Enhancement of Energy Recovery in a Phase Change Energy Storage Module with Embedded Radiation Absorbing Particles

Marwan Belaed and Muhammad Mustafizur Rahman

***Abstract*—The present study investigated combined enhancement of heat conduction and thermal radiation in a finned cylinder during the solidification (energy recovery) of a non-gray, non-opaque phase change material. Transient heat transfer in a symmetric, two-dimensional design is considered. The radiative transport equation is solved by using the Discrete Ordinate Method (DOM) while Finite Volume Method is used to discretize and solve equations for the conservation of mass, momentum, and energy. It was found that energy recovery time can be reduced by 74% by controlling the optical thickness property of the PCM with embedded radiation absorbing particles.**

***Index Terms*—Phase change material, radiation, solidification, thermal energy storage module.**

I. Introduction

Designing an effective energy storage system is essential for base load power generation using solar energy, which is gaining considerable attention in the renewable energy community. Currently, most thermal energy storage systems that have been commercially deployed use sensible energy storage materials. Alternatively, it has been already proven by researchers that latent heat energy storage systems using phase change materials (PCMs) can provide significant advantage compared to that of the sensible energy storage technology. PCM can keep up the temperature of the heat transfer fluid (HTF) required to maintain its potential to produce work in the power generation system. Using PCMs as Thermal Energy Storage (TES) medium can provide relatively low cost due to their high heat of fusion which results in smaller storage volume. One major drawback of PCMs, especially in large-scale systems, is their low thermal conductivity. This would cause a negative effect by delaying the phase change; hence force slow down the charge/discharge time. Fortunately, for high temperature energy storage applications geared towards electric power generation using solar energy, one can take advantage of enhancing thermal radiation alongside enhancing thermal conduction.

Several studies aimed at overcoming this issue of low energy storage and recovery rates by increasing the heat transfer area between the storage material and the heat transfer fluid. This was achieved by adding fins, heat pipes or microencapsulation of the PCM. Improving the thermal properties of the PCM such as density and thermal conductivity by including highly conductive nanoparticles and foams were also considered in some investigations. Yang et al. [1] numerically investigated the annular fins with different number of fins, height and thickness. They found that using annular fins in the PCM can reduce the melting time by 65%. Nithyanandam and Pitchumani [2] designed a thermal resistance network to study the response of PCM with four embedded heat pipes in terms of their effectiveness. It was found that the effectiveness of the heat pipes reduced with increase in the HTF mass flow rate, radius of the tube, and length of the system. On the other hand, the effectiveness could be increased by increasing the length of the evaporator and condenser sections. Nithyanandam and Pitchumani [3] presented a study of the latent heat energy storage system with embedded gravity-assisted heat pipes. The analysis found that a larger spacing between the pipes yields a lower heat transfer rate between the PCM and the HTF. Zeng et al. [4] experimentally developed a phase change material with enhanced thermal conductivity via in-situ polymerization. Elgafy and Lafdi [5] experimentally and analytically studied the thermal behavior of carbon nanofiber filled paraffin wax PCM. It was found that including the carbon nanofiber into the system enhanced the thermal conductivity. Khodadadi and Hosseinizadeh [6] improved the solidification time by using the nanoparticle enhanced PCM and nanofluid as HTF resulting an increase in the heat transfer rate between the PCM and the HTF. Mahdi and Nsofor [7] studied the effect of fins, nanoparticles, and a combination of both on the thermal behavior of PCM. The investigation found that using the fins alone gave more optimum results compared to the other two methods.

Using fins as means to improve heat transfer is an attractive method due to their compactness and simple structure. Popular fin configurations include annular, longitudinal, pin, and plate. Longitudinal fins are quite desirable as they allow for easier design and fabrication. The convenience of heat exchange with the storage medium is another advantage of these fins. Experimental and numerical studies by Velraj *et al*. [8] found that the thermal resistance between the liquid PCM and the module surface increased as solid phase started to form next to the inner wall during energy recovery. However, the presence of fins in the storage system led to an overall decrease in the solidification time. Castell *et al*. [9] experimentally investigated the natural convection heat transfer coefficient in a cylindrical phase change energy storage module with external vertical fins. The

