Development of a Phase Change Energy Storage Module with High Recovery Rate for Power Generation Applications

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ABSTRACT

Using phase change materials (PCMs) as a storage medium has gained great attention because of its low cost and desirable size. But poor thermal conductivity makes the use of PCM challenging as this dramatically increases the time needed to charge and discharge the energy storage module. 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. The present study investigated combined enhancement of heat conduction and thermal radiation in a finned cylinder during melting (energy storage) and solidification (energy recovery) of a non-gray, non-opaque phase change material. Transient heat transfer in an axisymmetric, two-dimensional design is considered. It was found that melting and solidification times can be reduced by 65% and 76% respectively by controlling the optical thickness property of the PCM with embedded radiation absorbing particles.

Keywords: Thermal energy storage module, Melting, Solidification, Phase change material.

1. INTRODUCTION

Solar energy is the most attractive form of renewable energy for electric power generation because of several advantages including being freely available, low cost, friendly to the environment, and sustainable. It is an option for the reduction of fossil fuel consumption that heavily contributes to the generation of greenhouse gases. Concentrated solar power is a feasible option because of large amount of incoming radiation from the sun that can be used with high conversion efficiency and low cost if integrated with an efficient energy storage system to cover cloudy days as well as nights. The development of a renewable power generation systems for baseload operation is expected to result in greatly reduced greenhouse gas production and therefore the threat of global warming.

The aim of this study is to develop an energy storage system that can be integrated with a concentrated solar power plant for the possible integration of renewable energy in baseload power generation. Most thermal energy storage systems that have been commercially deployed to date use sensible energy storage using a solid or liquid material. However, a latent heat energy storage system using phase change materials provides a significant advantage over the sensible heat energy storage system because of higher specific energy storage capacity which leads to a smaller storage tank and therefore a lower capital cost. The discharge of stored energy in the phase change materials can keep up the relatively high temperature of the heat transfer fluid required to maintain its potential to produce work in the power generation system when the direct collection of solar energy in a concentrated solar receiver is not available during nights and cloudy days.

One major drawback of using a commercially available phase change material in a large-scale system is its low thermal conductivity. This may cause a negative effect by reducing the rate of heat transfer which slows down the charging and discharging processes. The design of the system can be improved by using fins to provide extended surfaces for heat transfer [1], building a cascade system by layering different phase change materials with different melting temperatures in the direction of the flow of the heat transfer fluid [2], mixing the phase change material with micro/nanoparticles to improve thermal conductivity [3-4], and housing the phase change material in a tank with micro or macro-encapsulation for intimate heat transfer [5].

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 and convection. The rate of heat transfer by conduction and convection modes are linearly proportional to the temperature difference. On the other hand, the radiation heat transfer is proportional to the difference of temperature to the power of four. A material with low thermal conductivity can create an obstacle to the transport of heat during the process of phase change during charging and discharging of the energy storage system. This can be removed in a transparent phase change material by intimately mixing it with radiation absorber particles which changes the optical thickness of the medium. In this study, an infrared transparent phase change material combined with different concentration of heat absorbing nanoparticles for achieving a tailored absorptance for improving the radiative heat transfer in the phase change material packed in an internally finned cylinder that has an inner surface coated with a high emissivity material has been investigated. The purpose of this research is to investigate the influence of heat transfer rate between the radiating finned tube and the phase change material on the melting and solidification time of the phase change material which directly controls the rates of energy storage and release respectively in the thermal energy storage module. The selection of the phase change material was done by considering lower cost but higher heat capacity which simultaneously contribute to the reduction of the cost and the size of the energy storage tank and have a reasonably high melting temperature to open the possibility of renewable power generation with high thermal efficiency. Based on these requirements, Sodium Chloride (NaCl) was selected as the phase change material for this study which has the melting temperature in the range 800-802 ºC. In this investigation, the melting and solidification processes of the phase change material during charging and discharging of the internally finned cylindrical thermal energy storage module filled with Sodium Chloride along with uniformly distributed radiation absorption particles as shown in Figure 1 has been analyzed. The effects of temperature at the wall and optical thickness of the phase change medium on the melting and solidification processes have been modeled and simulated numerically. The novelty of the present investigation is the exploration of the effects of radiation in the enhancement of energy storage rate in a high melting/solidification temperature phase change material for potential application in baseload concentrated solar thermal power generation.

