International Journal of Multidisciplinary Research and Development
Online ISSN: 2349-4182, Print ISSN: 2349-5979, Impact Factor: RJIF 5.72
www.allsubjectjournal.com
Volume 4; Issue 8; August 2017; Page No. 99-106

Identification and analysis of thermal energy storage system with phase change materials and applications

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Abstract

Capital investment reduction, exergetic efficiency improvement and material compatibility issues have been identified as the primary techno-economic challenges. Thermal energy storage (TES) techniques is a good alternative to reduce the cost of solar-generated electricity, namely (1) sensible heat storage, (2) latent heat (tank filled with phase change materials (PCMs) or encapsulated PCMs packed in a vessel) and (3) thermo-chemical storage. Among these the PCM macro-encapsulation approach is one of the most-promising methods because of its high energy density and reduce the cost associated with the tank and increase the exergetic efficiency. There is a technological barriers to this approach to create a durable capsule, as well as an assessment of the fundamental thermal energy transport mechanisms during the phase change. This report includes heat transfer and induced fluid flow during melting and solidification of a confined storage. Emphasis has been placed on the thermal characterization of a single constituent storage module rather than an entire storage system.

Keywords: phase change material (PCM), thermal energy storage (TES), concentrating solar power plant (CSP)

1. Introduction

The rapidly increasing population growth and increasing standard of living in India gives rise to a greatly increased demand for energy. Today, India is the fifth largest energy consumer in the world [1]. As per data the world consumes 12000 million tonnes of oil equivalent (mtoe) of energy resources and India consumes 4.4% of the world total (524.2 mtoe). Global consumption of primary commercial energy (coal, oil & natural gas, nuclear and major hydro) has grown at a rate of 2.6% over the last decade. Reasonable use of solar energy would reduce consumption of fossil fuels, especially for winter space heating. This thesis introduces a seasonal thermal energy storage project which is the largest in Asia. Through the analysis of this system, it is possible to promote a mature model for building TES systems to solve the problem of the huge energy consumption in winter space heating.

According to Pilkington Solar International GmbH thermal energy storage can be classified by storage mechanism (sensible, latent, or chemical) and by storage concept (active or passive). These concepts and mechanisms are described below

1.1 Active thermal storage systems

Active thermal storage systems are characterized by forced convection in the storage material, the storage medium itself circulates. Active solar power setups rely on external energy sources or backup systems, such as radiators and heat pumps to capture, store and then convert solar energy into electricity.

1.2 Passive Storage System

For passive systems, a heat transport medium passes through the store to carry energy to and from a storage medium. The main disadvantage of this type of system is that, for sensible storage, the temperature differential driving the heat transfer decreases as the store is charged or discharged. Such systems can also be limited by the low thermal conductivity of some storage medium. Passive systems operate without the reliance on external devices. Rather, such as in greenhouses, solariums and sunrooms, solar energy captures sunbeams through glass windows that absorb and retain heat.

1.3 Molten Salt Energy Storage

Molten salt fulfill both requirement it is used as a heat transfer fluid (HTF) as well as a thermal energy storage medium. The salt mixture is non-toxic and inert. Use of molten salt is most flexible, efficient and cost-effective form of large scale energy storage system. This storage process need no backup to deliver constant energy such as the fossil fuels needed as backup for many other CSP technologies.

1.4 Phase Change Material (PCM)

The use of phase change materials for latent heat energy storage is an excellent **option**, because of its high energy density which reduces the size of the storage tank, and its potential to increase the energy and exergy efficiency in conventional steam Rankine cycles. PCM prevents from excessive heating by storing the excess heat during the day, and releasing it during the night. This used as thermal mass, it stores heat during the day and releases it during the night. Phase-change materials (PCMs) is capable to store large amounts of energy in relatively small volumes, hence reduces storage media costs.