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fins of different size were considered in this study. It was concluded that the fins enhanced heat transfer rate in general and longer fins provided shorter time for the heat to transfer. Solomon and Velraj [10] experimentally investigated the influence of different size of copper fins in a finned cylindrical phase change energy storage system. The results showed that fins play very significant role during the cooling of the liquid PCM. Rathod and Banerjee [11] carried out an experimental analysis of melting and solidification of PCM in a cylindrical geometry with three longitudinal fins. The fins were mounted on the heat transfer fluid tube externally. The results showed a good improvement in the processing time of the melting and solidification. Abdulateef *et al*. [12] presented a comprehensive review of numerical and experimental investigations on the use of fins for the enhancement of heat transfer between the phase change material and the heat transfer fluid in energy storage modules in terms of geometry, number, and location of fins. The main difficulties of designing and optimizing energy storage systems with fins were identified. It was realized that the complexity of the physical phase change processes in a complicated geometry can lead to more expensive computational cost.

Narasimhan *et al*. [13] numerically investigated the freezing of the PCM mixed with high conductive particles in a spherical storage system. The influence of fins along with the effects of dimensionless parameters such as Stefan and Biot numbers were investigated. The study concluded that these high conductive particles improved the heat transfer at locations far from the sphere wall rather than those locations near the wall. Radouane and El Qarnia [14] developed a two-dimensional model for the solidification process of PCM mixed with nanoparticles in a rectangular storage tank. The storage tank had a number of vertical slabs separated by rectangular channels. This study investigated the influence of aspect ratio, dimensionless HTF inlet temperature, and volumetric fraction of nanoparticles. The authors concluded that the freezing rate can be affected by the volumetric fraction of the nanoparticles. The solidification rate can be increased by decreasing the inlet temperature of the HTF. The heat transfer between the slabs and the HTF was improved by modifying the aspect ratio. Bechiri and Mansouri [15] used an analytical method to study the influence of volumetric heat generation rate on freezing and melting properties of encapsulated PCM. Mahdi and Nsofor [16] investigated the influence of alumina nanoparticles on PCM solidification in a triplex-tube TES system. Their study concluded that the presence of nanoparticles improved the phase change rate more at the final period of solidification process rather than at the earlier times. This is because conduction becomes the dominant process over convection when a significant portion of phase change material is solidified.

Pirasaki *et al*. [17] investigated the effects of radiation during high temperature phase change in a cylindrical module for possible thermal energy storage in power plants. It focused on the energy transport mechanism during the phase change process. An experimental set up was designed and constructed to investigate the charging and discharging in a vertical cylinder inside a tube furnace. The behavior of liquid fraction with the inclusion of radiation absorbing particles was analyzed. A much wider melting zone was observed in the presence of radiation absorbing particles. Zeneli *et al*. [18] numerically investigated a latent heat thermal energy storage system operating at ultra-high temperatures (~1410–2000 °C). They used silicon as the working fluid which has much higher latent heat compared to molten salts. No radiation exchange was included in their model. They presented the phase change and associated natural convection flow for five different storage vessel shapes, namely, cube, truncated cone, sphere, cut-off sphere and cylinder and compared their melting time.

The objective of our research is to study the effects of radiation which becomes a more dominant heat transfer mechanism at high temperature alongside conduction and convection. The thermal efficiency of a power plant increases with working fluid temperature, and therefore energy storage at a high temperature is much more beneficial for power generation applications using renewable energy. We plan to analyze the influence of heat transfer enhancements using fins in a non-opaque medium consisting of a transparent PCM (NaCl) with embedded nanoparticles to provide absorption of radiation from the surfaces. A two-dimensional transient heat transfer and phase change model is developed and solved numerically to explore the energy discharge process (solidification of PCM) with the variation of medium optical thickness.

II. Modeling and Numerical Simulation

Fig. 1 shows a schematic representation of the investigated system. It is a two-dimensional cross section of a horizontal longitudinally finned cylinder. It consists mainly of an opaque, gray and diffuse cylinder shell with 250 mm length and 100 mm diameter. The cylinder has 4 horizontal longitudinal fins with length of 30 mm. Both the fins and cylinder have a thickness of 1 mm. The problem is symmetric about the vertical plane passing through the axis of the cylinder and mid-plane of two vertical fins. Therefore, only half of the cylinder can be used for modeling and computation. In addition, due to the assumption of long cylinder where effects of end caps can be neglected, the problem can be modeled as two-dimensional with no variation along the length of the cylinder. NaCl is selected as the PCM for energy storage and the module is filled with the phase change material. By embedding with nanoparticles, the medium is made semitransparent which can absorb, store, and emit radiation.

