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Comparison of thermal performance between plate-fin and pin-fin heat sinks in natural convection

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ABSTRACT

The thermal performance of optimized plate-fin and pin-fin heat sinks with a vertically oriented base plate is compared analytically in natural convection. A new correlation of the heat transfer coefficient is proposed and validated experimentally to optimize pin-fin heat sinks, while a correlation of the heat transfer coefficient for plate-fin heat sinks is adopted from previous studies. The comparison is made under the same base-plate dimensions and fin height conditions. Two objective functions are used in optimizing the thermal performance: the total heat dissipation and the heat dissipation per unit mass for a given base-to-ambient temperature difference. When the total heat dissipation is used as an objective function, the optimized plate-fin heat sinks dissipate a larger amount of total heat than do the optimized pin-fin heat sinks in most practical applications. When the heat dissipation per unit mass is used as an objective function, on the other hand, the optimized pin-fin heat sinks dissipate a larger amount of the heat per unit mass than the optimized plate-fin heat sinks in most practical applications.

1. Introduction

Heat sinks are typically divided into forced convection and natural convection heat sinks based on the operating conditions. Forced convection heat sinks dissipate a larger amount of heat due mainly to such flow inducing devices as fans, but their reliability is lower than that of natural convection heat sinks because of these additional devices. Therefore, natural convection heat sinks are widely used in applications for which high reliability is required, and low performance may be tolerated. Two common types of natural convection heat sinks are plate-fin heat sinks and pin-fin heat sinks. Plate-fin heat sinks are easy to design and fabricate, so they are widely used in applications for which cost reduction is a main issue. Pin-fin heat sinks have omnidirectional performance because of their geometric characteristics, so they are widely used in applications for which heat sinks are used in various orientations. There have been many studies on these two types of heat sink [1–9] because of their advantages over the other types of heat sink. However, it is not yet known which type of heat sink between the two has better thermal performance in the natural convection mode.

Some previous studies have tried to answer this question. Sparrow and Vemuri [1] found an optimal fin population of pin-fin heat sinks by changing the number of fins for the fixed values of the fin diameter. The thermal performance of the pin-fin heat sink having the optimal number of fins was compared to that of a plate-fin heat sink under the constraint of the same surface area for both heat sinks. Their results showed that the pin-fin heat sink had lower thermal resistance than the plate-fin heat sink, by about 40%. However, the constraint of the same surface area places an undesirable limit on the thermal performance because the optimum surface area does not have to be the same for each type of heat sink. For a more meaningful comparison, therefore, the constraint of the same surface area needs to be removed.

Iyengar and Bar-Cohen [2] compared plate-fin heat sinks and pin-fin heat sinks that had been optimized using the least-material method. In this method, the optimum fin thickness (or fin diameter for pin-fin heat sinks) is determined when the fin height is given. Then, the optimum spacing between the adjacent fins is obtained by maximizing the amount of heat dissipated from the array for various values of the spacing. From their analytical results, they found that the optimized pin-fin heat sinks dissipate a larger amount of heat than do the optimized plate-fin heat sinks. However, there are some inherent limitations in the least-material method. This method is effective at reducing the mass of a single fin, but may not provide a mass-minimizing optimum design for the whole array of the heat sink. Therefore, some different approaches are needed to compare the thermal performance per unit mass of both types of heat sink.

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Nomenclature

A	surface area [m^2]
B	base plate thickness [m]
C_D	drag coefficient [-]
c_p	specific heat [kJ/kg-°C]
d	fin diameter [m]
El	Elenbaas number [–]
g	standard acceleration of gravity [m/s^2]
Gr	Grashof number [–]
H	fin height [m]
h	convective heat transfer coefficient [W/m^2 K]
K	permeability [m^2]
k	thermal conductivity [W/m-K]
L	heat sink length [m]
M	heat sink mass [kg]
n	number of fins [–]
Nu	Nusselt number [–]
P	pressure [Pa]
Pr	Prantl number [–]
Q	heat dissipation [W]
Ra	Rayleigh number [–]
Re	Reynolds number [–]
R_{th}	thermal resistance [K/W]
S	spacing of pin-fin array [m]
T_∞	ambient temperature [K]
T_b	base temperature [K]
u_D	Darcian velocity [m/s]
V	pore velocity [m/s]
W	heat sink width [m]
w_c	fin thickness of plate-fin [m]
w_w	channel spacing of plate-fin [m]