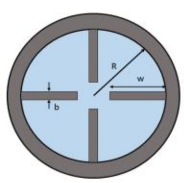

Fig. 1. Schematic of the energy storage module.

2. ANALYSES

We considered a two-dimensional axi-symmetric finned cylinder containing a phase change material as shown in Figure 1. The cylindrical energy storage module is 250 mm in length and 100 mm in diameter. There are 4 fins with length of 30 mm. The fins as well as the cylinder have a thickness of 1 mm. The phase change energy storage module is filled with Sodium Chloride mixed with a small concentration of radiation absorbing nanoparticles as the phase change composite material, which can absorb, conduct, emit and scatter any radiant energy. The inner surface of the shell as well as the fins have been considered as opaque, gray and diffuse surfaces. The thermo-physical properties of the phase change material (NaCl) as reported by Archibold et al. [5] and Rao et al. [6] have been used. These are listed in Table 1. A few assumptions were made in modeling the phase change energy storage system. These include: (a) the PCM is homogeneous and its properties are independent of temperature except for the density in the momentum equations, (b) the melting and solidification happen in the temperature range of 800–802 ºC, (c) the concentration of radiation absorbing particles is small enough that it does not affect the bulk properties of the phase change material except for thermal radiation properties, (d) the inner surfaces are coated with a high and uniform emissivity material, and (e) negligible contact resistance between the wall surface and the fins. Equations governing the conservation of mass, momentum, and energy were solved using the finite volume method. Enthalpy porosity formulation was used to model the solid-liquid phase change process. The discrete ordinate method was used to model the radiative transport in the semi-transparent medium with absorption, transmission, and emission at the walls as well as in the medium. The problem is symmetric about the vertical plane passing through the axis of the cylinder and mid-plane of two vertical fins. Therefore, only one half of the cylinder can be used for modeling and numerical computation. In addition, due to the assumption of long cylinder where effects of end caps can be ignored, the problem can be modeled as two-dimensional with no variation along the length of the cylinder.

Table 1 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)	$0.269 + 9.07 \times 10^{-4}$ 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)	$0.0034 - 2.194 \times 10^{-6}$ T
Melting temperature (ºC)	800.2-800.7
Absorption coefficient (m^{-1})	0–80
Latent heat of fusion (J/Kg)	479,289
Thermal expansion coefficient (K^{-1})	6.82×10^{-5}

To validate the computational scheme, the experimental data reported by Jones et al. [7] was used. This study considered the melting of paraffin in a vertical cylinder. For a fair comparison, fins were taken out and the same conditions that were used in the experimental study was reproduced for the numerical simulation. Fig. 2 demonstrates that a good agreement was reached between the results from our numerical simulation and the experimental data indicating that the simulation model developed in this study is fairly accurate.

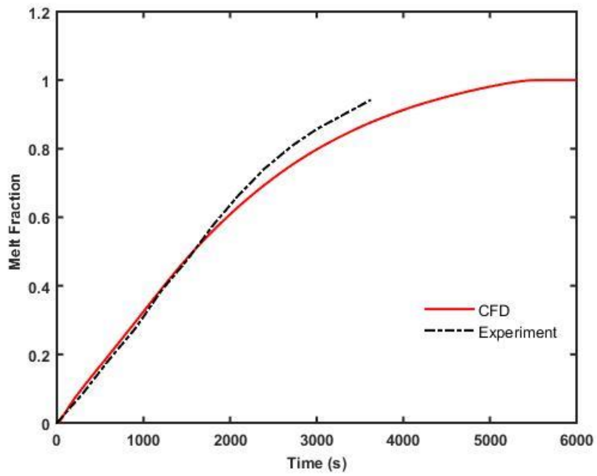

Fig 2. Comparison of numerical solution with experimental data reported by Jones et al. [7].

3. RESULTS FOR CHARGING

Figure 3 presents the effects of the optical thickness on the melting rate. Four different values of the optical thickness (0, 0.5, 2, and 4) were selected to compare the transport in a transparent medium with transport in a participating medium with different degree of absorption of radiation by the medium. It can be observed that all cases having radiation absorbing particles showed faster melting. At 5 minutes, the heat transfer starts forming the first melting layer and moves inward as time increases. The total transition time variation depends on the concentration of the radiation absorbing particles in the phase change material. Increasing the optical thickness from 0 (no absorbing particle – fully transparent phase change material) to 4 decreases the melting time (to reach liquid mass fraction of 0.999) from 92 min to 32 min, which is approximately 65%.

