International Journal of Thermal Sciences 126 (2018) 272–280

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Prediction methods for natural convection around hollow hybrid fin heat sinks

Nico Setiawan Effendi, Severianus S.G. R. Putra, Kyoung Joon Kim*

Department of Mechanical Design Engineering, Pukyong National University, Busan 48547, South Korea

A R T I C L E I N F O

Keywords:
Heat sink
Hollow hybrid fin
Natural convection
Correlation
Nusselt number

A B S T R A C T

This study investigates prediction methods for natural convection around hollow hybrid fin heat sinks (HHFHSs). The HHFHS is the staggered array of hollow pin fins concatenated with radially-placed plate fins. 3-D computational thermal models have been generated using a commercial CFD software package and used to develop correlations to predict Nusselt numbers around HHFHSs. Nearly hundred cases under various parametric conditions have been calculated to obtain a broad range of thermal data. Correlations for Nusselt numbers have been obtained by considering their dependence on Rayleigh number, internal and external diameters, and fin height. The correlations are seen to reasonably agree with the numerical results despite the complicated parametric dependence of the HHFHS. Crucial parametric dependence of the HHFHS has been also explored using the correlation.

1. Introduction

Heat sinks have been extensively used for the robust thermal management of electronic and photonic systems due to their simplicity and cost-effectiveness. Especially, passively-cooled heat sinks are more effective for the systems remotely located or requiring high energy efficiency such as LED luminaires [1,2]. Despite such popularity, the weight of the heat sink considerably affects the material cost, the energy efficiency, and the structural stability in the system level [3–5]. Consequently, the optimization for the light weight is necessary to develop energy efficient and cost-effective heat sinks for natural convection cooling applications.

Many researchers have rigorously contributed for the development of advanced fin-structured heat sinks in natural convection. Recent investigations are conducted into a polyphenylene sulfide (PPS) pin fin heat sink by Bar-Cohen et al. [3,4], lightweight heat sinks based on polymer composites by Mehmet et al. [5], heat sinks with hollow and perforated pin fins by Elshafei [6], heat sinks with various fin cross sections by Kou et al. [7], vertical cylinder heat sinks containing longitudinal fins by Sun et al. [8], a horizontal cylinder with longitudinal fins by Haldar et al. [9], vertically-mounted rectangular interrupted fins by Bahrami et al. [10], and horizontal rectangular fin arrays with perforations in fin base by Wong et al. [11]. Especially, rigorous researches have been recently conducted on the optimization of pin fin heat sinks. Aihara et al. [12] investigated the sideward-facing pin fin heat sink and formulated a Nusselt number correlation based on the horizontal spacing as a characteristic length. Sahray et al. [13,14] studied upward-facing square pin fin heat sinks. A Nusselt number correlation which depends on the fin height and spacing was presented. Kim et al. [15] developed a correlation to optimize sideward-facing pin fin heat sinks. Bar-Cohen et al. [3] optimized a polyphenylene sulfide (PPS) pin fin heat sink using least-material optimization method. Lee et al. [16] investigated an optimization of pin fin radial heat sinks.

In preceding studies, heat sinks with innovative fin structures were introduced for light weight natural convection cooling [17,18]. A penetrated hybrid fin heat sink (PHFHS) for cooling LED street lights under natural and forced convections was proposed and compared with pin fin heat sinks [17,18]. Despite its promising performance, the complexity of the fin structure might cause higher manufacturing cost. Hence, simpler fin structures were introduced and their thermal performances were computationally investigated [19]. Hollow hybrid fin heat sinks (HHFHSs) based on the simpler fin structure was studied. It was found that the mass-based thermal performance of the HHFHS might be superior to the classical pin fin heat sink (PFHS) [20,21]. Despite the demonstrated feasibility of the HHFHS, the optimization methodology should be obtained to understand its optimum performance. It is expected that the correlation-based optimization would be effective and concrete. Hence, this study develops an effective correlation for general representation of the natural convection around the HHFHS.