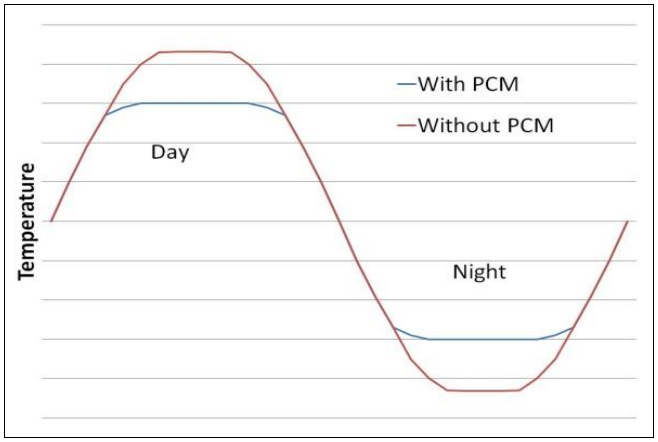

Fig 1: The functioning of PCM.

The objective of the present investigation is to develop and solve a comprehensive model that accurately predicts the melting and solidification processes of an encapsulated PCM in the order to quantify and correlate the individual contributions of all the fundamental energy transport modes.

2. Related Work

Nearly all materials are phase change materials. An extensive study shows that parrafin and salt hydrates are useful PCMs for households. Salts and sugar alcohols are used for higher temperature ranges. The Concentrated Solar Power (CSP) plant uses salt to store energy for later use. This can ease the part of the intermittency problem of solar power.

2.1 Melting of a Confined PCM by Conduction and Natural Convection

Paterson fist develops a logical solution for the one dimensional spherical melting problem, considering stagnant liquid phase, which means that, the transfer of heat within the molten material is only by conduction. And assume the absence of buoyancy induced natural convection in the melt layer and the solid fraction of the PCM remains at the center of the sphere. This is the main drawbacks of this model.

Vishnu Rajpuria [2] analyzed the unconstrained melting (vertical motion of the solid phase due to its higher density) of a low melting temperature PCM. The mathematical model was solved using a finite difference technique. S. K. Roy [3] performed heat transfer experiments for the melting of a phase change medium in a Pyrex glass spherical capsule. The free expansion of the medium in the void space within the sphere was permitted. By the study we concluded that the melting process was extensively affected by the movement of the solid toward the base of the sphere. The melting of Sodium Nitrate ($NaNO_3$) in a square cavity has been explored numerically by Wang *et al.* An alternate TES apprach based on heat pipe technology has been proposed by Shabgard *et al.* [4] using KNO_3 as PCM. A thermal network model was used to predict the transient response of the system. Two different configurations were analyzed and the influence of the orientation on the thermal response of the system was evaluated.

2.2 Melting of a Confined PCM by Conduction and Radiation

In the model, an absorbing-emitting, gray gas was assumed as the participating medium while uniform and equal temperatures were imposed at the shell surfaces. A uniform internal heat generation rate per unit volume through the gas was also considered. Numerical predictions were reported, and the study concluded that the gas temperature variations are greater when the absorption coefficient increases for a fixed geometry. Viskanta and Merriam [5] performed a parametric investigation on the steady state conduction and radiation heating and cooling processes of an absorbing, emitting, scattering and gray medium enclosed in the space between two black, isothermal and concentric spheres.

2.3 Solidification of a Confined PCM by Conduction

In this model assumes that the medium is initially at the phase change temperature. Therefore, no heat transfer is allowed across the liquid phase, and the heat only flows in the solid portion. This simplified model is known as the single phase Stefan problem. Closed-form, semi-analytical solutions of this problem were presented by a number of investigators [6] based on the similarity variable approach, asymptotic theory and parameter-perturbation methods.

The PCM volume reduction during solidification in a partially filled spherical shell has been studied by Assis *et al.* [7]. In his model, the domain was initially partially filled with liquid paraffin wax, with air in the remaining volume. Numerical results and experimental observations tells that a void space is created inside the capsule due to PCM volume reduction during freezing.

As per the literature review, the available solutions for the phase change problem is not for physical reality or may not be fully applicable to thermal energy storage in concentrating solar power plants. In this context, the primary objective of this study is to examine the individual interaction of all the fundamental energy transport modes during the melting and freezing of a phase change material restrained in spherical shells. The primary objective of this examination is to provide additional information about the key elements in any phase change problem, i.e., solid-liquid interface position and phase distribution at a given time after the application of a thermal driving force, particularly under operating thermal conditions related to thermal energy storage for concentrating solar power plants.

