Applied Thermal Engineering 91 (2015) 234–244

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Constructal design of horizontal fins to improve the performance of phase change material rectangular enclosures

Rasool Kalbasi, Mohammad Reza Salimpour*

Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

HIGHLIGHTS

- Effect of adding horizontal fins on the efficiency of a PCM heat sink is studied.
- There is in an optimum horizontal fins number at which operation time is maximized.
- Adding complexities to the heat sink will not necessarily improve the performance.

ARTICLE INFO

Article history:
Received 2 June 2015
Accepted 9 August 2015
Available online 20 August 2015

Keywords:
Constructal
PCM
Horizontal fin
Enclosure
Aspect ratio

ABSTRACT

Invoking phase change material (PCM) based heat sinks as a technique for thermal management is an appropriate cooling scheme for transient or short term applications. The latent heat of the most PCMs is desirably high but the thermal conductivity is unacceptable. This issue can be improved by incorporating high conductive fins into the PCM based heat sink. The purpose of the current study is to determine the effect of adding horizontal fins to improve the efficiency of a heat sink. The required time for the maximum temperature of the heat sink to reach its critical value is maximized invoking constructal theory. Degrees of freedom are the number of enclosures, horizontal fins number and heat sink aspect ratio, while the entire surface area and the PCM content are constraints. The results indicate that the best maximum safe operation time occurs in an optimum value for the horizontal fins number. The results show that for low number of enclosures, heat sinks with high aspect ratios are superior; while, for high number of enclosures, heat sinks with low aspect ratios have better performance. Moreover, adding geometrical complexities to the heat sink will not necessarily improve the performance of the enclosure.

1. Introduction

Phase change materials are extensively used for thermal control applications. The latent heat of PCMs is extremely high so that they can absorb significant amount of thermal energy through melting at a short temperature range. PCMs can be used in a type of cooling scheme called passive; also it is used for transient or short term applications. A passive thermal control unit with PCM must have three components, a phase change material, heat exchanger surface and appropriate PCM container. Relying on the thermal or chemical properties of PCMs such as melting point, latent heat and to be congruent, organic paraffin is mainly the most suitable nominees for passive cooling of electronic devices. A detailed list of PCMs which have been studied is addressed in [1].

The thermal conductivity of most PCMs is low. Thus, thermal gradient across the PCM is large and hence thermal performance of a heat sink with PCM is inferior. Several techniques have been studied to enhance the heat transfer in heat sink embedded with PCM. Insertion of metal fins [2], metal foam [3], metal powder [4], using nano PCM [5], different configurations of finned tubes [6] and micro-encapsulation of the PCM [7] are included in some of the techniques.

The shape and size of the PCM container should be selected according to the PCM melting time. PCMs are usually positioned in cylindrical, spherical or rectangular containers. Studies on spherical and cylindrical containers demonstrate that natural convection flow in the liquid PCM can be indicated by recirculation cells.

Akhilesh et al. [8] studied the effect of adding vertical fins to a heat sink which received heat from top. Results showed that there was an optimum fins number. Beyond this number, the performance could not be enhanced, considerably.

* Corresponding author. Tel.: +98 31 33915210; fax: +98 31 33912628.
E-mail address: salimpour@cc.iut.ac.ir (M.R. Salimpour).

http://dx.doi.org/10.1016/j.applthermaleng.2015.08.024
1359-4311/

Nomenclature

A	Area (m^2)
b	Width (m)
C_p	Specific heat at constant pressure (J/kg K)
d	Vertical distance between the horizontal fins (m)
g	Acceleration due to gravity (m/s^2)
H	Enclosure height (m)
H	Enthalpy (kJ/kg)
H_b	Height of base plate (m)
h	Horizontal fin height (m)
k	Thermal conductivity (W/m K)
L	Latent heat (J/kg)
LR	Length ratio of horizontal fins
N	Enclosure numbers
n	Horizontal fin numbers in the half of enclosure
Nu	Nusselt number
q	Heat input (W)
q''	Heat flux (W/m^2)
Ra	Rayleigh number
T	Temperature (K)
t	Time(s)
t_f	Half fin thickness (m)
V	Velocity (m/s)
VOF	Volume of fluid
W	Horizontal fin length (m)
W_0	Enclosure length (m)
x, y	Coordinate axes

