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Method to improve geometry for heat transfer enhancement in PCM composite heat sinks

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Abstract

Use of composite heat sinks (CHS), constructed using a vertical array of 'fins' (or elemental composite heat sink, ECHS), made of large latent heat capacity phase change materials (PCM) and highly conductive base material (BM) is a much sought cooling method for portable electronic devices, which are to be kept below a set point temperature (SPT). This paper presents a thermal design procedure for proper sizing of such CHS, for maximizing the energy storage and the time of operation until all of the latent heat storage is exhausted.

For a given range of heat flux, q'', and height, A, of the CHS, using a scaling analysis of the governing two dimensional unsteady energy equations, a relation between the critical dimension for the ECHS and the amount of PCM used (ϕ) is determined. For a ϕ, when the dimensions of the ECHS are less than this critical dimension, all of the PCM completely melts when the CHS reaches the SPT. The results are further validated using appropriate numerical method solutions. A proposed correlation for chosen material properties yields predictions of the critical dimensions within 10% average deviation. However, the thermal design procedure detailed in this paper is valid, in general, for similar finned-CHS configurations, composed of any high latent heat storage PCM and high conductive BM combination.

Keywords: Heat transfer enhancement; Scale analysis; Phase change material; Composite heat sink; Electronics cooling

1. Introduction

Thermal management is seen as one of the most significant bottlenecks in the development of faster microprocessors used in portable electronic devices [1]. As the reliability of the electronic components is a very strong function of temperature [2], their cooling (thermal) design should successfully address the issue of keeping the working temperature of such devices below a critical value, characteristic of individual configurations.

Use of phase change materials (PCM) based heat sinks are prevalent in the recent decade [2–6] in cooling portable devices such as palm pilots, cellular phones and personal digital assistants, as these devices seldom are used for more than a few hours continuously at peak load and their 'idle' time is typically long enough to solidify the molten PCM for reuse. PCMs are also

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Nomenclature

A	height of the CHS, m, Fig. 1
b	melt-front distance from x axis at a given time t, m, Fig. 2
B	width of PCM in ECHS, m, Fig. 2, Eq. (10)
BM	base material, Table 1
c	specific heat, kJ/kg K
CHS	composite heat sink
D	overall width of CHS, m, Fig. 1
E	energy per unit area, J/m^2
ECHS	elemental composite heat sink
E_R	enhancement ratio, Eqs. (9) and (27)
F	number of fins (1 fin = 2 × ECHS) per unit length, Eq. (12)
k	thermal conductivity, W/m K
L	latent heat of PCM, kJ/kg
N	number of fins (1 fin = 2 × ECHS), Eq. (11)
PCM	phase change material, Table 1
q''	heat flux, W/m^2
SPT	set point temperature criterion, Eq. (1)
Ste	Stefan Number, Eq. (21)
t	time, s
T	temperature, °C
x, y	Cartesian coordinates

Greek symbols

γ	heat capacity ratio, Eq. (22)
Γ	net energy inside ECHS calculated numerically/$[q''(B + d)t]$
δ	width of BM in ECHS, m, Fig. 2
ϕ	ratio of volume of PCM to total volume of CHS
ρ	density, kg/m^3
σ	standard deviation, Eq. (6)
σ_{REL}	relative average deviation, Eq. (26)
τ	time taken by CHS to reach SPT, Eq. (20), s
ζ	length scale factor in correlation Eq. (25)

Subscripts

BM	base material (here, aluminum, Table 1)
c	critical value
i	initial value
I	isothermal case, Eq. (7)
M	melting point
MAX	maximum
NI	non-isothermal case, Eq. (8)
P, PCM	phase change material
SET	set point

used in heat sinks cooling devices where heat dissipation is expected to vary with time [4]. The objective of PCM usage in such instances is to keep the temperature of the electronic device below a critical temperature—usually the junction temperature of silicon, which is 90 °C [5,6].

However, PCMs (such as paraffin, Eicosane) are characterized by very low thermal conductivity [7,8] and so directly dissipating the heat generated by the electronics into a column of PCM from the top results in the electronic components reaching unsafe temperatures (above their junction temperatures) even before a significant quantity of the PCM melts, not fulfilling the purpose of exhausting the latent heat storage for cooling. In the light of this, active research is being done [2,3,7] in designing a composite heat sink (CHS), involving PCM and a base material (BM) to 'bring' the heat into the PCM—one common CHS design being that of BM fins protruding into a reservoir of PCM [2,9–11]. Sasaguchi and Kusano [10] have performed excellent investigations using quasi-steady models for finned PCM-CHS by treating them as porous media and a similar quasi steady model analysis for finned PCM-CHS geometry not very different from the one considered in this paper has been proposed by Krishnan et al. [11] for a hybrid heat–sink. However, they have not considered the sizing of the geometry of the CHS for better performance. Natural convection inside the molten PCM then becomes important [12,13] which could alter the time of operation of the CHS.

When receiving a constant rate of energy from the electronics (constant heat flux crossing a boundary), an 'efficient' CHS could be one that completely exhausts its PCM latent heat storage (maximum energy is stored) in the longest time (thus increasing the time of operation of the electronics), without allowing the electronics to reach unsafe temperatures. Hence, it is essential that the CHS is designed with a judicious combination of high conductivity BM (carrying away the heat, quickly from the electronics) with the PCM (storing the heat as latent heat). The cost of the CHS is directly related to the quantity of PCM and BM used and their manufacture into 'fin' shapes (Fig. 1a). Hence, this situation translates to the question of how, for a given quantity of PCM, one can choose the 'best' dimensions of BM and PCM within the CHS, for better performance. The objective of this paper is to delineate a design procedure that would answer the above question for a set of CHS design constraints (Table 1).

2. Composite heat sink

Fig. 1 illustrates, schematically, the CHS studied in this paper. The CHS is insulated on all sides but for the top wall through which the heat dissipated from