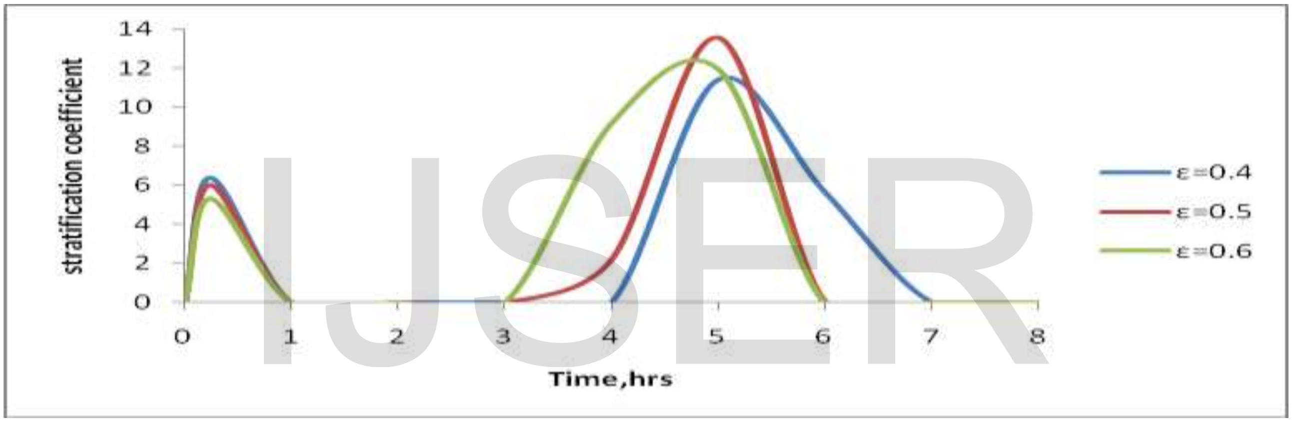

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Fig. 9 Variation of stratification coefficient value with time for kpcm=0.5W/m-K, kenv=2.5 W/m-K, dc=0.09m

Fig10 shows that the variation of void fraction brings about a slight increase in the stratification value. As the void fraction increases, the temperature gradient increases which results in high stratification value. The maximum value and large variation of stratification is achieved for maximum values of diameter.

Fig11 shows that the variation of thermal conductivity of PCM brings about a slight increase in the stratification value. This happens for all values of diameters of the capsule, although higher diameters yield relatively large variation in stratification coefficient value as compared to that for lower values of diameter. A higher value of diameter of the capsule can be seen to result in higher heat transfer coefficient on the outside of the capsule i.e. between HTF and outer surface of the capsule wall. But as the value of capsule diameter increases the number of capsule layers in the system will be small which results in low temperature gradient in the system.

Fig12 shows that the variation of thermal conductivity of capsule material brings about a slight variation in the stratification value with small diameter. Higher diameters yield relatively higher variation in stratification value as compared to that for lower values of diameter. A higher value of diameter of the capsule can be seen to result in higher heat transfer coefficient on the outside of the capsule i.e. between HTF and outer surface of the capsule wall.

Fig13 shows the variation of average stratification coefficient as a function of size of capsule for different sets of values of other parameters. It can be seen that for all values of thermal conductivity of the envelope, the value of average stratification coefficient first increases and then decreases with an increase of diameter of the capsule. It is found that for the set of high value of thermal conductivity of PCM and void fraction the increment of average stratification coefficient increases and gives the maximum value.