3. Methodology and Processes

In this chapter, we develop the model to study the heat transfer and fluid dynamics during the melting of sodium nitrate encapsulated in a metallic spherical shell and subjected to a constant temperature boundary condition at the outer wall of the shell. Although this chapter primarily focuses on $NaNO_3$, with a melting point of 306.8 ºC, the proposed numerical model will be extended in later chapters to predict the melting process of other PCMs under different boundary conditions and different shell material.

Physical Situation and Mathematical Model

The following assumptions are considered: (1) the PCM is continuous, homogeneous and isotropic; (2) the PCM liquid phase is a viscous Newtonian fluid; (3) the flow is laminar, has no viscous dissipation (4) the melting occurs in the interval between 306.3 and 306.8, where the density in this interval varies linearly from 2130 kg/m3 at 306.3 to 1908 kg/m3 at 306.8, (5) the PCM volumetric expansion due to melting has been neglected for simplicity (6) the thermal expansion of the shell material induced by the temperature differences has been neglected.

A tool has been developed to study the heat transfer between HTF (heat transfer fluid) and PCM (phase change material) in a shell and tube heat exchanger system. The proposed structure is a vertical inline shell and tube heat exchanger, with the following specifications; Copper tubes (BWG 20) are used with 0.5 in outer tube diameter, 1 in tube pitch, 0.02 in fin thickness and 8 fins in each tube and the tube length to the tube outer diameter ratio of 5.

In the initial state, the solid PCM fills 84 % of the enclosed space. This is assumed in order to accommodate a significant increase in the PCM volume during the solid liquid phase transition, with large difference in solid and liquid density that exists in reality. Consequently, the continuity, momentum, and thermal energy equations can be expressed as follows:

Continuity equation

$$\frac{\partial\rho}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}(\rho v_r r^2)+\frac{1}{r sin\theta}\frac{\partial}{\partial\theta}(\rho v_\theta sin\theta)=0$$

Momentum equation

$$\rho\left(\frac{\partial\nu_r}{\partial t}+\nu_r\frac{\partial\nu_r}{\partial r}+\frac{\partial_\theta}{r}\frac{\partial\nu_r}{\partial\theta}-\frac{\nu_\theta^2}{r}\right)=-\frac{\partial P}{\partial r}+\eta\left[\nabla^2\nu_r-\frac{2\nu_2}{r^2}-\frac{2}{r^2\sin\theta}\frac{\partial(\nu_\theta\sin\theta)}{\partial\theta}-\frac{2\nu\theta\cot\theta}{r^2}\right]-\rho g_r\beta(T-T_m)$$

$$\rho\left(\frac{\partial\nu_\theta}{\partial t}+\nu_r\frac{\partial\nu_\theta}{\partial r}+\frac{\nu_\theta}{r}\frac{\partial\nu_\theta}{\partial\theta}+\frac{\nu_r\nu_\theta}{r}\right)=-\frac{1}{r}\frac{\partial P}{\partial r}+\eta\left[\nabla^2\nu_\theta+\frac{2}{r^2}\frac{\partial\nu^2}{\partial\theta}-\frac{\nu_\theta}{r^2\sin^2\theta}\right]-\rho g_\theta\beta(T-T_m)$$

Where, ∇ is the Laplace operator and is defined as

$$\nabla^2=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)$$

Energy equation

$$\frac{\partial h}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\nu_r h)+\frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\nu_\theta\sin_\theta h)=\alpha\nabla^2 h-\frac{1}{\rho c_p}\left(\frac{\partial\lambda}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\nu_r\lambda)+\frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\nu_\theta\sin\theta\lambda)\right)$$

