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Experimental investigation of phase change material melting in rectangular enclosures with horizontal partial fins

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ABSTRACT

This paper presents an experimental investigation of phase change material (PCM) melting in a transparent rectangular enclosure with and without horizontal partial fins. The enclosure was heated isothermally from one side while the other walls were thermally insulated. Experiments were performed with wall temperatures of 55, 60 and 70 °C ($3.6 \times 10^8 \leqslant Ra \leqslant 8.3 \times 10^8$) for finned and unfinned enclosures. Visualization of the melting process and the temperature field were performed directly. Both qualitative and quantitative information about the melting phenomena were obtained using digital photographs of the instantaneous melt front evolutions and temperature recordings at the vertical mid-plane of the enclosure. Temperature histories revealed that the thermally stratified region became smaller as the number of fins increased. Experimental data were used to calculate melt fractions, heat transfer rates and Nusselt numbers during the melting process. Furthermore, two correlation equations were developed using the dimensionless parameters to predict the Nusselt number and melt fraction. Also, in order to evaluate the improved thermal performance of the enclosure in the presence of partial fins, two other parameters were defined, melting enhancement ratio and overall fin effectiveness. Experimental results indicated that increasing the number of fins decreased the melting time and increased the total heat transfer rate while the surface-averaged Nusselt number reduced. Melting enhancement ratio and overall fin effectiveness increased with increasing the number of fins and decreased with raising the wall temperature. Melting enhancement ratios decreased with time after reaching some maximum values indicating that partial fins are more beneficial during the initial time of the melting.

1. Introduction

Thermal energy can be stored in a material as sensible heat by raising its temperature or as latent heat during the phase change process. Sensible heat storage systems have low specific heat capacity. On the other hand, thermal energy storage systems based on phase change materials (PCMs) are particularly attractive because of their high energy storage capacity and isothermal behavior during charging (melting) and discharging (solidification) processes. There is a wide range of applications for PCMs such as solar thermal systems [1,2], desalination [3], heat recovery [4], buildings [5,6], refrigeration [7], electronics cooling [8,9] and spacecrafts [10,11].

PCMs can be generally classified into metallic and nonmetallic groups. Metallic PCMs such as tin and gallium have high thermal conductivity but they are rarely used for commercial purposes due to their high cost, high density and very high or low phase change temperature. In contrast, nonmetallic PCMs including paraffins, fatty acids and hydrated salts have lower cost and a wider range of melting temperature which make them as promising candidates for different thermal applications. However, they suffer from low thermal conductivity leading to slow charging and discharging rates, hence requiring heat transfer enhancement techniques. Various methods for heat transfer enhancement of PCMs have been proposed and studied by many researchers. Some of the most common methods include using extended surfaces [12–17], impregnation of porous materials [18–21], placement of high thermal conductivity metal structures [22,23], embedding heat pipes [24,25], dispersing high conductivity particles [26–28], adding carbon fibers [29,30] and carbon nanotubes [31,32]. Dispersing high thermal conductivity materials into PCMs seems to be less practical compared with incorporating metal structures into PCMs since the dispersed material usually agglomerates and sediments to the bottom of the enclosure in long-term operation [33]. It has been reported that low concentration of nanoparticle in PCM can improve the melting rate. However, melting rate is decelerated in the presence of high concentration of nano-additives as a result of the increased viscosity which leads to a significant degradation of natural convection during the melting process [34,35].

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Nomenclature

A_w	total heat transfer area including base and fins (m^2)
D	depth of the enclosure (m)
$Fo = \frac{\alpha t}{H^2}$	Fourier number
H	height of the enclosure (m)
HAR	heat transfer area ratio
$\bar{h}$	surface averaged heat transfer coefficient (W/m^2 K)
h_{SL}	latent heat (kJ/kg)
k	thermal conductivity (W/m K)
L	fin length (m)
N	number of fins
$\overline{Nu}(t)$	surface averaged Nusselt number
$\langle \overline{Nu} \rangle$	time averaged Nusselt number
$\overline{Q}(t)$	surface averaged heat transfer rate
$\langle \overline{Q} \rangle$	time averaged heat transfer rate
$Ra = \frac{g\beta(T_w - T_m)H^3}{\nu\alpha}$	Rayleigh number based on the height of the enclosure
Ste^*	modified Stefan number
t	time (s)
T	temperature (°C)
T_m	melting temperature (°C)
T_w	wall temperature (°C)

Greek symbols

$\varepsilon_{\text{fin overall}}$	overall fin effectiveness
α	thermal diffusivity (m^2/s)

Using high thermal conductive fins in latent heat thermal storage systems is one of the simple, reliable and effective approaches to enhance the melting rate. Hence, this study is focused on the use of fins to improve the melting rate of the PCM. There are many studies related to heat transfer enhancement in PCM enclosures equipped with metallic internal fins. These researches can be divided into two groups based on the fin type: partitioning fin or partial fin.