Greek symbol

α	thermal diffusivity [m^2/s]
β	volumetric thermal expansion coefficient [1/K]
ε	emissivity [–]
η	fin efficiency [–]
μ	dynamic viscosity [N-s/m^2]
v	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	Stefan–Boltzmann constant [W/m^2 K^4]
φ	porosity [–]

Subscripts

1	limiting case 1
2	limiting case 2
3	limiting case 3
4	limiting case 4
array	array
b	base
d	diameter
eff	effective
f	fluid
fin	fin
h	horizontal
L	heat sink length
pin	pin-fin heat sink
plate	plate-fin heat sink
ratio	ratio
Sparrow	Sparrow and Vemuri
s	solid
v	vertical

The objective of the present study is to determine which type of a heat sink performs better under fixed volume conditions between plate-fin heat sinks and pin-fin heat sinks. The fixed volume condition means that, physically, the space specified by the length, width, and fin height of a heat sink is fixed in the present study. Two objective functions are used for the comparison: the total heat dissipation and the heat dissipation per unit mass for a given base-to-ambient temperature difference. When the first objective function is maximized, the thermal resistance, which is defined as the base-to-ambient temperature difference divided by the total heat dissipation, is minimized. Thus, the higher value of the first objective function means a greater heat dissipation capability under a given volume of a heat sink. The second objective function estimates how efficiently a heat sink can dissipate heat at relatively small mass. Therefore, the second objective function plays an important role in designing heat sinks in applications for which the mass of a heat sink is an important factor. Each objective function will be maximized to optimize each type of heat sink analytically using the correlations of the convective heat transfer coefficient. For plate-fin heat sinks, the correlation of the heat transfer coefficient suggested by Bar-Cohen and Rohsenow [3] is used. For pin-fin heat sinks, a new correlation of the heat transfer coefficient will be proposed and validated experimentally. This correlation will be used to study the effects of the diameter, the horizontal spacing, and the vertical spacing on the heat transfer coefficient. After each type of heat sink is optimized, the thermal performances of the optimized plate-fin heat sinks and the optimized pin-fin heat sinks are compared for each objective function. Finally, region maps for the ratio of the total heat dissipation and the heat dissipation per unit mass are suggested. The region maps can help thermal engineers to determine which type of natural convection heat sink is better than the others according to specific constraints.

2. Correlation of the heat transfer coefficient for pin-fin heat sinks

In optimizing the thermal performance of the plate-fin heat sinks, a correlation of the heat transfer coefficient suggested by Bar-Cohen and Rohsenow [3] can be used. In optimizing the thermal performance of the pin-fin heat sinks, no reliable correlation that can be applied in a wide range of the geometric parameters is available. Hence, a new correlation of the heat transfer coefficient for pin-fin heat sinks will be proposed in this section.

In the present study, the asymptotic method proposed by Churchill and Usagi [10] is used to propose a new correlation of the heat transfer coefficient for pin-fin heat sinks. For plate-fin heat sinks, there are only two limiting cases associated with channel spacing (w_c): small spacing and large spacing [3]. However, there are four limiting cases for pin-fin heat sinks because there are two types of fin spacing: horizontal spacing (S_h) and vertical spacing (S_v). Limiting case 1 means densely-positioned pin-fins with small horizontal spacing and small vertical spacing. Limiting case 2 means a vertical single array of pin-fins with large horizontal spacing and relatively small vertical spacing. Limiting case 3 means a horizontal single array of pin-fins with large vertical spacing and relatively small horizontal spacing. Limiting case 4 means an isolated horizontal cylinder with large horizontal and vertical spacing. Each limiting case is analyzed, and these cases are integrated through the asymptotic method to predict the heat transfer coefficient in the intermediate region for the four limiting cases.