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Multi-objective optimization of a honeycomb heat sink using Response Surface Method

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ABSTRACT

The aim of this study is to find optimum values of design parameters of a heat sink having hexagonal aluminum honeycomb fins by using the Response Surface Method (RSM) and the Pareto based multi-objective optimization. In this context, fin height (H), fin thickness (t), longitudinal pitch (S_y), angle of attack (θ) and Reynolds number (Re) are selected as design variables while Nusselt number (Nu) and friction factor (f) are chosen as objective functions. Firstly, the RSM with the face centered central composite design (FCCCD) has been employed to construct mathematical models required in multi-objective optimization problem definition. In the next step, accuracy and validity of these mathematical models are proved both statistically and experimentally. Finally, a Pareto based multi-objective optimization study has been conducted to determine optimum values of the design parameters that maximize Nu and minimize f. It is concluded that Pareto solution set obtained provides important insights into the design parameters and allows designers freedom to make a selection among the optimal solutions.

1. Introduction

The failure of an electronic device depends on a few parameters such as temperature, vibration, humidity and dust [1]. The operating temperature with a value of 55% is the most affecting factor among these parameters [1]. The relationship between the operating temperature and failure rate factor defined as the ratio of failure rate at any temperature to failure rate at 75 °C is almost exponential [2]. That means reliability of an electronic device decreases with increasing operating temperature [2]. Therefore, heat arising from electronic devices must be dissipated to improve reliability of electronic devices, and to have a long life and high performance electronic device. Heat sinks are generally used to overcome these overheating problems that lead to corruption of electronic devices. Furthermore, miniaturized sizes of heat sinks in parallel to advancement of packaging technologies [3], and increase of power density at integrated circuits have made thermal system engineering applications as a key factor for development of microelectronic technologies. Aforementioned facts necessitate realization of heat transfer mechanism at optimum conditions as it should be required to find optimum conditions to maximize efficiency of any engineering system considered [4–6]. Therefore, in the literature, numerous studies are dedicated to optimization of heat sinks having various fin geometries such as rectangular, diamond, square, cylindrical, annular, tapered or pin fins [7,8]. In addition to above mentioned fin types, with their superior properties, metallic honeycomb structures stand out as a prospective candidate for heat sink applications. The various applications of honeycomb structures are reported in [9]. According to the paper, in many engineering applications, honeycomb structures have an extensive usage area such as structural load support, impact energy absorption and thermal management. Due to their structural morphologies and thermal characteristics, they have large surface-area-to-volume ratio, low pressure drop and high conductivity walls. These properties make them suitable for the use of compact heat exchangers and heat sink applications [9–13]. However, in the literature, studies related to heat sink applications of honeycomb structures are rather limited.

The literature review related to the optimization of various heat sinks, the Response Surface Method (RSM), the Pareto based multi-objective optimization and heat transfer applications of honeycomb structures are reported below. Lu [12] analyzed the heat transfer performance of micro cell aluminum honeycombs in compact heat exchangers by using analytical models, and found optimal cell morphology. Dempsey *et al.* [13] examined heat transfer and pressure drop characteristics of the Linear Cellular Alloys (LCA) heat sinks having square cells under laminar

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Nomenclature

A	heat transfer area (m^2)
D_h	hydraulic diameter of channel (m)
F	objective functions
f	friction factor ($\Delta P/((L_t/D_h)(\rho u^2/2))$)
h	mean heat transfer coefficient (W/m^2 °C)
H	fin height (mm)
k	thermal conductivity of air (W/m °C)
L	length of base plate (m)
L_t	length of test chamber (m)
Nu	Nusselt number (hD_h/k)
$\dot{Q}$	heat transfer rate (W)
Re	Reynolds number [$u\,D_h/\nu$]
S_y	longitudinal pitch (mm)
t	fin thickness (mm)
T	steady state temperature ($^\circ C$)
u	mean inlet velocity of air (m/s)
W	width of base plate (m)
x_i	independent design parameters
y	desired response or yield