Where h is the sensible enthalpy and λ the latent heat

$$h=h_{ref}+\int_{T_{ref}}^{T}c_p dT$$

Here h_{ref} and T_{ref}□□ are the reference sensible heat and temperature, respectively. The enthalpy porosity technique, originally introduced by Voller and Prakash and Brent *et al.* was used to track the liquid-solid interface. In this method, the motion of the interface is not openly tracked. Instead it is determined via a linear relationship between the latent heat and the temperature, i.e.,$\lambda=\phi L$ where ϕ is the liquid volume fraction of the computational cell where phase change is occurring ($0<\lambda<L$) and (L) is the latent heat of fusion. Liquid fraction is defined based on the following relations:

$$\phi=\begin{cases}\phi=0; & T<T_s\\ \dfrac{T-T_s}{T_m-T_s} & T_s<T<T_m\\ \phi=1; & T>T_t\end{cases}$$

The aforementioned methodology introduces a damping term in each of the momentum equations in order to inhibit the velocity value arising from those equations on the solid phase. A Darcy damping term is used and is defined as:

$$S=C\frac{(1-\phi)^2}{(\phi^3-\in)}\nu_i$$

4. Results and Discussion

The PCM materials selected in our study are paraffin wax ($C_{28}H_{58}$) of 61 ^{0}C melting point domestic applications and sodium nitrate ($NaNO_3$) of 307 ^{0}C melting point for power generation system. The following cases have been discussed as heat storage parametric study;

- The effect of the HTF injection
- The effect of volume expansion during melting
- The effect of the fins and its geometry
- The effect of the HTF inlet velocity

4.1 The effect of volume expansion during melting

The influence of the phase change material (PCM) volume change during melting due to the difference between the density of the solid and liquid phase on the system was considered. It can be seen that the required time for complete melt reduced by 27.43 % when the volume change was taken into consideration. This decrease in melt time caused due to the following two reasons; the increase in the heat transfer surface area between the HTF and the PCM as volume increase. The convection heat transfer occurs due to the decrease in the PCM density during melting process. Thus, the volume change during melting has a significant effect, and must be considered.

4.2 For medium melt temperature (paraffin wax) PCM the effect of the HTF injection

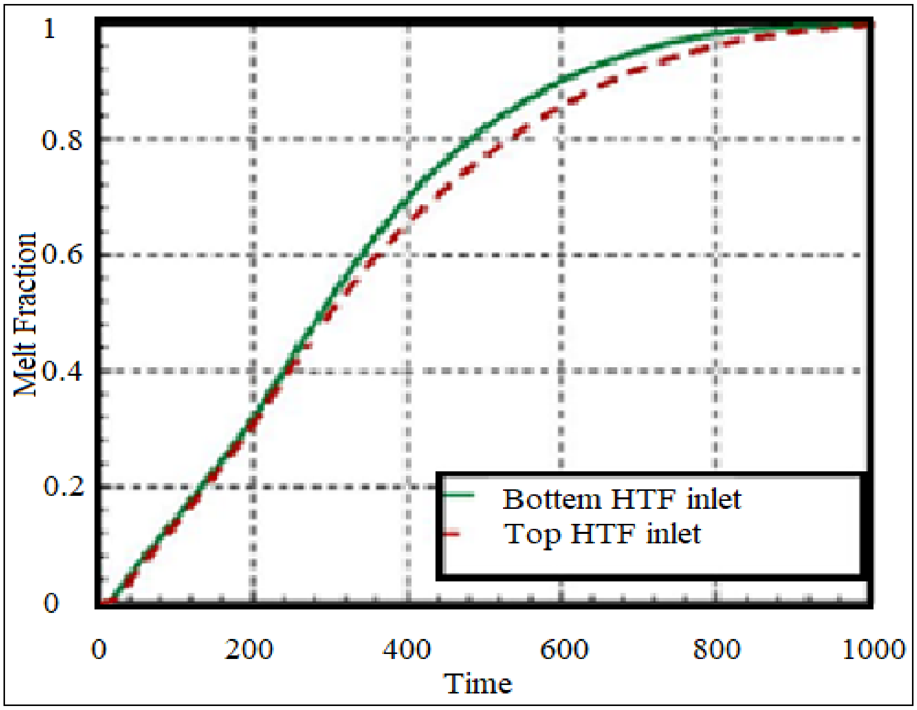

Fig 2: Melt fraction during charging with bottom and top HTF injection for tubes without using fins

