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Heat transfer correlations for PCM-based heat sinks with plate fins

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ABSTRACT

Characterization of melting process in a Phase Change Material (PCM)-based heat sink with plate fin type thermal conductivity enhancers (TCEs) is numerically studied in this paper. Detailed parametric investigations are performed to find the effect of aspect ratio of enclosure and the applied heat flux on the thermal performance of the heat sinks. Various non-dimensional numbers, such as Nusselt number (*Nu*), Rayleigh number (*Ra*), Stefan number (*Ste*) and Fourier number (*Fo*) based on a characteristic length scale, are identified as important parameters. The half fin thickness and the fin height are varied to obtain a wide range of aspect ratios of an enclosure. It is found that a single correlation of *Nu* with *Ra* is not applicable for all aspect ratios of enclosure with melt convection taken into account. To find appropriate length scales, enclosures with different aspect ratios are divided into three categories, *viz.* (a) shallow enclosure, (b) rectangular enclosure and (c) tall enclosure. Accordingly, an appropriate characteristic length scale is identified for each type of enclosure and correlation of *Nu* with *Ra* based on that characteristic length scale is developed.

1. Introduction

Thermal management issues for electronic devices arise because of their increased functionality, complexity and compactness, thus resulting in high heat dissipation. In this context, phase change material (PCM)-based cooling technique is a viable and potential solution due to their high latent heat storage [1–4]. This cooling technique is widely used as an alternative cooling method for various applications such as wearable computers, power electronics, communication equipment, space craft and avionics. Passive thermal management scheme of PCMs can be used in situations where heat dissipation is periodic or transient.

The phase change behavior of PCM is extensively studied experimentally and numerically for the last few decades. Ho and Viskanta [5] reported an experimental study on the evolution of melt front and heat transfer during melting and solidification of *n*-Octadecane in a two-dimensional rectangular cavity consisting of a heated bottom and two conducting sidewalls. Various aspect ratios of the cavity were used. The study showed that natural convection during melting plays an important role on melt shape, melting rate and heat transfer. The effect of initial subcooling of the solid on melting process was also studied. A correlation was also developed between Nusselt number and Rayleigh number based on a characteristic length corresponding to the instantaneous melt layer thickness. Choi and Cho [6] experimentally investigated the thermal performance of PCM (paraffin) slurry flowing through a rectangular channel with an aspect ratio of 0.2 in a multi chip module. They concluded that the use of PCM slurry improved the performance, compared to the water cooling for highly integrated multi chip modules. Zhang and Bejan [7] studied melting of *n*-Octadecane in a tall enclosure (aspect ratio $\sim$ 5) with a constant heat flux supplied from one of the sidewalls. The temperature of the opposite wall was kept constant. They developed a steady state heat transfer correlation between Nusselt number (*Nu*) and Rayleigh number (*Ra*) based on heat flux and the height of enclosure. Gadgil and Gobin [8] simulated numerically two-dimensional melting of a phase change material in a rectangular enclosure heated from one side. Their results show that aspect ratio of enclosure has a strong influence on the melting curve. Pal and Joshi [9] established, computationally and experimentally, the role of melt convection while investigating transient characteristics of melting of *n*-Triacontane in a side heated tall enclosure of aspect ratio 10, by a uniformly dissipating heat source. They developed correlations for the volumetric molten fraction and heat transfer rates based on the constant heat flux to design a PCM-based heat sink with vertically mounted heat source.

However, nearly all organic PCMs have unacceptably low thermal conductivity which makes it difficult to utilize the heat storage capacity completely. The rate of heat transfer can be

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Nomenclature

A	Area (m^2)
g	Acceleration due to gravity (m/s^2)
h	Convective heat transfer coefficient at the interface between fin and PCM ($W/m^2.K$)
H	Height of fin (m)
H_b	Height of base plate (m)
c	Specific heat (J/kg·K)
k	Thermal conductivity (W/m.K)
L	Length (m)
L_p	Latent heat of fusion of PCM (J/kg)
Nu	Nusselt number
P	Pressure (Pa)
$2p$	Pitch (m)
q''	Heat flux (W/m^2)
Ra	Rayleigh number
Ste	Stephan number
Fo	Fourier number
S	Source term ($kg/m^2 \cdot s^2$ or W/m^3)
t	Time (s)
t_f	Half fin thickness (m)
T	Temperature (°C)
ΔT	Temperature difference (°C) *i.e.* ($T_b - T_m$)
u_i	Velocities in x, y and z directions (m/s)
V	Volume (m^3)
x, y, z	Coordinate axes

Greek symbols

α	Thermal diffusivity (m^2/s)
ε	Liquid fraction
β	Thermal expansion coefficient (1/K)
ρ	Density (kg/m^3)
μ	Dynamic viscosity (Pa-s)
γ	Kinematic viscosity (m^2/s)