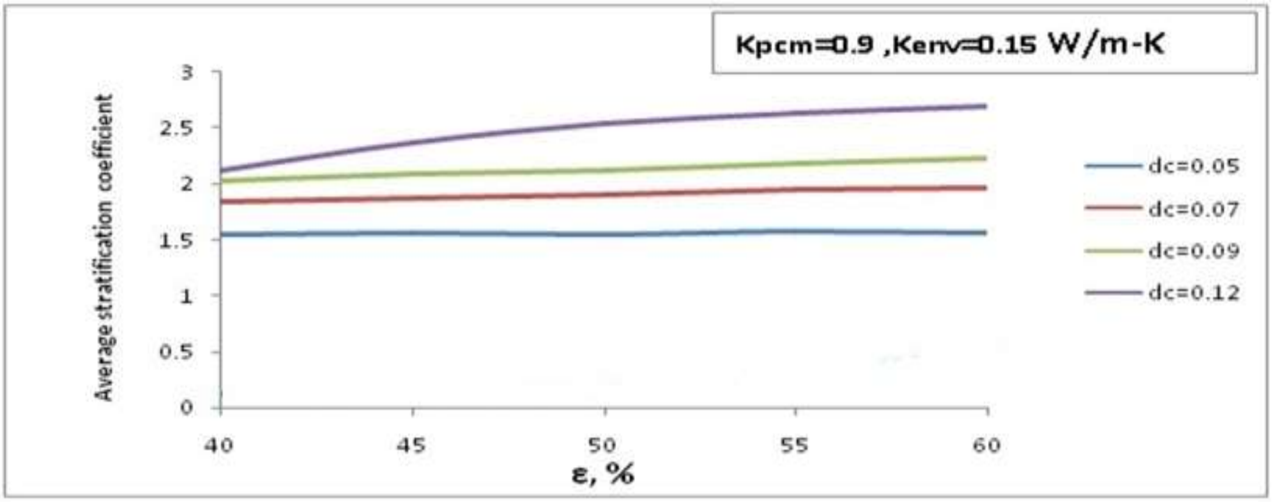

Fig.10 Variation of Average stratification coefficient with void fraction for kpcm=0.9 and kenv=0.15

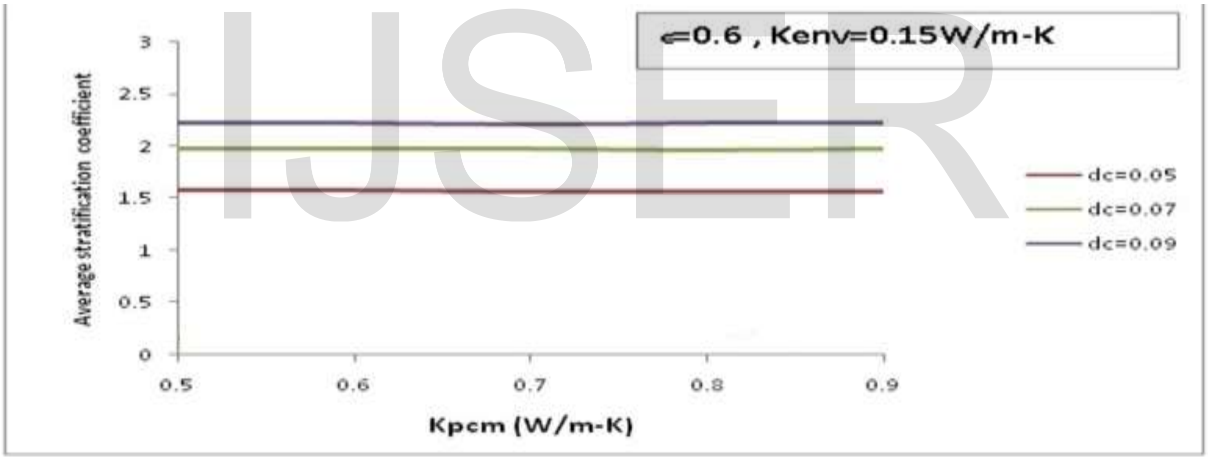

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Fig.11 Variation of Average stratification coefficient with Thermal Conductivity of PCM for ε=0.6 and kenv=0.15 W/m-K