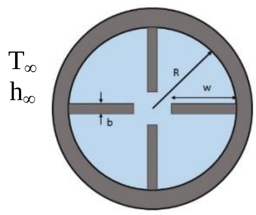


Fig. 1. Schematic representation of the system configuration.

For building a numerical model for the solidification process, a few simplifying assumptions were made: (1) the storage material is homogeneous, and its properties are independent except for the density. (2) solidification of NaCl occurs in the range of (T_m= 800.2–800.7 °C), (3) constant inlet temperature of the heat transfer fluid and negligible wall heat transfer resistance, (4) flow is laminar and has no viscous dissipation. In order to model the presence of natural convection at the beginning of the solidification process, Boussinesq approximation is used for temperature dependent density variation in the momentum equation. Table I presents the properties of PCM used in the simulation [19], [20]. Since the embedded nanoparticles were of very small quantity compared to the PCM, they did not have any significant contribution to thermo-fluid properties contributing to conduction and convection heat transfer but affected the optical properties controlling the radiation heat transfer.

TABLE I PCM PROPERTIES

Properties (T in K)	
Specific heat - Solid phase (J/kg K)	1662.3 - 0.4218T
Specific heat - Liquid phase (J/kg K) 3289.3 - 3.4589 T + 0.0014173 T^2	
Thermal conductivity (W ⁄ m K)	- 0.269 + 9.07 x 10^{-4} T
Density - Solid Phase (kg⁄m^3)	2160
Density - Liquid phase (kg⁄m^3)	2168.1 - 0.5663T
Density - Mushy zone (kg⁄m^3)	1,290,180 -1200T
Dynamic viscosity (kg⁄ms)	0.0034 - 2.194 x 10^{-6} T
Melting temperature (°C)	800.2-800.7
Absorption coefficient (m^{-1})	0–80
Latent heat of fusion (J/Kg)	479,289
Thermal expansion coefficient (K^{-1})	6.82 x 10^{-5}

The governing equations can be presented as:

Conservation of mass:

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

Conservation of momentum in the radial direction:

$$\rho\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial\theta}-\frac{v_\theta^2}{r}\right)=-\frac{\partial P}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rv_r)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial\theta^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial\theta}\right]-\rho g_r\beta(T-T_m) \quad (2)$$

Conservation of momentum in the polar direction:

$$\rho\left(\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial\theta}+\frac{v_r v_\theta}{r}\right)=-\frac{1}{r}\frac{\partial P}{\partial\theta}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rv_\theta)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial\theta^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial\theta}\right]-\rho g_\theta\beta(T-T_m) \quad (3)$$

Conservation of energy:

$$\frac{\partial h}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(rv_r h)+\frac{1}{r}\frac{\partial}{\partial\theta}(v_\theta h)=\alpha\nabla^2 h-\frac{\partial\lambda}{\partial t}-\frac{1}{r}\frac{\partial}{\partial r}(rv_r\lambda)-\frac{1}{r}\frac{\partial}{\partial\theta}(v_\theta\lambda)-\frac{1}{\rho}\nabla\cdot q_r \quad (4)$$

Here, ∇ is the Laplace operator in the cylindrical coordinate [21]. In equation (4), the radiative flux, q_r was determined using the discrete ordinate method as introduced by Menguc and Viskanta [22] and Jamaluddin and Smith [23]. In this study, it is assumed that there is no radiation on the cylinder's outer wall and scattering of radiation can be neglected. The radiation intensity was calculated at each location of the medium to determine the local radiative heat flux.

The boundary conditions needed to solve these equations included no-slip condition at the solid-fluid interface (inner surfaces of the cylinder and surfaces of the fins). The PCM is initially fully liquid with initial temperature T_o higher than its melting temperature T_m. For time > 0, the outer surface is exposed to the convective boundary with heat transfer coefficient h_∞ and free stream temperature T_∞ smaller than the PCM's freezing temperature. The temperature difference between the T_∞ and T_o allows heat to move across the wall to heat up the HTF and the solidification layer starts to form next to the wall and the fins. It may be noted that the model included the solid medium (container and fins) and the phase change material (in solid or liquid phase) and therefore had to be solved as a conjugate heat transfer problem where conduction was the only mode of heat transfer in the solid medium and both convection and radiation were included for heat transfer in the phase change material.