Subscript

b	Base
c	Cooling period
f	Fin
h	Heating period
p	PCM
∞	Ambient
m	Value at melting temperature
ref	Reference state

enhanced by incorporating high thermal conductivity materials, known as thermal conductivity enhancer (TCE) into the PCM. TCE is distributed in the PCM in the form of metal matrix, fins and uniformly dispersed high thermal conductivity particles. In case of fins, TCE can be distributed in two ways, *viz. (i)* plate type fins and *(ii)* pin type fins. Most of the experimental and numerical studies are concentrated on the plate type PCM-based heat sinks. Wirtz et al. [10] reported the evaluation of a solid- solid dry PCM (organic compounds) incorporated in a plate fin heat sink, under natural convection air cooling. The solid- solid PCM was filled in the lower portion of the space between fins. They presented advantages of the use of the dry PCM by comparing thermo physical properties of solid- solid organic compounds, paraffin compounds, salt hydrates and a metallic alloy. Nayak et al. [11] developed a generalized computational model to evaluate the performance of some common types of TCE distribution considering conduction heat transfer in the solid regions and natural convection heat transfer in the melted PCM. They concluded that the addition of TCE in PCM leads to lower chip temperature. It is also evident from the work of Nayak et al. [11] that the melt convection plays a significant role in the thermal performance of a PCM-based heat sink. The melt convection improves the temperature uniformity by enhancing the effective heat transfer coefficient within the PCM. Recently, Saha and Dutta [12] investigated the role of melt convection on the optimum design of plate type PCM-based heat sink. They found that the optimum fin pitch with melt convection is different from that without melt convection.

As several geometric and other parameters influence melt convection which ultimately determines the performance of a PCM-based heat sink, it is important to establish heat transfer correlations based on relevant non-dimensional numbers. Recently, Shatikian et al. [13] proposed a correlation of Nusselt number with the combination of Rayleigh number, Stefan number and Fourier number based on constant heat flux. They analyzed PCM-based heat storage unit where the top surface of internal fins are exposed to air. They considered two Rayleigh numbers based on height and half pitch of fin in the correlation. However, the model was not tested for a wide range of aspect ratios of PCM-based heat sink, and hence the correlations may be applicable only in a limited sense only.

In the present paper, characterization of melting process in a plate fine type PCM-based heat sink heated uniformly from the bottom is presented. The melt convection generally depends on various non-dimensional numbers, such as Nusselt number (Nu), Rayleigh number (Ra), Stefan number (Ste) and Fourier number (Fo), based on a characteristic length scale. The enclosure is the space enclosed by two fins and the base plate of the heat sink. The aspect ratio (a_p) of an enclosure changes either with fin pitch or with its height. The objective is to investigate the effect of aspect ratio of enclosure in heat sink on the Nu–Ra relation. Based on the aspect ratio ranges, the PCM-based heat sinks are categorized into three types of enclosures, *viz.* (a) shallow enclosure, (b) rectangular enclosure and (c) tall enclosure. The physics of melt convection and heat transport, and hence the appropriate length scale for calculation of Rayleigh number will be different for each type of enclosure. In other words, a single correlation of Nu–Ra relation is not likely to hold good for the entire range of aspect ratio. The aim of the present work is to derive correlations on the basis of appropriate characteristic length scales for each type of enclosure.

2. Description of the physical problem

A typical thermal storage unit (TSU) used for electronic cooling is shown schematically in Fig. 1(a). It consists of plate-fin type TCE of uniform thickness ($2t_f$) with a base plate of thickness, H_b and PCM is filled in the space ($2p$) between fins. A constant heat flux, q'' is distributed uniformly at the bottom of the TSU. Fig. 1(b) shows an elemental TSU which represents a symmetrical domain chosen for the analysis. The aspect ratio (a_p) of an enclosure is defined as $H/2p$, which is the ratio of height of fin and the spacing between two fins. The length of the heat sink (L) is chosen in such a way that at the beginning of the numerical analysis, aspect ratio of the enclosure is small, *i.e.* $H/2p \rightarrow 0$. In this study, the length *(L)* of the heat sink is taken as 20 mm. The base height *(H_b)* is kept constant at 2 mm. Fin height (H) and half fin thickness (t_f) are varied to obtain different aspect ratios ($H/2p$). The half fin thickness *(t_f)* is varied as 0.2, 2.2, 4.2, 6.2, 8.2, 9.2 and 9.9 mm, whereas the total height ($H + H_b$) of the heat sink is varied as 2.7, 3.1, 5, 10, 20, 25, 30, 35 and 40 mm.