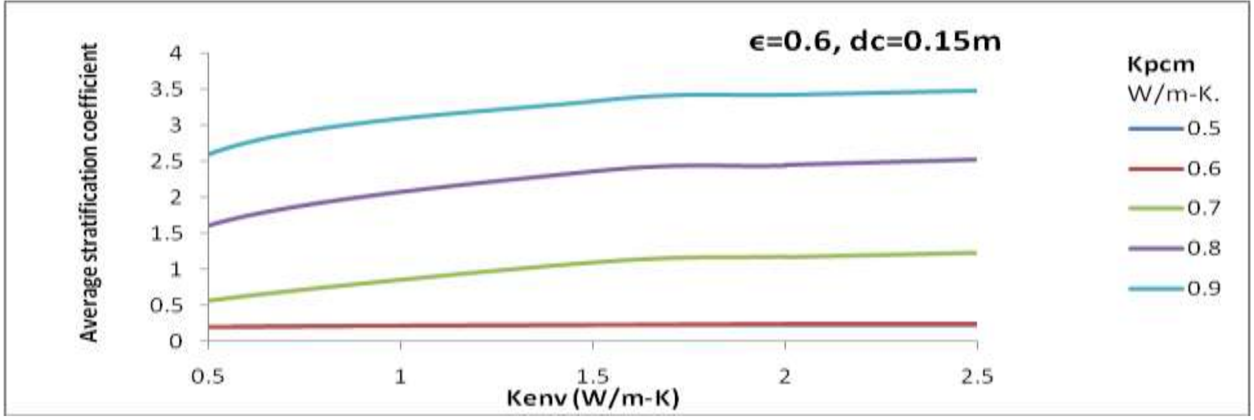

Fig. 12. Variation of Average stratification coefficient with Thermal Conductivity of Capsule for ε=0.6 and dc=0.15

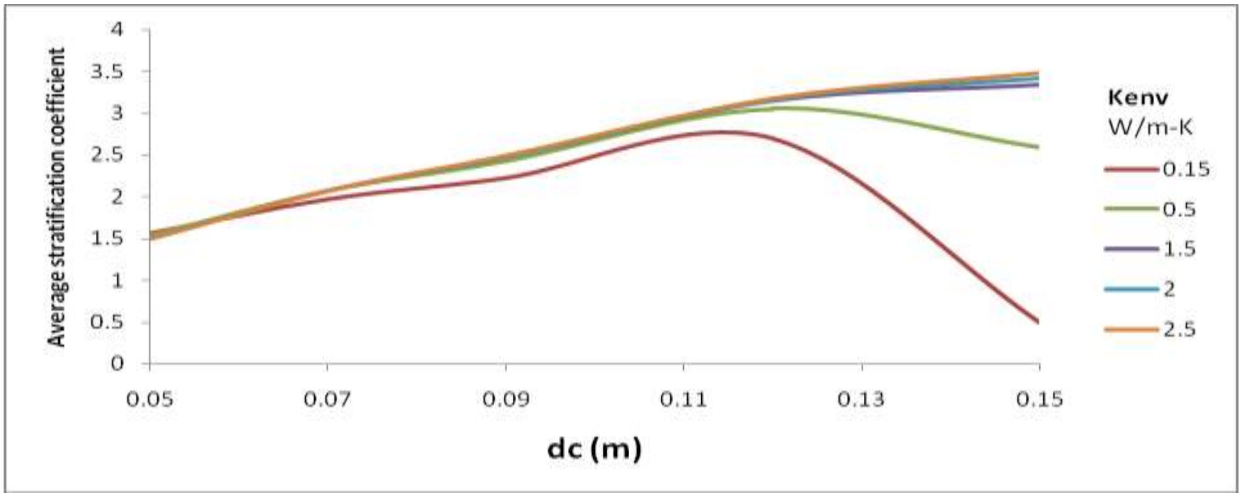

Fig. 13. **Variation of Average stratification coefficient with size of Capsule for ε=0.6, kpcm=0.9**

<u>Table</u> Avg ST_{wu}, Kpcm 0.5-0.9

K_{env} (W/m-K)	ϵ	Diameter(D_c),(m)			
		0.05	0.07	0.09	0.15
0.15	0.4	0.01	0.01	0.01	0
0.15	0.6	0.03	0.01	0.01	0.35
2.50	0.4	0.01	0.01	0	1.21
2.50	0.6	0.03	0.01	0.01	1.25

Conclusion

A latent heat storage system comprising of encapsulated PCM (wax) stacked in a cylindrical tank has been studied with respect to the parametric effects on its performance. Based on the thermal analysis, optimum values of system parameters, namely, capsule size, void fraction of capsule bed and thermal conductivities of PCM and the capsule material have been discussed. Out of the system parameters, namely, capsule diameter, void fraction and thermal conductivies of PCM and envelope; capsule diameter has the maximum effect in the range of parameters studied. The maximum changes as a result of parametric changes in the entire range has been found in descending order of capsule diameter, thermal conductivity of envelope, thermal conductivity of PCM and void fraction changes. Based on the analysis the optimum values of system parameters are ε=0.6, k_{pcm}=0.9 W/m-K, k_{env}=2.5 W/m-K, dc=0.15m.

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