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Numerical optimization of a PCM-based heat sink with internal fins

Peleg P. Levin, Avraham Shitzer, Gad Hetsroni *

Department of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

This study presents an optimization procedure for the design of a Latent Heat Thermal Management System (LHTMS), used for cooling an electronic device with transient and high heat generation. The LHTMS consists of Phase Change Material (PCM) combined with internal fins, which are used for creating high conductive paths into the PCM.

The optimization is performed with a sole aim of minimizing the LHTMS height, while still maintaining the capability of absorbing the heat generated by the electronic device, and without exceeding the maximum allowable temperature.

Two dimensional, three-parametric, finite element (FEM) simulations are performed, with systematically varying both the number and thickness of the fins under several LHTMS heights.

The optimized results of this study are presented and discussed, emphasizing the derived optimal PCM percentages, which are an essential parameter in designing an LHTMS. These results show that optimal PCM percentages depend on the number and the length of the fins, the heat flux at the interface, and the difference between the critical and liquidus temperatures of the PCM.

1. Introduction

One of the fast advancing technologies, used for stabilizing the temperature of high power density electronics experiencing power spikes, is the incorporation of PCM (Phase Change Material) into traditional heat sinks such as the standard pin fin and the longitudinal plate fins. The advantage of most PCMs is the relatively high thermal storage density which allows the design of a compact and passive LHTMS (latent heat thermal management system). Unfortunately, most of these PCMs have relatively low thermal diffusivities in both the liquid and solid phases. Thus combining pins or longitudinal plate fins inside the PCM improves its heat transfer capabilities due to the high thermal conductivity paths created by the incorporated metal elements. These paths decrease the thermal gradients in the PCM and allow the maintenance of the temperature across it closer to the melting temperature of the PCM.

Shanmugasundaram et al. [1] have investigated numerically the performance of an LHTMS which consists of a metallic container enclosing a series of vertical aluminum fins embedded in a PCM (Aristowax). The thermal performance was investigated by varying the number of fins, while keeping the total mass constant for both the aluminum and the PCM. The investigation was carried out for two additional different values of the total mass. The authors report that an increase in the number of fins leads to a significant improvement in the thermal performance of the system, while also making the temperature distribution across the heat source near-isothermal. In addition, it was found that a very large number of fins does not result in any significant additional gain in the thermal performance.

Leland and Recktenwald [2] have used a finite difference model implemented in MATLAB to optimize the geometry of a PCM heat sink subjected to a constant heat flux at its bottom base and forced convection to the surroundings, at the top. The purpose of the study was solely to minimize the critical time of the heat sink, i.e., the time needed to reach the maximum allowed temperature. They concluded that in such a case, there should be a small gap between the fin tip and the top of the enclosure. The search for the optimal point was performed by a rather simple, trial-and-error, variation of three parameters: the width of the fins, the thickness of the base and the width of the gap between the fin tip and the enclosure rear end, changing each parameter at a time, while the number of fins was held constant for all cases. Effects of convection in the molten PCM, edge effects at the ambient boundary and variations in power density in the heat sink base were neglected in this study. The optimal PCM percentage, obtained in their study, was 72.5% for a heat flux of 16 kW/m^2. Another interesting conclusion was that the isotherms of the PCM were nearly parallel to the longitudinal fin.

Abbreviations: FEM, finite elements method; LHTMS, latent heat thermal management system; PCM, phase change material.

* Corresponding author. Tel.: +972 48 292058; fax: +972 48 238101.
E-mail address: hetsroni@techunix.technion.ac.il (G. Hetsroni).

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Nomenclature

c_p	specific heat	q	power density at the LHTMS interface
d_c	width of the cell	Q	power dissipated by the electronic device
d_F	thickness of the fins	Ra	Rayleigh number
d_I	thickness of the interface	t	time
d_P	breadth of the gap between the fins	T_0	initial temperature of the LHTMS
d_R	thickness of the rear end	T_{cr}	critical/the maximum allowed temperature
g	standard gravity acceleration	T_I	interface temperature
H	height of the LHTMS	T_l	liquidus temperature of the PCM
k	thermal conductivity of the PCM	T_m	average melting temperature of the PCM
ℓ	fins length ratio	T_s	solidus temperature of the PCM
L	length of the LHTMS	W	width of the LHTMS
n_F	number of internal fins	α	thermal diffusivity
n_l	number of fins per unit system width	γ	thermal expansion coefficient
Nu	Nusselt number	ν	viscosity
P	volumetric percentage of PCM		

Akhilesh et al. [3] analyzed an LHTMS, consisting of a heat sink with PCM between its fins. Through analysis and simulations they demonstrated that the maximization of critical times can be achieved when the LHTMS geometry is designed such that complete melting of all the PCM is achieved simultaneously when the critical temperature is reached. Using scaling analysis, the authors came up with an estimate of critical fin thickness which assures complete melting, and presented its correlation vs. PCM percentage. In addition, for the parameters of the study, it was hypothesized that the critical time of the LHTMS increases linearly with PCM percentage.