The governing equations along with boundary conditions were discretized using the finite volume method and resulting algebraic equations were solved using the SIMPLE (semi-implicit method for pressure linked equations) algorithm. The discrete-ordinate method (DOM) was used to account for radiation exchanges. In the setup of the problem, the solid-liquid transition zone was considered as porous with porosity identical to the liquid fraction. In general, the model defines the volume fraction of the i^{th} fluid (α) as:

$$\alpha=\frac{\text{volume of the phase in a cell}}{\text{volume of the cell}} \quad (5)$$

and it takes the following values:

$$\alpha_i=0 \quad \text{if the cell is empty of the } i^{th} \text{fluid}$$
$$\alpha_i=1 \quad \text{if the cell is full of the } i^{th} \text{fluid} \quad (6)$$
$$0<\alpha_i<1 \quad \text{if the cell contains the fluid interface}$$

As the material solidifies, the porosity approaches zero. The under-relaxation factors were 0.4, 0.7, and 0.6 for pressure, velocity, and enthalpy, respectively.

The energy released from the tank can be calculated by finding the solidified mass during the cooling as a function of the solid fraction with time.

$$f=\frac{M-m}{M} \quad (7)$$

$$m=M(1-f) \quad (8)$$

By knowing solid fraction, the total heat transferred during the solidification process can be calculated based on the fundamental thermal energy balance as given by

$$Q=m\left[\left\{\int_{T_s}^{T_m}C_{ps}\,dt\right\}+L+\left\{\int_{T_m}^{T_l}C_{pl}\,dt\right\}\right] \quad (9)$$

III. VALIDATION

To validate the computational scheme, an experimental investigation by Jones *et al.* [22] from the literature for the melting of paraffin in a vertical cylinder has been used. For a fair comparison, fins were taken out and the same parameters and boundary conditions from the experimental study were used in the numerical study. In addition, the problem was solved for the case of melting. It can be observed from Fig. 2 that a good agreement was reached between the results from our numerical simulation and the experimental results published in [22]. This illustrates that the current simulation model is reasonably accurate.

