International Journal of Heat and Mass Transfer 81 (2015) 760–766

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Multi-objective optimization of water-cooled pinfin heatsinks

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ARTICLE INFO

Article history:
Received 17 December 2013
Received in revised form 27 October 2014
Accepted 27 October 2014
Available online 19 November 2014

Keywords:
Optimization
Pinfin heatsink
Pareto ranking method

ABSTRACT

This paper presents the multi-objective optimization of water-cooled pinfin heatsinks. The heat transfer rate and pressure drop were the objective functions, and four parameters (height, diameter, longitudinal pitch, and transverse pitch) of pinfin geometry were the design variables. The relationship between the objective functions and the design variables for pinfin heatsink was calculated by using our own semi-analytical equations. We applied two kinds of constraints. One is the clearance distance between the tip of the pins and the flow channel wall, and the other is the minimum gap between pins considering cost-effectiveness and manufacturability. The best trade-off curves between the pressure drop and the heat transfer rate were calculated using genetic algorithm. We found the similarity of the best trade-off curves under two different constraint conditions when the multiplication of the pin height and the minimum gap between pins were the same. We also showed that the small clearance causes the reduction of pressure drop while maintaining high heat transfer performance. Our calculated solutions were validated by comparing with experimental results. The pressure drops could be predicted within an error of 30%, and the effective heat transfer rates agreed within an error of 10%.

1. Introduction

The design and optimization of heatsinks have received a great deal of attention for many years as well-designed heatsinks enable product miniaturization. Plate-fin and pinfin configurations are the most common of the various heatsinks available. The three-dimensional flow pattern in the pinfin layout is complex due to flow separations. Hence, fewer papers have discussed optimization of pinfin heatsinks than optimization of plate-fin heatsinks.

Zukauskas [1] presented empirical correlations between the Reynolds and Nusselt numbers for infinitely long round cylinders in a cross flow. Khan et al. [2] derived analytical solutions that resulted in forms similar to Zukauskas's correlations using an integral method for boundary-layer analysis. The application of equations proposed by the above-mentioned references is very wide, especially for designing heat exchangers but limited to long pinfins and tube banks. Because the pin surface is assumed to be nearly isothermal in their model, we need to modify it by adding endwall effects (i.e. the heat transfer from the base plate and the fin efficiency of the pin surface) for heatsink applications. There are two main considerations when designing a heatsink. The first is endwall effects of the base plate, and the second is the coolant bypass flow that occurs between the tip of the pins and the flow channel.

In the 1980s, research groups at the National Aeronautics and Space Administration (NASA) [3–5] and Arizona State University [6–10] provided numerous experimental data with endwall effects in applications of gas-turbine engine airfoils that had short circular cylinders. However, these experimental data were limited to only a few geometries. Chiang and Chang [11] recently attempted shape optimization using the response surface method (RSM). They used polynomial functions as a response surface. Also, empirical correlation exists between the Reynolds and Nusselt numbers on the endwall (i.e. base plate) for various geometries in recent years [12]. In addition to that, Horiuchi and Nishihara proposed a semi-analytical method to predict Nusselt number and pressure drop considering the coolant bypass flow that occurs between the tip of the pins and the flow channel [13]. There are many other significant studies predicting the heat transfer and the pressure drop of heatsinks with top bypass flow. Dogruoz et al. nicely summarizes the use of conventional correlations for both heat transfer and pressure drop [14].

As for optimization of pinfin geometry, there have been many more numerical studies than experimental works. Matos et al. [15] found an optimum shape for pinfin layouts by solving two-dimensional governing equations. Li and Kim [16] applied a multi-objective optimization technique using the genetic algorithm (GA) to optimize a pinfin array using three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations with the shear-stress transport (SST) turbulence model. In their analysis with RSM, the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.057
0017-9310/

Nomenclature

A	area [m^2]
C_1, C_2	coefficients [–]
C	clearance between the tip of the pins and the flow channel [m]
D	pin diameter [m]
f	friction factor [–]
h	average heat transfer rate [W/(m^2K)]
H	pin height [m]
L	longitudinal distance of the heatsink [m]
M	coefficient [–]
N	number of rows in flow direction [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
q	power of heat [W]
Q	flow rate [m^3/s]
R	thermal resistance $\equiv (T_b - T_{liquid})/q$ [K/W]
R_{SP}	spreading resistance [K/W]
Re	Reynolds number $\equiv uD/\nu_{liquid}$ [–]
S_X	longitudinal gap between the pins [m]
S_{XY}	diagonal gap between the pins [m]
S_Y	transverse gap between the pins [m]
T_b	base temperature [K]
T_{liquid}	liquid temperature [K]
u_{pin}	average velocity between pins [m/s]
u_c	average velocity within the clearance region [m/s]
X	longitudinal pitch [m]
Y	transverse pitch [m]