This paper introduces the physical structure of the HHFHS and then reports the CFD models of the HHFHSs for 36 configurations to obtain

* Corresponding author.
E-mail address: kjkim@pknu.ac.kr (K.J. Kim).

https://doi.org/10.1016/j.ijthermalsci.2018.01.002
Received 24 July 2017; Received in revised form 4 January 2018; Accepted 4 January 2018

Nomenclature

D	fin diameter [mm]
g	gravity [m/s^2]
H	fin height [mm]
h_c	convective heat transfer coefficient [W/m^2-K]
k	thermal conductivity [W/m-K]
M	heat sink mass [kg]
N	fin number
Nu	Nusselt number
P	pressure [Pa]
Pr	Prandtl number
Ra	Rayleigh number
S	fin spacing [mm]
T	temperature [°C]
ΔT	temperature difference between the heat sink and the ambient [K]
u	x – velocity [m/s]
v	y – velocity [m/s]
w	z – velocity [m/s]

Greek symbols

α	thermal diffusivity [m^2/s]
β	volumetric thermal expansion coefficient [1/K]
η	efficiency
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]

Subscripts

f	fin
i	internal
max	maximum
o	external
p	perforation
s	spacing
∞	free stream

Superscripts

cor	correlation
mod	modified
num	numerical

broad thermal data needed for the development of a Nusselt number correlation. Then, the paper shows the experimental validation of the CFD modelling methodology, representative thermal and flow fields of the HHFHS, and the comparison of the thermal performance of the HHFHS with those of hollow and solid PFHSs. In the following section, the paper discusses the development of the Nusselt number correlation using rigorous results for 108 calculation cases. Finally, the paper reports parametric effects of the fin wall thickness and the fin height on natural convection around the HHFHS.

2. Hollow hybrid fin heat sinks

The hollow hybrid fin heat sinks (HHFHSs) consist of hollow hybrid fins (HHFs) in a staggered array. The HHF is a hollow pin fin with radially-placed plate fins and a perforation near the fin base. The configuration parameters of the HHFHS are shown in Fig. 1. H is the fin height, D_i is the internal fin diameter, D_o is the external fin diameter, D_p is the perforation diameter, W is the total width of the hybrid fin, and S is the fin spacing, directly related with the fin number, N. Table 1 summarizes the values of H, D_i, D_o, D_p, W, S, and N used for the numerical study. The heat sink base size is 75 mm × 75 mm x 5 mm. The selected material for the heat sink is aluminum 6063.

3. Numerical modelling

3.1. CFD model

Computational fluid dynamics (CFD) analysis has been rigorously conducted for 108 cases, which are 36 configurations shown in Table 1 at three base temperatures of 50, 70, and 90 °C, to obtain a broad range of thermal data for the development of a Nusselt number correlation.

ANSYS ICEM CFD and FLUENT were used for the mesh generation and the calculation, respectively. The numerical analysis assumed steady and incompressible flow and boussinesq approximation for the density model. The milestone of the numerical analysis is to generate purely convection heat transfer data around the HHFHSs, and thus thermal radiation was excluded.

Governing equations for the computations are shown in Eqns. (1)–(6) [22,23] as follows.

The continuity equation is expressed as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

Momentum equations are expressed as

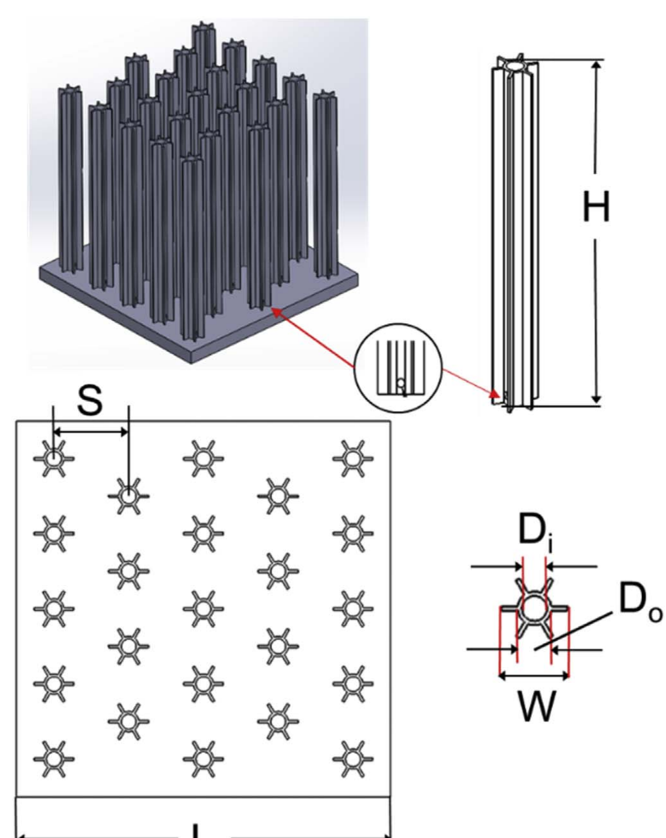

Fig. 1. The structure of a HHFHS.