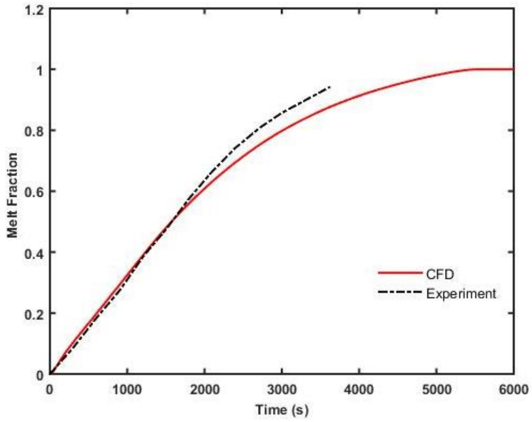


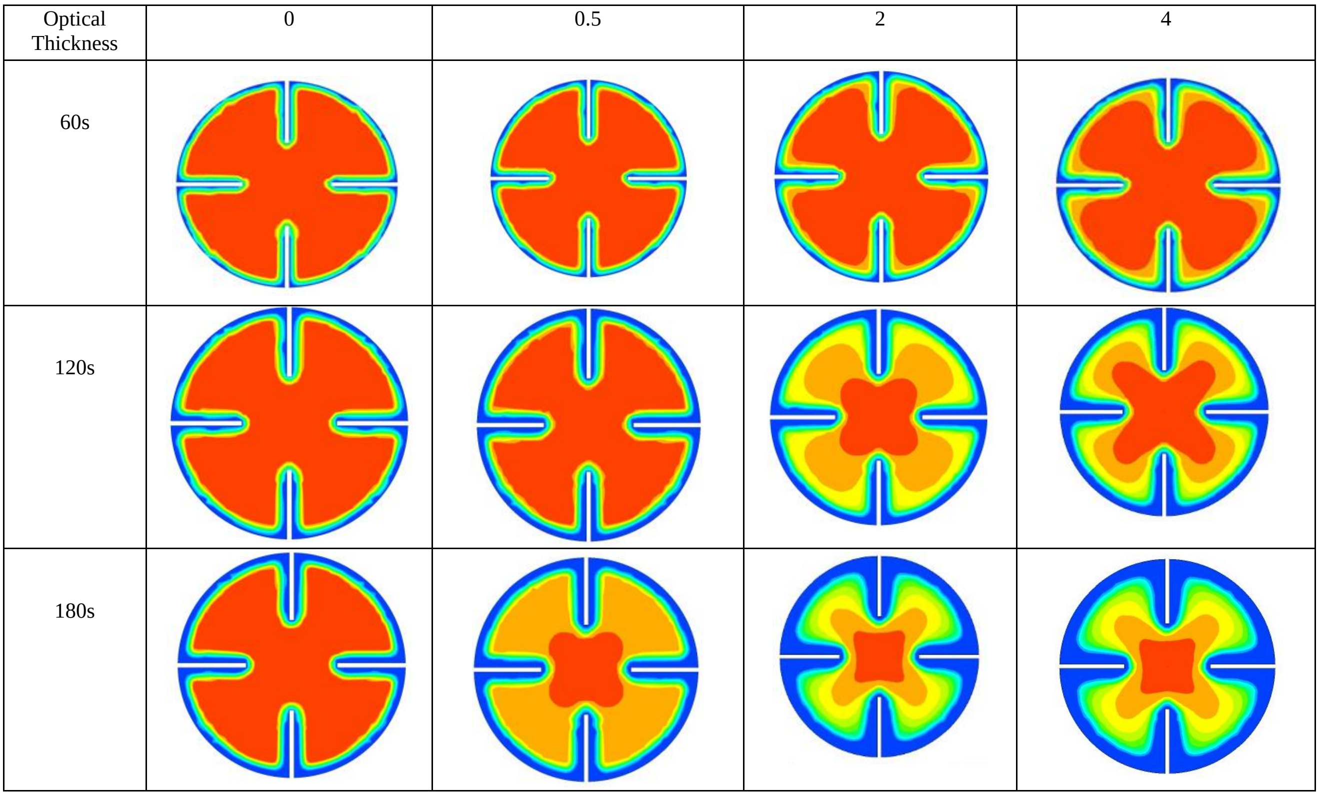
Fig 2. Comparison with experimental data reported by Jones *et al*. [24].

IV. Results and Discussion

The progression of the solidification process as the energy is extracted from the thermal energy storage module is demonstrated in Fig. 3. The red color indicates the liquid phase and the blue color indicates the solid phase in these figures. The mushy zone undergoing the phase change from liquid to solid is indicated by yellow color in between these regions. The PCM optical thickness has been modified by mixing the PCM with radiation absorber particles. The optical thickness is a dimensionless parameter quantifying the level of participation of the medium in the radiation exchange process. In the present investigation, the optical thickness was calculated from the equation $\tau = (k_a + \sigma_s) R_{i.}$ In all the cases, the scattering coefficient (σ_s) was assumed to be equal to zero. Fins provided a pathway to conduct heat from the inner part of the cylinder to the cylinder wall to facilitate a faster energy dissipation from the energy storage module to the working fluid outside the cylinder.

The solidified layer is formed next to the wall and the fins. This layer steadily grew as heat is released from the PCM to the cold HTF. The presence of both the fins and the radiation absorber particles enhanced the solidification rate. It can be seen from Fig. 3 that the rate of the solid fraction increased with increase of optical thickness of the PCM. The growth of solid layer occurs faster because of heat releasing from the PCM increases as a result of participation of radiation absorber particles that help the expansion of the solid layer. This implies that increasing the concentration of radiation absorber particles is more favorable for solidification enhancement than using fins only.

When there are no radiation absorbing particles, the optical thickness is zero and the PCM medium is fully transparent to thermal radiation. It can be seen from Fig. 3 that heat is released out of PCM primarily by conduction and therefore a thin layer of mushy zone is seen between liquid and solid regions. When radiation absorbing particles are added to the medium and the optical thickness increases to 0.5, 2, and 4, there is more and more participation of the PCM medium in the heat transfer process and a wider mushy zone is seen between liquid and solid regions. The enhancement of energy release with increase of is radiation absorbing particles is clearly seen as the solidification rate increases.