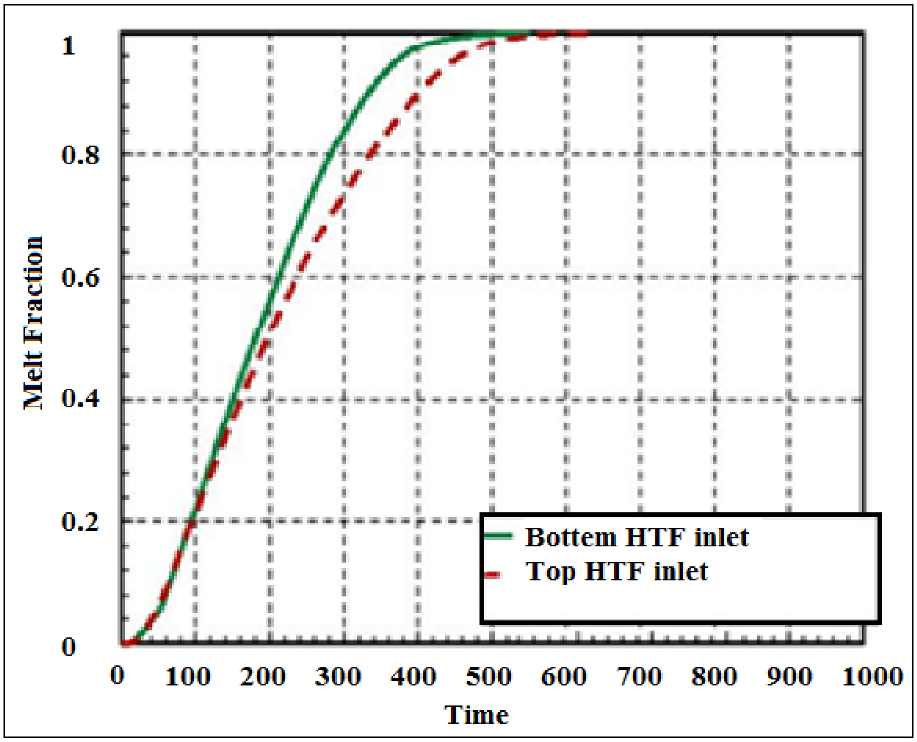

Fig 3: Melt fraction during charging with bottom and top HTF injection for tubes with using uniform fins

4.3 The effect of the fins and its geometry

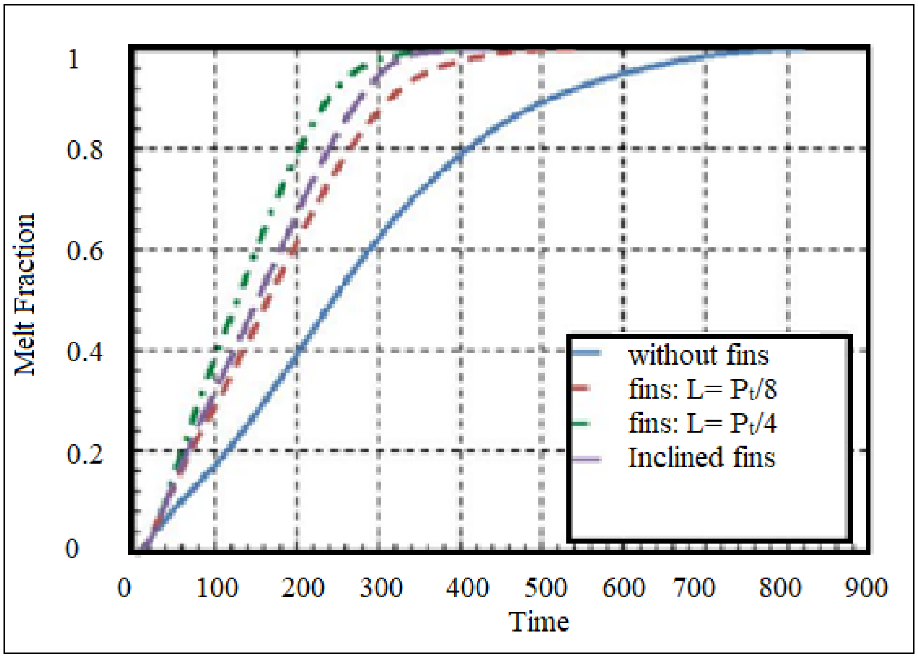

Fig 4: Effect of fins and its geometry on melt time for medium melt temperature PCM at 0.01 m/s

