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Parametric Effect on Bed Temperature 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. 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 (Dc) 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 were determined for charging process as function of these parameters.**

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

1. INTRODUCTION

Several analytical and experimental studies [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 [3].

[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 [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 2.1 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 2.2 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

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.

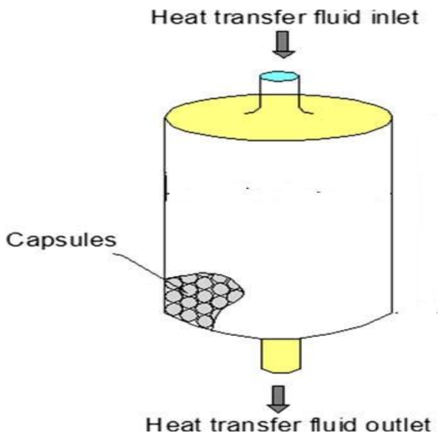

Fig 1 System model

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.

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.

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

$$Q(t) = \left[\frac{T_{fin} - T_{pcm}}{R_f + R_{env}} \right] \quad (1)$$

Where,

$$R_f = \frac{1}{hS_c} \quad (2)$$

Where

S_c= Surface area of the capsule

S_c= 4 π r_e^2 (3)

$$h = \frac{hv * Dc}{6 * (1 - \varepsilon) * \alpha} \quad (4)$$

$$hv = 650 \left(\frac{G}{Dc} \right)^{0.7} \quad (5)$$

$$G = \left(\frac{m_f}{A} \right) \quad (6)$$

$$R_{env} = \frac{1}{4\pi k_{env}} \left[\frac{1}{r_i} - \frac{1}{r_e} \right] \quad (7)$$

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

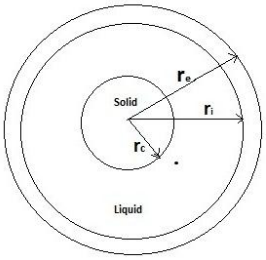

Fig 2. Energy balance over a spherical capsule

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

$$m_f \times C_{pf}\ (T_{fin} - T_{fout}) = n\,Q\,(t) \tag{8}$$

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:

$$\rho_{pcm} \times C_{Ppcm} \times V_{pcm} \times \left(\frac{dT_{pcm}}{dt}\right) = Q\,(t) \tag{9}$$

Where,

$$V_{pcm} = \left(\frac{4 \times \pi \times r_i^3}{3}\right) \tag{10}$$

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:

$$Q(t) = \left[\frac{T_{fin} - T_{pcm}}{R_f + R_{env} + R_C}\right] \tag{11}$$

$$R_c = \frac{1}{4\pi k_{env}}\left[\frac{1}{r_c} - \frac{1}{r_i}\right] \tag{12}$$

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

$$Q = m \times L_f \tag{13}$$

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

$$V_1 = \left(\frac{M - m}{\rho_{pcms}}\right) \tag{14}$$

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

$$V_{pcm} = \left(\frac{4 \times \pi \times r_{c1}^3}{3}\right) \tag{15}$$

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.

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. The temperature distribution in the bed is the most important aspect.

Temperature distribution in bed

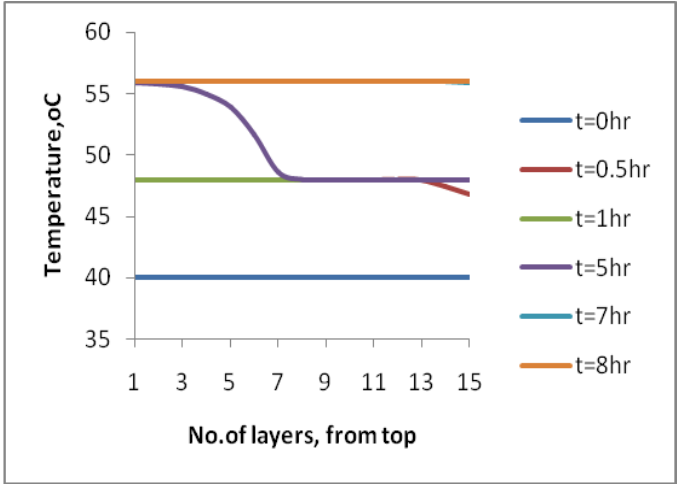

Fig 3. Temperature of PCM along the height of the tank as function of time for ε=0.4, kpcm=0.5 W/m-K, kenv=2.5 W/m-K, dc=0.09m