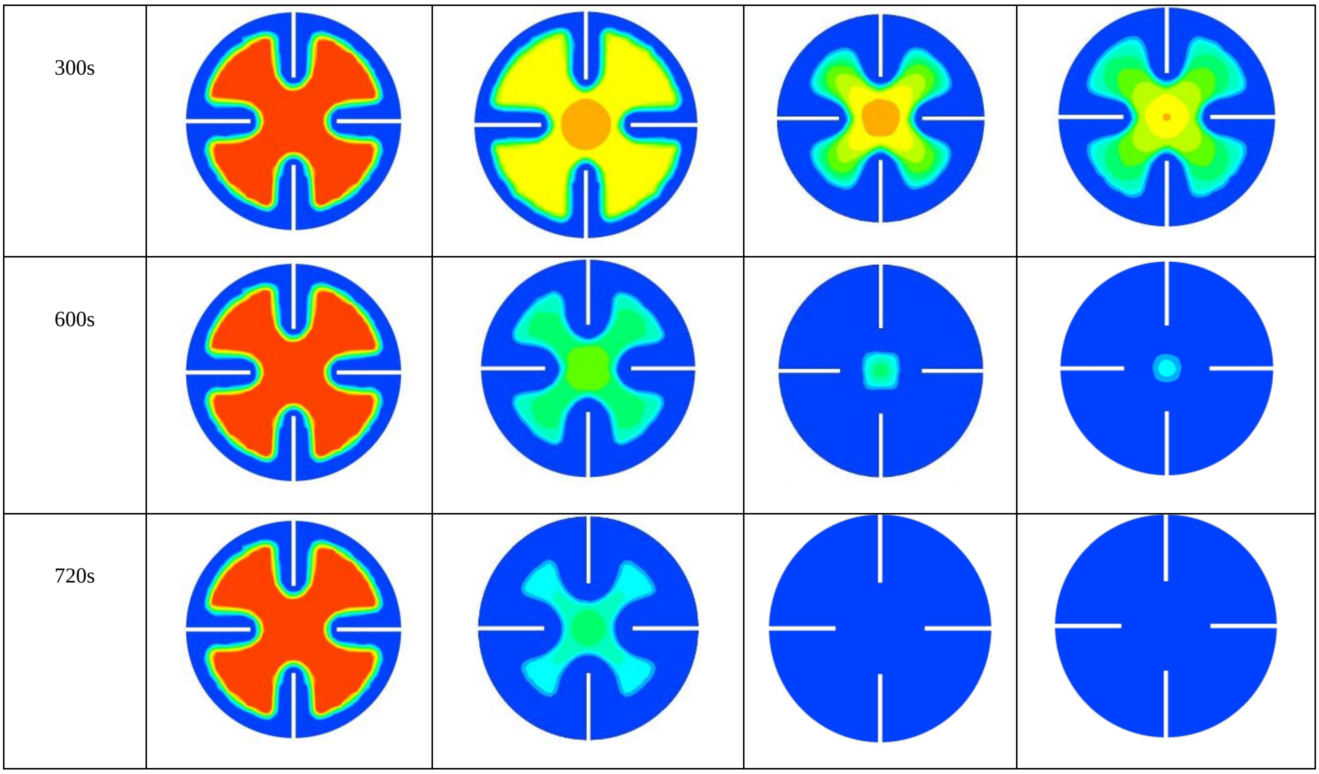


Fig. 3. Solidification contour.

It can be also noticed that a large gain can be realized by comparing solidification patterns for optical thicknesses of 0 and 0.5. However, the gain is rather small when the optical thickness is changed from 2 to 4. After 720 minutes, in case 4 the PCM was completely solidified while in case 1 twice as much time was needed. Therefore, the embedding of radiation absorbing particles in an otherwise transparent PCM like NaCl can greatly enhance the energy release rate during the extraction of energy from the phase change thermal energy storage module.