Partitioning fins extend into the PCM from the hot wall and divide the PCM enclosure into smaller individual enclosures so that the PCM is confined between the fins [36–38]. Reddy [36] carried out a numerical study on the melting process of paraffin wax in a solar integrated collector water heating system. The PCM was stored in a tilted rectangular enclosure heated from top and cooled from below. The simulation was performed with 4, 9 and 19 partitioning fins and without fins. Finned enclosures showed higher melting rates in comparison with enclosures without fins, while the best performance was attained with 9 fins.

Gharebaghi and Sezai [37] investigated the enhancement of energy storage rate in a rectangular enclosure with partitioning fins which was filled with paraffin (RT27). Both horizontal and vertical modules were investigated with different fin spacings and wall temperatures. The heat transfer increased with decrease in the fin spacing for both the vertical and horizontal modules. It was also found that there is no distinct difference between the melting time of horizontal and vertical modules.

Huang et al. [38] evaluated the effect of applying PCM on limiting the temperature rise of a silicon photovoltaic device and consequently maintaining the electrical conversion efficiency of the photovoltaic module. The average temperature on the front surface of the system was measured for finned and unfinned cases. The temperature rise on the front surface decreased and thermal stratification within the PCM reduced as the number of fins increased. Despite the beneficial effect of adding partitioning fins, the reduced time of the temperature control and increased weight of the system due to the metal fins were mentioned as potential problems of this system.

Shatikian et al. [12] numerically simulated melting of PCM (paraffin wax) between partitioning vertical fins in a horizontal heat sink with constant base temperature. They performed a parametric study to consider the effect of fin length, fin thickness and fin spacing on melting rate. The melting rate accelerated as the fin spacing decreased. They generalized the results through dimensional analysis and showed that for wide vertical PCM layers, convection motion in the melted PCM should be taken into account. In another study, the same authors [39] considered the melting process in the same physical model by applying a constant heat flux to the horizontal base plate.

Akhilesh et al. [17] performed a numerical study to find the appropriate size of composite heat sink constructed from a vertical array of partitioning fins extended downward from a horizontal base plate. The study excluded the role of natural convection inside the melted PCM and found that increasing the number of fins beyond a critical value does not show any significant enhancement in thermal performance of the composite heat sink.

Levin et al. [40] presented an optimization procedure for the design of a PCM based heat sink used for transient cooling of electronic devices. Neglecting the internal convection in the liquid PCM, it was found that optimal PCM percentage depends on the number and length of the fins, heat flux, and the difference between the critical and melting temperature of the PCM.

Wang et al. [41] numerically investigated the effect of orientation of a PCM (paraffin wax) based heat sink with vertical partitioning fins. It was concluded that the orientation of the heat sink has a limited effect on the thermal performance of the system.

Unlike the partitioning finned enclosure in which the PCM is confined between the fins, in an enclosure with partial fins, the melted PCM can flow between the fins. Plate fins with a length less than the PCM thickness [42,43] and pin fins [13] can be classified as partial fins.

Lacroix and Benmadda [42] studied convection-dominated melting of PCM (*n*-octadecane) in a vertical rectangular enclosure with partial plate fins which extended horizontally from the heated wall. The study included the effect of number and length of the fins on the melting rate. It was concluded that a few longer fins significantly accelerate the melting process while the effect of shorter fins is much less significant. Applying a few longer fins was found to be more efficient for reducing the melting time than increasing the temperature of the vertical wall.

Huang et al. [43] numerically and experimentally investigated thermal regulation of building integrated photovoltaic system by applying PCM in a rectangular enclosure attached to the rear side of the photovoltaic module. The effect of using partial plate fins on operational efficiency of the photovoltaic facade was studied. Thermal performance of the photovoltaic system was increased by using metal fins in the PCM enclosure. However, increased number of fins hampered the convection driven flow of the melted PCM and decreased the beneficial effect of natural convection on regulating the temperature of the photovoltaic module.

Baby and Balaji [13] investigated the thermal performance of finned heat sinks filled with PCM (*n*-eicosane) for thermal management of electronic devices. Experiments were performed for heat sinks with vertical fins (partitioning or pin fins) and without fins while a uniform heat load was applied to the base plate. Among the fin geometries, the heat sink with pin fins showed the maximum performance.