4.4 For high melt temperature (sodium nitrate) PCM: The effect of the HTF inlet velocity

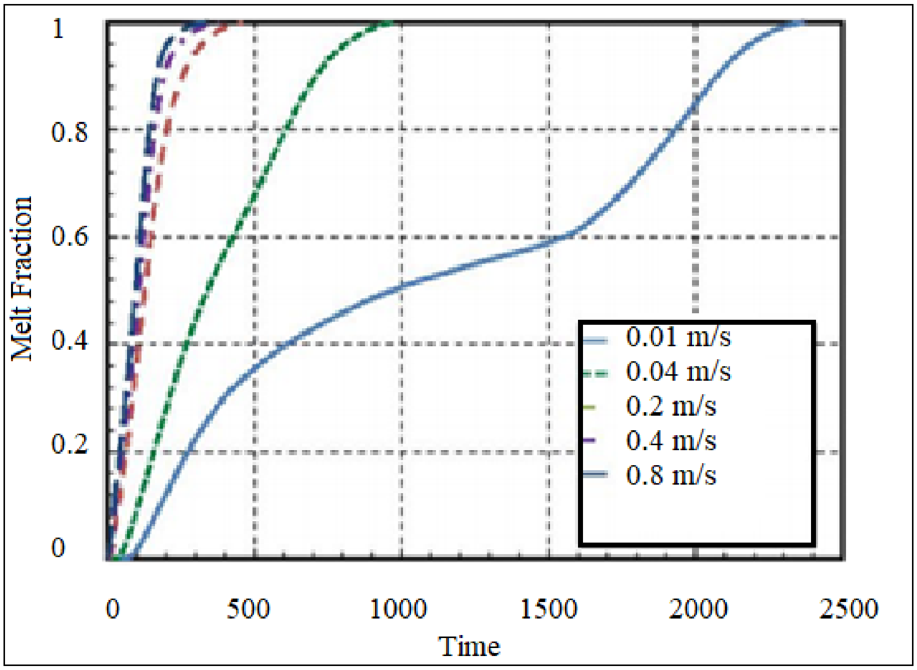

Fig 5: Effect of inlet hot fluid velocity on melt time for high melt temp PCM

4.5 Completely Filled Model ($NaNO_3$)
Melting Of Sodium Nitrate in a Spherical Shell

The values of $\varkappa$ were selected for this study to lie between the limiting cases corresponding to the low and high thermal conductivity values. The shell material parameter $\varkappa$

($\varkappa = 1 - k_{pcm}/k_{shell}$)

A sub cooling parameter ξ has been defined as

$\xi = 1 - \frac{T_i}{T_m}$. ……….equation (10)

Table 1: Analyzed study cases

Case number	R_i (m)	$T_w - T_m$ (°C)	Gr_R	Ste	χ	ξ
1		5	1.32×10^4 8.98	0.048		
2	0.010	10	2.69×10^4 8.90	0.097	0.966	0.00259
3		15	4.13×10^4 8.81	0.145		
4	0.0092	12.6	2.68×10^4 8.84	0.122	0.966	0.00259
5	0.011	7.5	2.66×10^4 8.93	0.072		
6	0.015		9.09×10^4			
7	0.020	10	2.15×10^5 8.90	0.097	0.966	0.00259
8	0.025		4.21×10^5			
9	0.034	9.6	9.09 × 104 35	0.097	0.966	0.00259
10	0.02	10	2.15 × 105 8.90	0.097	0.6709	0.0259
11					0.9945	

Table 2: Dimensionless groups

Group	Definition
Stefan number	$\mathrm{Ste} = \dfrac{C_p(T_w - T_m)}{L}$
Grashof number	$Gr_R = \dfrac{g\beta(T_w - T_m)R_i^3}{v^2}$
Prandtl number	$\Pr = \dfrac{v}{\alpha}$