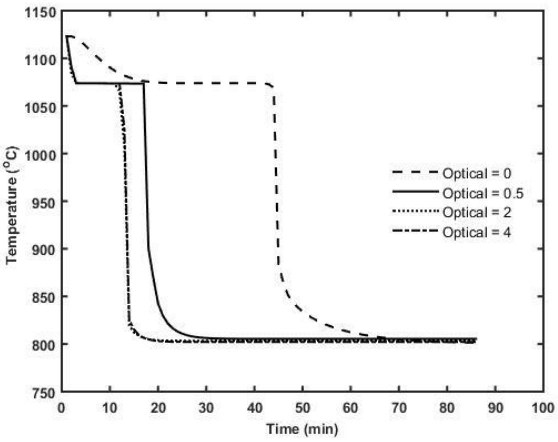


Fig. 4. The effect of optical thickness on the center point temperature.

The rate of energy extraction is a major factor in designing of latent heat thermal energy storage systems. The history of the temperature at the mid-point of the energy storage module was tracked in this study and presented in Fig. 4. The cases in each graph line was to show different amount of radiation absorbing particles which controlled the optical thickness. It can be seen that the midpoint was initially at a liquid state and then starts to cool down as heat is released by the module to the heat transfer fluid outside the module. When temperature reaches the freezing temperature and solidification starts, the temperature becomes almost constant as it passes through the mushy zone. After some time, the temperature decreases again until reaching the equilibrium temperature which indicates the completion of energy extraction. It can be also observed that when the optical thickness of the PCM is equal to 0, the PCM temperature reached the equilibrium temperature after 70 minutes whereas, it takes 25 and 18 minutes with optical thicknesses equal to 0.5 and 2&4, respectively. When the optical thickness equals to 0.5, energy extraction time was reduced by approximately 65 %; while in case of optical thickness equal to 2 & 4, energy extraction time was reduced by 74 % when compared to the case with optical thickness equals to 0.

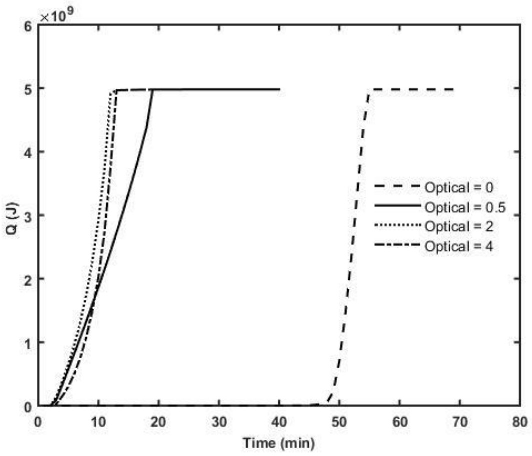


Fig. 5. Total heat retrieved during solidification.

Fig. 5 demonstrates the variation of total energy release rate of the latent heat energy storage system with different optical thicknesses. In the beginning, the PCM releases the heat in the form of sensible heat. As soon as the phase change temperature is reached, the heat will release in the form of latent heat. Similarly, when the temperature passes the phase change temperature, heat is released again in the form of sensible heat. It can be clearly seen in Fig. 5 that the heat release time from the storage system improved significantly with increase in the optical thickness of the PCM medium, given that the PCM with optical thickness equal to 4 has the shortest energy discharge time, followed by the PCM with optical thickness equal to 2 and 0.5, respectively.

V. Conclusion

Numerical modeling of the energy extraction process in a latent heat energy storage module has been performed. The solidification process of a semitransparent phase change material blended with radiation absorbing nano particles in a two-dimensional finned cylinder has been investigated. The three heat transfer mechanisms i.e. conduction, convection, and radiation during high temperature solidification process have been considered in this study to explore the enhancement of energy recovery from a phase change thermal energy storage system for possible baseload renewable power generation. The variation of the distribution of solid and liquid phases, tracking of the temperature profile, and total energy released with time are presented. It was found that the cooling of PCM was dominated by thermal radiation. The case with higher amount of radiation absorbing particles yielded lesser cooling time. This is due to higher optical thickness of the phase change material. It was found that the energy extraction time for the highest amount of the absorbing particles showed a reduction of about 74% when compared to transparent PCM with no absorption of radiation. The results of this study can be useful for designing an efficient latent heat energy storage system that can be integrated to a concentrated solar thermal power plant.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Marwan Belaed developed the numerical model, carried out calculations, and prepared plots for presentation. Muhammad Mustafizur Rahman wrote the paper using the results reported by Marwan Belaed. All authors have approved the final version.

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