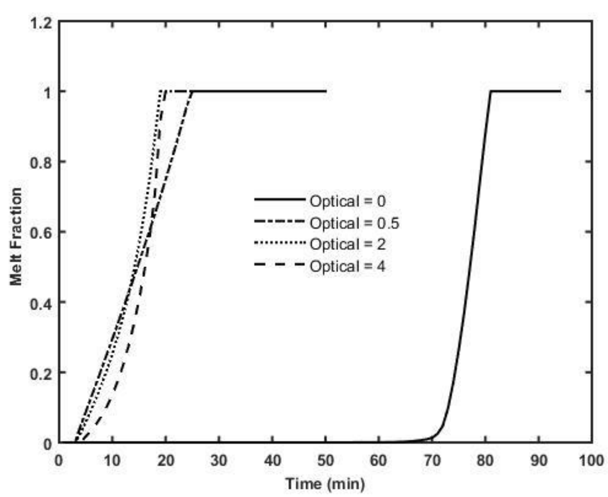

Fig. 3. Effects of the optical thickness on charging time.

Figure 4 presents the effect of the optical thickness on temperature profile of the phase change material at the center of the finned cylinder during the charging process. We can observe that an increase of optical thickness property by inserting radiation absorbing particles in the phase change material improves the melting rate resulting in faster initiation of melting happening around 4 minutes comparted to around 30 minutes for transparent phase change material (optical thickness = 0). This is because of marked improvement of transport by radiation compared to regular modes of conduction and convection heat transfer.

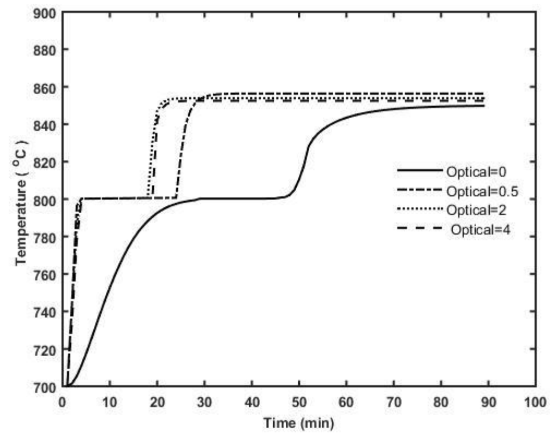

Fig. 4. The effects of the optical thickness on the center point temperature.

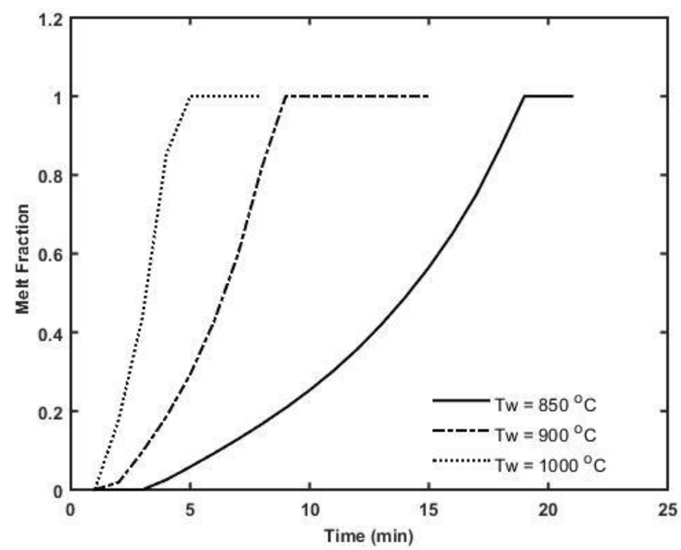

Fig. 5. Effect of heat transfer fluid temperature on melt fraction.

The inlet temperature of the heat transfer fluid is an important parameter that needs a high level of attention in the design of thermal energy storage systems using phase change materials. Higher charging temperature of the heat transfer fluid causes a lowering of charging time. For this part of the investigation, the composite phase change material with an optical thickness equal to 2 was considered. Figure 5 demonstrates the variation of the liquid fraction during a complete charging process for three different values of the inlet temperature of the heat transfer fluid. We can observe from Figure 5 that a higher inlet temperature of the heat transfer fluid increases the heat exchange between the outer and inner surfaces, which in turn increases the heat radiation inside the cylinder. The charging process takes 20 minutes when the inlet temperature of the heat transfer fluid is 850 ^oC. It reduces to 10 and 5 minutes when the inlet temperature of the heat transfer fluid is increased to 900 ^oC and 1000 ^oC, respectively.