These findings were obtained for an assumed, one-dimensional linear temperature profile in the molten PCM and lumped-parameter treatment of the fins. Thus, deviations from the numerical results arise as the heat flux to the LHTMS base and/or the fins length increase. Nonetheless, it could be expected, based on their findings [3], that for low heat fluxes and relatively short fins, the optimal PCM percentage would approach unity, as critical times increase linearly with PCM percentage.

Srinivas and Ananthasuresh [4] have implemented the Simple Isotropic Interpolation with Penalty method (SIMP) in performing topology optimization of heat sinks combined with PCM. Topology optimization is a systematic design technique which aims at arriving at an optimal distribution of material within a given design to minimize an objective function while satisfying certain constrains. The method they utilized requires an initial guess for the PCM and aluminum fractions in the design domain. They demonstrated that the optimization might produce only a local minimum in the proximity of the initial guess. A search for the global minimum of the optimization parameter was not discussed in that study.

Shatikian et al. [5,6] explored numerically the melting in a heat storage unit with vertical internal aluminum fins. Three and two dimensional transient simulations were performed using the Computational Fluid Dynamics (CFD) method. In these simulations, a most complete formulation had been attempted, which considered PCM internal convection, PCM volume change associated with phase transition, density and viscosity variation in the liquid PCM and heat transfer to the surrounding air. In a detailed parametric investigation, it was demonstrated how the melting process is affected by changes in the geometry of the system and boundary conditions. Changes in geometry included thickness and length of the fins. While varying the thickness of the fins, the thickness ratio of a fin to a PCM layer was held constant, at an arbitrary ratio of 0.3. A dimensional analysis of the results showed that the Nusselt number and melt fraction depend on the product of the Fourier and Stefan numbers, while for relatively wide vertical PCM layers, the Rayleigh number is also included, accounting for internal convection at advanced stages of melting. The analysis was achieved both for constant temperature and constant heat flux boundary conditions at the base of the heat storage device. The dimensional analysis showed consistent results for both cases. However, it appears that for a constant heat flux at the base, fin efficiency considerations could not be used for generalization.

An advanced optimization technique, based on genetic algorithm (GA) combined with conventional finite volume numerical method, was implemented by Narasimhan et al. [7] for the optimization of a PCM based heat sink. The optimization was performed for 4 parameters representing the geometry of a segment within the heat sink: fin and PCM layer thickness, thickness at the base and rear end of the heat sink. A 16 bit number was used as a signature for a particular design specifying all the variables. In the GA method, an initial population of representative numbers begins to "breed" by implementing crossover and mutation operators. In each generation, a new population is created which retains the "best individuals" of the previous generation and replaces the rest of the "individuals" by their "offspring". The fitness function, which indicates an individual's chances of reproducing and surviving through generations, used in this study, is chosen to account for maximizing critical time and ensuring complete melting of the PCM. Different weights were applied to both optimization parameters while assuring that full utilization of the PCM remains the primary objective. For a constant heat flux of 25 kW/m^2, the optimal thickness of the heat spreading base was 2.5% of the length of the fins, the critical time correlated linearly with the length of the fins with slightly better results than introduced by Akhilesh et al. [3], and, the optimal PCM percentage correlated linearly with the length of the fins in the range of 50 mm to 100 mm, yielding values of 79% and 73% at both ends, respectively. In addition, the total width of the fin and PCM layer thickness was consistently chosen as the minimal boundary set for the parameter, corroborating that the best design should comprise of an infinite number of internal fins with an infinitesimal thickness, to facilitate better heat distribution in the PCM heat sink.

In a recent study, Balaji et al. [8] have attempted to optimize composite heat sinks by considering trapezoidal and parabolic shapes of the internal fins. Although these shapes did not yield any advantage during melting, over rectangular shaped fins with optimal dimensions as presented by Akhilesh et al. [3], it was concluded that, for these shapes, the time required for total resolidification was much lower. It was then proposed to perform a multi-objective optimization, where a compromise is made with regard to the critical time, in order to achieve a shorter period of