The dimensionless parameters that are used to characterize the energy transport and fluid flow have been introduced in Table 2. It is appropriate to describe each parameter briefly before to start the discussion of the results. The Stefan number (Ste), defined as the ratio of the sensible heat and the latent heat of fusion. The Grashof number measures the ratio between the buoyancy and viscous forces. The Prandtl number tells relation between momentum diffusivity and thermal diffusivity. The Grashof number values are based on the shell inner radius, on the temperature difference between the wall and melting temperatures and fluid properties evaluated at the reference temperature

$$\left(T_{ref} = \frac{(T_m + T_w)}{2} \right)$$

In order to correlate the main results of this study and to develop applicable expressions regardless of any change in the system parameters, the dimensionless quantities that characterize the natural convection-dominated melting process in a spherical shell have been arranged in the form $FoSte^a Gr_R^b Pr^c \chi^d \xi^e$. For the following exponents a = 0.33, b = 0.27, c = 0.37, d = 072 and e = -0.02. Based on that, the following correlation is proposed.

$$MF = 1 - \left[1 - \frac{FoSte^{0.33} Gr_R^{0.27} \Pr^{0.37} \chi^{0.72} \xi^{-0.02}}{9.5} \right]^{1.8}$$

This correlation seems valid in a range encompassing the simulated cases:

$0.048 \le Ste \le 0.145$, $32x10^4 \le Gr_R \le 4.21x10^5$, $8.90 \le Pr \le 35.0$, $0.00259 \le \xi \le 0.0259$, $0.6709 \le \chi \le 0.9945$

A dimensionless quantity that includes the average Nusselt number, at the inner surface of the shell, in combination with the controlling parameters of the problem is proposed, as

$$= \frac{NuSte^f}{Gr_R^g \Pr^h \chi^i \xi^j}$$

4.6 Solidification of Sodium Nitrate in a Spherical Shell

The parameters analyzed in the course of this investigation are the melt degree of superheat (T_0 - T_m), the external heat transfer coefficient that characterizes the outer shell wall boundary condition, outer wall of the capsule in order to represent the discharging process in a packed bed system.The Biot number ($Bi = \frac{h_\infty R_i}{k_{sol}}$) has been used to characterize this effect where three different heat transfer coefficients (h_∞) have been evaluated and there, influence on the thermal behavior of the system was analyzed. Study cases 4-6 describe this effect. Three different shell sizes have been analyzed in this study with inner radius of 15, 25 and 35mm respectively. These conditions are represented by study cases 6-8. To make participation of thermal radiation, the PCM has been modeled as a semitransparent, non-gray medium in all the study cases presented in Table 3. A seven-band model, based on the experimental results reported by Ramdas [8] has been used to account for the spectral dependence of the PCM optical properties.

Table 3: Geometrical and thermal parameters

Case	R_i (m)	$T_w - T_m$ (°C)	Gr_R	Bi	Ste_{Liq}
1	0.015	1	8.77×10^5	5	0.0096
2	0.015	5	4.46×10^4	5	0.048
3	0.15	10	9.09×10^4	5	0.096
4	0.015	20	1.90×10^5	1	1.195
5	0.015	20	1.90×10^5	5	1.195
6	0.015	20	1.90×10^5	10	1.195
7	0.025	20	8.81×10^5	16.67	1.195
8	0.035	20	2.42×10^6	23.34	1.195

The PCM has been treated as it not become weak and and not emit any radiation hence we say the shell inner surface emissivity equal to zero, has been also included in the analysis, or we can say thermal radiation does not play any role. The size of the shell and thermal radiation heat transfer within the PCM. These parameters have been selected based on a practical point of view of the possible use of $Nano_3$for storage of thermal energy in concentrating solar power plants. Eight different study cases have been defined to identify the aforementioned parameters and are presented in Table 3.

4.7 Multi Capsule Model

A practical scenario of the analyzed thermal storage system consists of an arranged porous bed of capsules held in a cylindrical container through which a heat transfer fluid flows and transports energy to or from the PCM material contained within the capsules.