Greek symbols

δ	boundary layer thickness [m]
ΔP	pressure drop [Pa]
η	fin efficiency [–]
λ_{liquid}	thermal conductivity [W/(m K)]
ν_{liquid}	kinematic viscosity [m^2/s]

Subscripts

base	endwall (base plate)
eff	effective area (the heatsink footprint size)
liquid	liquid coolant
pin	pin surface
c	clearance regions

second-order polynomial was utilized as a response surface. The method for entropy generation minimization (EGM) can also be applied to optimize pinfin heatsinks [3,17]. If clear specifications for heat transfer rate and pressure drop are given, it is easier for heatsink designers to specify graphically the optimum shapes for pinfin layouts using the multi-objective optimization technique than to monitor the entropy-generation rate.

As several researchers have explained [11,15], RSM with polynomial regression has been widely used for a variety of engineering applications because it has advantages of enabling low-cost simulations and a simpler methodology than executing Computational Fluid Dynamics (CFD) with RANS. Nevertheless, the polynomial model may be too simple when considering complex three-dimensional flows due to flow separations within the pinfin array. Thus, polynomial surface regression may not be sufficiently accurate to represent precisely the relationship between design variables (DVs) and objective functions (OFs) [18]. Kriging models, as alternatives to traditional polynomial response surfaces, therefore lead the way to building accurate global approximations of design space since these models can represent linear and nonlinear functions equally well [19,20]. The authors applied the Kriging model to the multi-objective optimization technique based on experimental data of various geometries [21]. We noticed that the experimental uncertainty and lack of data with the Kriging model result in the bumpy response surface (i.e. non-dominated solutions similar to the Pareto-optimal trade-off curve). To avoid such the bumpy response surface, we need to either increase the experimental data or modify the prediction method from the Kriging model.

Here, we present the multi-objective optimization using GA and empirical equations rather than the Kriging model in order to avoid the bumpy Pareto-optimal trade-off curve. Heat transfer rate and pressure drop were the objective functions, and four parameters (height, diameter, longitudinal pitch, and transverse pitch) were the design variables in this study. The relationship between the objective functions and the design variables for the direct-water-cool power module that has pinfin heatsink was calculated by using our own empirical equations [12,13]. We applied constraint using the ratio of the height over the minimum gap considering cost-effectiveness and manufacturability from the engineering point of view. Toward this end, optimum solutions to the objective functions were illustrated, and we derived the design rules for design variables.

2. Multi-objective optimization procedures

The following multi-objective optimization technique was applied with an in-house program. We constructed the problem presented in five steps as follows.

i. Define "OFs", "DVs", and constraints "CTs."

First, the user defines OFs, DVs, and CTs

- Objective functions (OFs) : h_{eff}, ΔP
- Design variables (DVs) : D, H, X/D, Y/D
- Constraints (CTs) : Two CTs in Table 1

Here h_{eff} is the effective heat transfer coefficient based on the size of the footprint, ΔP is the pressure drop, H is the pin height, D is the pin diameter, X is the longitudinal pitch, Y is the transverse pitch, S_Y is the transverse gap, S_{XY} is the diagonal gap between the pins, and C is the clearance between the tip of the pins and the flow channel. The minimum gap is located diagonally or transversely depending on Y/X. These geometric parameters are defined in Fig. 1(a). The pitches in DVs are normalized by the pinfin diameter to reveal nonrealistic configuration such that either $X/D < 1$ or $Y/D < 1$ means the fins are overlapping. The CTs were categorized into two kinds of the pin height (H) and the minimum gap (min{S_Y, S_{XY}}) considering cost-effectiveness, which is related to manufacturability and sensitivity to clogging. We consider two cases in this study as shown in Table 1. Case 1 is the ideal case, which is manufacturable but expensive. On the other hand, Case 2 is a more practical case that is cheaper to fabricate than Case 1.

Table 1
Two CTs considered in this study.

	Max H [mm]	Min{S_Y, S_{XY}} [mm]	C [mm]	Cost
Case 1	7.5	1.3	0.0	High
Case 2	5.5	1.8	1.0	Low