Greek symbols

α	Thermal diffusivity (m^2/s)
α_q	q^{th} fluid's volume fraction in the cell
β	Thermal expansion coefficient ($1/K$)
ε	Liquid fraction
μ	Dynamic viscosity ($N\ s/m^2$)
ρ	Density (kg/m^3)
φ	PCM volume fraction
$\forall$	Volume (m^3)

Subscripts

Al	Aluminum
air	Air
amb	Ambient
b	Base
cri	Critical
f	Fin
ini	Initial
l	Liquid
m	Melting
max	Maximum
mushy	Mushy zone
opt	Optimum
PCM	Phase-change material
ref	Reference
s	Solid
t	Total

Shatikan et al. [9] analyzed the heat sink embedded PCM with vertical fins attached to horizontal heated surface. Results showed that the convection in wider case was more noticeable than the narrow case. The fluid motion was rarely observed in narrow case. The effect of PCM orientations and power input to heat sink was considered experimentally by Kandasamy et al. [10] and Wang et al. [11]. They found that various orientations have no significant effect on thermal performance. On the other hand, the power input had a great effect. In 2008, experiments done by Kandasamy et al. [12] revealed that the performance of a PCM-based heat sink is better than the heat sink without PCM. Wang et al. [13] demonstrated that the variation of melting time has no linear function with PCM volume. In other words, when the value of V_{PCM}/V is doubled or tripled, the melting time is less than two or three-fold. They found that with the increase of V_{PCM}/V (grown height of PCM inside the cavities), natural convection is a major contributing factor for melting time. Hosseinizadeh et al. [14] carried out a series of experimental tests to examine the effect of several parameters. Fin features such as height, thickness and numbers had a positive influence on thermal performance. They reported that there is no additional enhancement beyond an optimum fin thickness. Correlations between Nu and Ra for different aspect ratios of PCM-based heat sinks were studied by Saha and Dutta [15]. They derived correlations for three cases: narrow–middle–wide. Saha and Dutta [16] analyzed PCM-based heat sinks with vertical fins by the assistance of genetic algorithm to find the optimum fins number. The optimization procedure was performed for two cases. Results illustrated that the optimum fins number varies if the convection is neglected.

PCM solidification in coaxial tubes with external and internal horizontal fins was studied by Jmal and Baccar [17]. The influence of natural convection and the effect of fins number on the solidification time were the main examined targets of the numerical approach. Results showed that in thermal storage systems equipped with fins, energy transfer from PCM to airflow occurs at a faster rate.

Transient three-dimensional simulations were managed to examine a multi-fin heat sink with PCM. Different parameters such as fins number, heating power level, various orientation heat sinks were studied by Wang and Yang [18]. Through this study, the finding indicated that the use of PCM in the aluminum heat sink would give electronic packages a more stable operation temperature. Kamkari and Shokouhmand [19] performed a series of experiments to predict melt fractions and melting Nusselt numbers at different wall temperatures for transparent rectangular enclosures (with and without fins) heated isothermally from one side. A numerical model and analytical correlations for simulating the influence of the number, length and thickness of the fins on the melting process was reported by Sharifi et al. [20]. The prediction of analytical correlations which have been derived for the rapid and slow melting regimes, were in good agreement with the numerical model except for the late stages of melting in relatively long fin cases.

Many researchers throughout the world have invoked constructal law for better engineering [21,22]. This direction is called constructal design and with it not only better configurations are sought but also better strategies for generating the geometry are looked for. For example, Salimpour et al. [23] invoked constructal theory for geometric optimization of an array of circular and noncircular ducts. Lorenzini et al. [24] used constructal law to optimize the geometry of Y-shaped cavities intruded into a solid conducting wall. They wanted to minimize the temperature of hot spots. Salimpour and Menbari [25] used constructal theory to optimize a dendritic path flow structure for minimizing overall flow and thermal resistances in convective cooling of a ring-shaped body. Feng et al. [26] optimized tree-shaped fluid networks in a disc