Physical Situation and Model Assumptions

The following assumptions are made to simplify the mathematical model. (1) The capsules are oriented concentrically and vertically along the radial and axial directions. (2) Fluid flow distribution is uniform along the radial direction of the system. (3) Axial heat transfer due to contact between the capsules is negligible. This assumption follows from the fact that the capsules have a point contact. Also, a uniform separation distance of 1mm between the capsules. (4) The heat loss from the storage tank to the surroundings is assumed to be negligible. Thus, an insulated boundary condition was assumed at the side wall of the domain.

It should be pointed out that the velocity distribution of the HTF determines the convective component of the thermal energy transfer within the boundary layer at the outer surface of each capsule. Therefore, the nature of the flow has a significant effect on the external convective heat transfer rate. The ability to model the external convective energy transport is one of the key contributions of this model as compared to the previously reported models where the boundary condition at the outer shell surface have uniform heat flux or constant temperature.

The common stages that characterize the temperature history during melting are observed, e.g. solid phase sensible heating where the temperature increases with time followed by a sharp change in slope with and almost horizontal trend indicating phase change and the liquid phase sensible heating where temperature increases with time. The multi-capsule model helps in predicting the melting dynamics of NaCl under different. Simultaneous conduction, natural convection and thermal radiation heat transfer were included in the model. A non-linear effect of both parameters on the melting time is observed with faster melting as the surface emissivity and inlet mass flow rate increase. It is observed that, the melting time decreases 9.2%, 17% and 23% in the cases where the inner surface emissivity increases from 0.1 to 0.3, 0.6 and 1.0 respectively. The melt time decreases 25%, 36% and 42%.

5. Conclusions and Future Scope

In this research, the influence of the natural convective heat transfer mechanism due to the difference between solid and liquid densities was evaluated, and we conclude that it plays an important role during the charging mode. A bottom injection for charging process is recommended due to upward moving of liquid PCM. Additionally, with heat transfer enhancement methods; Increasing the inlet HTF velocity and by using uniform fins on PCM side the melt time reduced significantly. The volume expansion during melting has a significant effect on melting time due to increasing both heat transfer area and natural motion of PCM. The uniform fins of fin height equal to one fourth of the tube pitch are most useful. Turbulent flow of HTF reduces melting time due to higher turbulence heat transfer coefficient so, the inlet HTF velocity is very important parameter for the melting process and should not be less than 0.8 m/s.

We also conclude our results in following points:

- It was found that the Grashof and the Stefan numbers strongly enhance the melt fraction rate of $NaNO_3$. Prandtl number make a great impect on the melt fraction rate under constant Grashof and Stefan numbers.
- It was found that when the shell material parameter (χ) is in the range of 0.966-0.994 there is no significant difference in the total time to complete melting, under the analyzed conditions.
- The presence of natural convection induces the initial formation of an asymmetrical solid PCM layer from the bottom of the capsule. It is believed that this factor is responsible for the slight variation in the solid layer thickness along the shell symmetry line, with the smallest layer thickness at the top and the greatest layer thickness at the bottom.
- As the Biot number decreases from 5.0 to 1.0, the freezing time increases from 28.5 to 57.8min. However, a significantly smaller difference in the freezing times was observed when the Biot number decreases from 10 to 5.
- When thermal boundary condition is fixed, the solidification time decreases by 21.2% to 60.2% as Ri decreases from 35mm to 25mm and 15mm respectively
- The thermal radiation reduces the melting time by 10% as compared no radiation condition. The melting time decreases by 9.2%, 17% and 23% when the inner surface emissivity increases from 0.1 to 0.3, 0.6 and 1.0 respectively.

Recommendations for Future Research

The following topics may be outlined as recommendations for future research.

- Modeling of thermal and pressure induced stresses in the shell for mechanical design of packed bed heat exchangers.
- Thermal modeling of different PCMs and capsule shapes, such us cylinders or rectangular containers. And the comparison with the results obtained for spherical shells.

- The impact of time and position dependent wall boundary conditions on melting and freezing dynamics.

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