4. RESULTS FOR DISCHARGING

The variation of total energy release rate of the latent heat energy storage system with different optical thicknesses is presented in Fig. 6. In the beginning of the process, the phase change material releases the heat in the form of sensible heat. As soon as the phase change temperature is reached, the heat releases in the form of latent heat. Similarly, when the temperature passes the phase change temperature, heat is again released in the form of sensible heat. It can be observed that the heat release time from the thermal energy storage system became significantly smaller with increase in the optical thickness of the medium. The composite phase change material with optical thickness equal to 4 has the shortest energy release time, followed by the medium with optical thickness equal to 2 and 0.5, respectively.

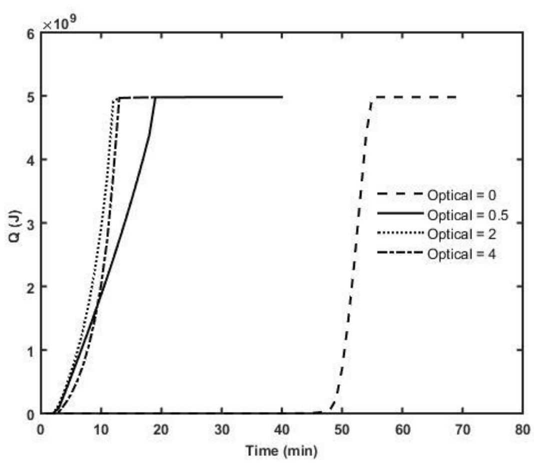

Fig. 6. Heat retrieved during discharging.

5. CONCLUSION

The results of a comprehensive numerical analyses of a thermal energy storage module containing fins and radiation absorbing nanoparticles in the phase change material during charging and discharging processes are presented. Four different optical thicknesses have been considered: 0, 0.5, 2, and 4. Three different heat transfer fluid inlet temperatures (850, 900, and 1000 ^oC) have been investigated. It was found that the melting rate which is directly related to the charging rate of the energy storage module increases significantly in the presence of thermal radiation. Increase in the concentration of the radiation absorbing particles enhances the total heat transfer rate and consequently the melting rate. The charging time of the energy storage module could be reduced by as much as 65% by using fins and radiation absorbing particles. It was also found that the inlet temperature of the heat transfer fluid had significant effects on the melting rate of the phase change material and should be considered while designing energy storage modules. The detailed analyses of the energy discharge process also showed significant influence of thermal radiation and enhancement of that using the radiation absorbing nanoparticles. The results of this investigation can be quite useful for designing an efficient latent heat energy storage system that can be integrated to a concentrated solar thermal power plant.

REFERENCES

[1] X. Yang, Z. Lu, Q. Bai, Q. Zhang, L. Jin, and J. Yan, “Thermal performance of a shell-and-tube latent heat thermal energy storage unit: role of annular fins,” Applied Energy, Volume 202, Pages 558-570, 2017.

[2] T.K. Aldoss and M.M. Rahman, “Comparison between the single-PCM and multi-PCM thermal energy storage design,” Energy Conversion and Management, Volume 83, Pages 79-87, 2014.

[3] A. Elgafy and K. Lafdi, “Effect of carbon nanofiber additives on thermal behavior of phase change materials,” Carbon, Volume 43, Pages 3067-3074, 2005.

[4] J. Khodadadi and S. Hosseinizadeh, “Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage,” International Communications in Heat and Mass Transfer, Volume 34, Pages 534-543, 2007.

[5] A.R. Archibold, M.M. Rahman, D.Y. Goswami, E.K. Stefanakos, “The effects of radiative heat transfer during the melting process of a high temperature phase change material confined in a spherical shell,” Applied Energy, Volume 138, Pages 675-684, 2015.

[6] A.S.M. Rao, K. Narender, K.G.K. Rao, N.G. Krishna, “Thermophysical properties of NaCl, NaBr, and NaF by γ-ray attenuation technique,” Journal of Modern Physics, Volume 4, Pages 208-214, 2013.

[7] B. Jones, D. Sun, S. Krishnan, S. V. Garimella, “Experimental and numerical study of melting in a cylinder,” International Journal of Heat and Mass Transfer, Volume 49, Pages 2724-2738, 2006.