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Analytic approach to thermal optimization of horizontally oriented radial plate-fin heat sinks in natural convection

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ABSTRACT

In this study, horizontally oriented radial plate-fin heat sinks in natural convection are optimized analytically and experimentally. The thermal resistance is selected as an objective function under the constraint of a given base-to-ambient temperature difference. For thermal optimization, a new correlation of the heat transfer coefficient for the radial plate-fin heat sinks is developed using the asymptotic method and validated experimentally. While the existing correlation has a limited applicable range, the newly developed correlation covers complete ranges of the three design parameters for a fin geometry: fin thickness (t), fin length (L), and number of fins (n_{fin}). Using this new correlation, the thermal performance of a radial plate-fin heat sink is optimized with respect to these three design parameters. Finally, optimum fin geometries for applications with various sizes are obtained, since the newly suggested correlation is applicable to various physical sizes which are characterized by the base diameter (D) and the fin height (H).

1. Introduction

For outdoor electronic devices such as remote radio heads (RRHs) and LED bulbs, which are supposed to be used for long periods of time in an unattended condition, natural convection heat sinks are widely used due to their high reliability [1]. Various fin shapes are used for natural convection heat sinks depending on applications [2]. For LED bulbs, radial plate-fin heat sinks, which consist of a circular base and radially arrayed rectangular plates, are widely used, as depicted in Fig. 1 [3]. When using radial plate-fin heat sinks, as with other types of heat sinks, the primary interest is to find the optimum fin geometry that provides maximum thermal performance under a given physical size. Accordingly, studies have been conducted to find the optimum fin geometry for radial plate-fin heat sinks [4–6].

Costa and Lopes [4] performed a study to find an optimum fin geometry of a radial plate-fin heat sink using numerical simulations. The sensitivity of the thermal performance with respect to the change in design parameters such as fin thickness, fin length, and number of fins was investigated by performing CFD analysis. From a reference fin geometry, the design parameter with the highest sensitivity was preferentially changed, and the same procedure was repeated until the thermal performance reached a desired value. Their optimization method requires a large amount of computational cost and time since the thermal performance must be evaluated numerically for each fin geometry. In addition, another sequence of calculations needs to be performed in order to obtain an optimum geometry for other applications.

If a Nusselt number correlation is available, it is possible to optimize the thermal performance of a heat sink analytically with a low computational load [7]. For that reason, studies have been conducted to develop a Nusselt number correlation for radial plate-fin heat sinks. Yu et al. [5] investigated thermal characteristics of radial plate-fin heat sinks numerically and suggested a Nusselt number correlation. They found that if the fin length is too large, the thermal performance can degrade because the deterioration in the heat transfer coefficient due to the large flow resistance in the center region outweighs the increment of the surface area. Their correlation mainly covered this large fin length region, so the thermal performance increases monotonically as the fin length decreases within their applicable range. However, in the actual situation, as the fin length decreases, the thermal performance peaks at its maximum point, and then decreases because the significant reduction in the surface area overshadows the increment of the heat transfer coefficient. Their correlation has a limited applicable range and cannot be used in obtaining the optimum fin length. Therefore, it is necessary to develop a new correlation accounting for the two competing effects associated with the flow resistance and the surface area.

In this study, horizontally oriented radial plate-fin heat sinks in natural convection are thermally optimized. For optimization, a new correlation of the heat transfer coefficient for radial plate-fin heat sinks is developed. The asymptotic method [8] is used in order for this

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Nomenclature

A	surface area [m^2]
b	base thickness [m]
c_p	specific heat [J/kg K]
D	base diameter [m]
g	standard acceleration of gravity [m/s^2]
H	fin height [m]
h	convective heat transfer coefficient [W/m^2 K]
K	permeability [m^2]
k	thermal conductivity [W/m K]
L	fin length [m]
$\dot{m}$	mass flow rate [kg/s]
n_{fin}	number of fins [–]
P	pressure [Pa]
Pr	Prandtl number [–]
Q	heat transfer rate [W]
Ra	Rayleigh number [–]
R_{th}	thermal resistance [K/W]
r	radial coordinate [m]
s	streamwise coordinate [m]
s_{fin}	fin spacing [m]
T	temperature [K or °C]
t	fin thickness [m]
u_D	Darcian velocity [m/s]
x	X-coordinate [m]
y	Y-coordinate [m]
z	Z-coordinate [m]

Greek symbols

α	thermal diffusivity [m^2/s]
β	volumetric thermal expansion coefficient [1/K]
ϕ	porosity [–]
η_{fin}	fin efficiency [–]
μ	dynamic viscosity [N s/m^2]
ν	kinematic viscosity [m^2/s]
θ_c	angle between adjacent fins [–]
ρ	density [kg/m^3]

Subscripts

1	primary length scale
2	secondary length scale
base	base
bottom	bottom
conv	convection
experimental	experimental result
f	fluid
fin	fin
fully	fully-developed limit
h	horizontal direction
heater	heater
hs	heat sink
isolated	isolated limit
min	minimum value
numerical	numerical result
obtained	obtained result from the experiments or numerical simulations
opt	optimum value
predicted	predicted result by the proposed equation
rad	radiation
s	solid
side	side
top	top
total	total
v	vertical direction
∞	ambient

Superscripts

–	average
^	total hydrostatic
*	effective

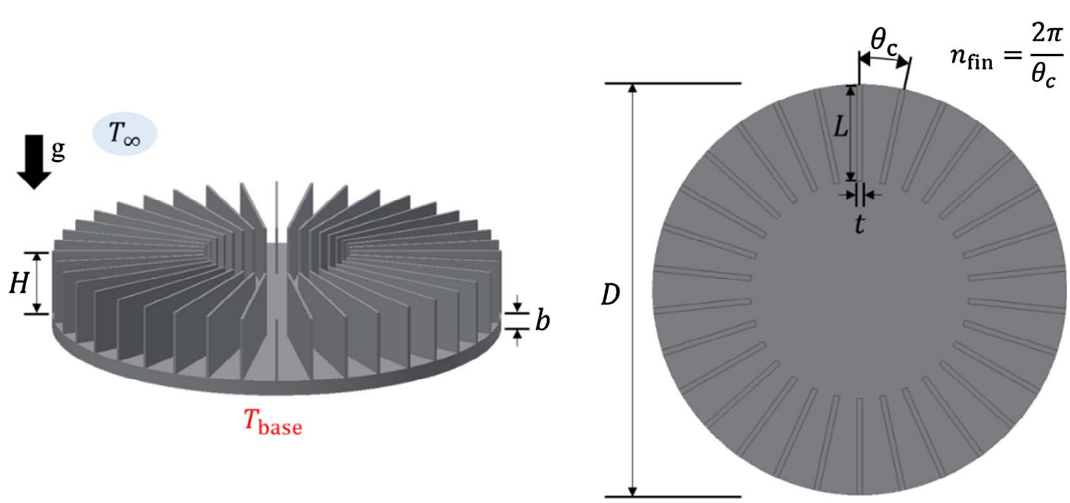

Fig. 1. Radial plate-fin heat sink in natural convection.

correlation to have a wider applicable range. The newly proposed correlation is validated experimentally. Using this correlation, a fin geometry that minimizes the thermal resistance is obtained by varying the fin thickness, the fin length, and the number of fins. Finally, optimum fin geometries at various physical sizes are obtained within the applicable range of the proposed correlation.

2. Numerical and experimental studies

Before obtaining the correlation of the heat transfer coefficient for radial plate-fin heat sinks, numerical analysis and experiments are conducted. Numerical simulation offers data required to determine the correlating exponents for the composite relation proposed by the