Effect of void fraction

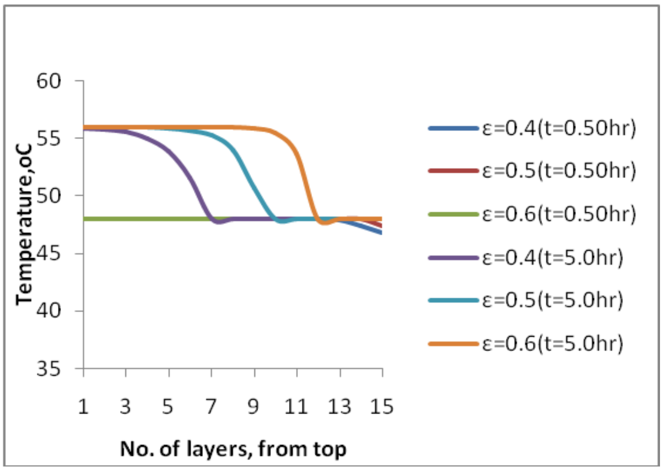

Fig.4 Temperature of PCM along the height of the tank as function of time for Kpcm=0.5 W/m-K, kenv=2.5 W/m-K, dc=0.09m

Effect of thermal conductivity of capsule material

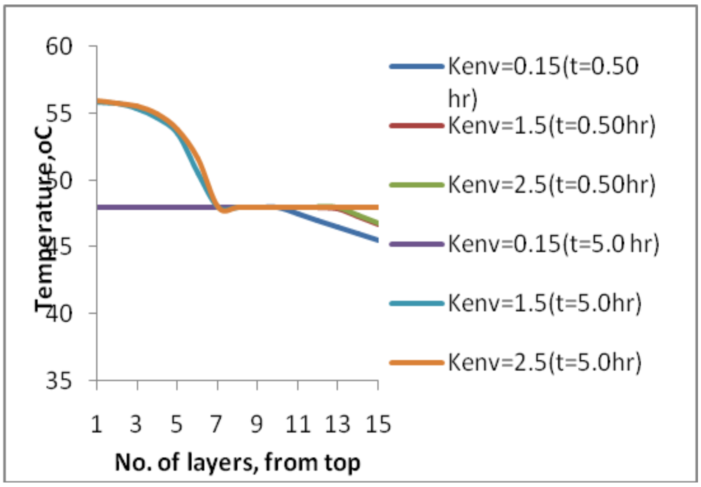

Fig.5 Temperature of PCM along the height of the tank as function of time for ε=0.4, kpcm=0.5 W/m-K, dc=0.09m

Effect of thermal conductivity of PCM

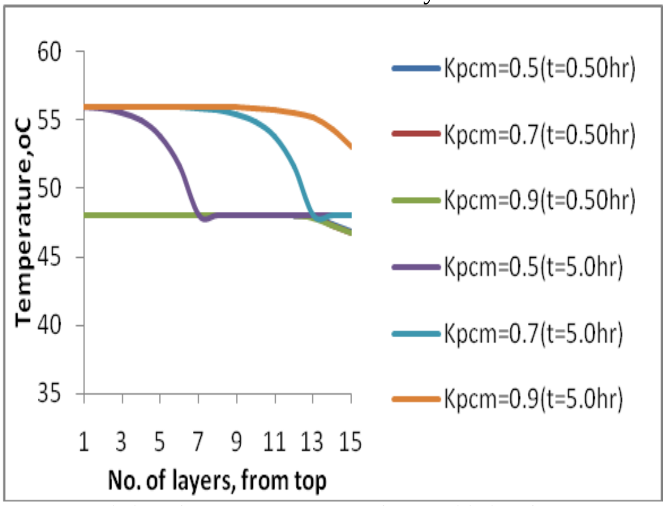

Fig.6Variation of average temperature of PCM with time for ε=0.4, kenv=2.5 W/m-K, dc=0.09m

Effect of Diameter of capsule

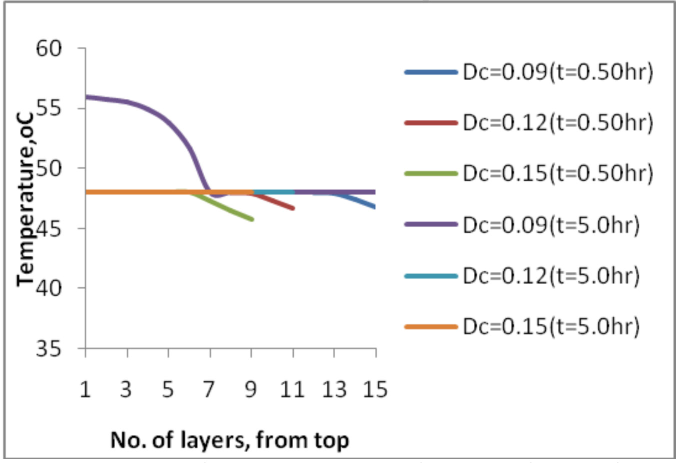

Fig.7 Temperature of PCM along the height of the tank as function of ε=0.4, kpcm=0.5 W/m-K, kenv=2.5 W/m-K,

Out of the system parameters, namely, capsule diameter, void fraction and thermal conduct ivies 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

5. 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.

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