Greek letters

ΔP	pressure drop (Pa)
ε	fitting error
θ	angle of attack (°)
υ	kinematic viscosity of air (m^2/s)
ρ	density of air (kg/m^3)

Superscripts

L	lower limit
U	upper limit

Subscripts

b	bulk
$cond$	conduction
$conv$	convection
in	inlet
$loss$	losses
n	number of independent design parameters
out	outlet
s	surface
rad	radiation

Abbreviations

ANOVA	Analysis of Variance
CCD	Central Composite Design
CFD	Computational Fluid Dynamics
DOE	Design of Experiment
FCCCD	Face Centered Central Composite Design
LCA	Linear Cellular Alloys
NBI	Normal Boundary Intersection Method
RSM	Response Surface Method
TLBO	Teaching–Learning-based Optimization

flow conditions, both experimentally and numerically. In the experimental part of the study, they measured pressure drop along the honeycomb channels and total heat transfer rate of the LCA heat sinks. Then, they compared these experimental measurements with numerical results obtained from both a finite difference code and commercially available finite volume method based software. Wen *et al.* [10] conducted an analytical study to find the optimal design of 2D cellular metallic sandwiches for various cell topologies, under laminar forced convection conditions at constant pumping power. They checked the accuracy and validity of their analytical model by comparing the predictions with Computational Fluid Dynamics (CFD) results. Liu *et al.* [11] proposed an analytical model that accomplishes the assumptions in the corrugated wall model, to examine thermal performance of sandwich metallic honeycomb structures subjected to forced convection conditions. They investigated accuracy of the new method proposed by comparing the results with those obtained from the corrugated wall model, the effective medium model and numerical simulation. They reported that their method is accurate and gives close results to numerical results. In their numerical study, Park *et al.* [3] employed the RSM and CFD to find the optimum levels of various design parameters of a plate-fin heat sink. Chiang [14] carried out an experimental study to investigate the effects of selected design parameters on thermal performance of a parallel-plain fin heat sink and to find optimal values of these parameters subject to mass and space constraints using RSM and the sequential approximation optimization method. In their experimental study, Chiang *et al.* [7] used the RSM to predict and optimize thermal resistance and pressure drop of a pin–fin heat sink. They found the optimum levels of the selected design variables of a pin fin heat sink under the defined space and mass limitations. Chen *et al.* [15] conducted a multi-objective optimization study to determine structural design of a serpentine-channel heat sink. They adopted channel width, fin width, channel height and inlet velocity as design variables and total thermal resistance and pressure drop as objective functions. They employed a multi-objective artificial swarm fish algorithm with a variable population size to get Pareto optimal solutions. In their study, Horiuchi *et al.* [16] worked on the Pareto based multi-objective optimization of pin fin heat sinks. They used semi-analytical equations to find the relationship between objective functions (heat transfer rate and pressure drop) and four independent design parameters (height and diameter of the pin fins, longitudinal and transverse pitches). Then, they employed genetic algorithm for the multi-objective optimization. Rao *et al.* [17] investigated the performance of a plate-fin heat sink equipped with flow-through air cooling systems and impingement-flow system. In multi-objective optimization definition, they selected entropy generation rate and material cost with five constraints as objective functions while they consider number of fins, height of fins, spacing between two fins and oncoming air velocity as design parameters. They obtained dynamic heat dissipation performance of the heat sink by a commercial software. Then, they obtained Pareto fronts by Teaching–Learning-based Optimization (TLBO) algorithm to compare the performance of two cooling systems.

To the authors' knowledge, there is no experimental investigation dealing with the optimization of design parameters of a heat sink having hexagonal aluminum honeycomb fins under turbulent forced convection conditions. This paper reports, therefore, the results of an experimental study that has been conducted to determine optimal values of the design parameters of a honeycomb heat sink using the RSM and the Pareto based multi-objective optimization. The organization of this paper is as follows. Section 2 explains the experimental facilities and summarizes the analysis of experimental data. Then, Section 3 includes application of the RSM and Pareto based multi-objective optimization study, and combines evaluation and interpretation of the results. Finally, Section 4 summarizes the findings.