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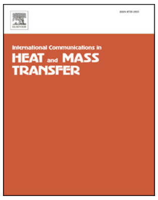

Second law analysis of an array of vertical plate-finned heat sink undergoing mixed convection ☆

Biplab Das, Asis Giri *

Department of Mechanical Engineering, North Eastern Regional Institute of Science and Technology, Itanagar-791109, India

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ABSTRACT

Second law analysis of an array of vertical plate-finned heat sink undergoing mixed convective heat transfer is investigated. The fluid flow and temperature fields are evaluated numerically solving the mass, momentum and energy conservation equations. The effects of Grashof number, inlet velocity, clearances, and fin spacing on entropy generation, Nusselt number, pumping power ratio and by-pass factor are presented. Total dimensionless entropy generation continuously decreases with clearances for all fin spacing, while Nusselt number shows an optimum value, especially at higher inlet velocities. There exists an optimum range of fin spacing at which Nusselt number is maximum for all Grashof numbers. The pumping power ratio shows significantly higher value for smaller fin spacing and at optimum fin spacing it decreases approximately by an order of magnitude. At optimum clearance, flow by-pass is significantly low.

1. Introduction

Plate-finned heat sinks are extensively used for augmenting heat transfer in many fields, like aerospace technologies, chemical engineering processes, power plants, oil refineries and electrical plants, to name a few. For the viability of further enhancement of a system, it is very much relevant and justified to perform Second law analysis. Although the fundamental work of entropy production may be dated back to the time of Clausius and Kelvin's studies on irreversible aspect of the Second law of thermodynamics, incorporation of entropy generation in heat transfer may be duly credited to Bejan [1], and is relatively new.

Sasikumar and Balaji [2] studied entropy production analysis from a convecting–radiating vertical fin on horizontal rectangular duct. Study was made with a consideration of constant convective heat transfer coefficient on fin surface. Later, Rakshit and Balaji [3] studied heat transport process on the same configuration with variable convective heat transfer coefficient by using combined approach of CFD and genetic algorithms.

Additional study on vertical plate-finned heat sink on a horizontal base subjected to both horizontal and vertical cooling stream under laminar forced convection could be seen in Shih and Liu [4], who examined optimal design methodology based on entropy generation. A study on entropy generation on the same configuration subjected to turbulent flow was made by Jian-Hui et al. [5] using a combined approach of CFD and combined optimization technique.

Least energy optimization of forced convection heat transfer from plate-finned heat sinks had been studied by Iyenger and Bar-Cohen [6] and Culham Muzychha [7]. Entropy generation was calculated based on the inlet temperature of fluid flowing over the surface, since heat transfer and pressure drop data were taken from other sources. It would be more justified to calculate entropy based on the temperature at which heat transfer occurs. Heat transfer occurs only when the extended surfaces are subjected to higher or lower temperature than the ambient. Therefore, entropy generation based on inlet fluid temperature is under/overestimated whenever extended surfaces are elevated to lower/higher temperature. Thus, the results of entropy generation minimization in these studies need to be assessed thoroughly by evaluating local entropy generation along with global entropy generation as shown by Andreozzi et al. [8]. One solution to find exact entropy generation of over the extended surface is to do CFD simulations of the whole flow domain that calculates the local entropy generation.

Literature reveals that investigations of entropy production, purely based on CFD simulations are scarce in literatures. Moreover, entropy generation analysis from vertical plate-finned heat sinks attached to a vertical base under mixed convection is not paid due attention, albeit there exists significant amount of studies on mixed convection heat transfer [9–12]. However, most of these studies on mixed convection heat transfer over the fin surface are limited to hydrodynamically developed case. Therefore, the present study is intended to analyze entropy production from a hydrodynamically developing laminar mixed convection flow over vertical shrouded fin arrays attached to vertical

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* Corresponding author.
E-mail address: measisgiri@rediffmail.com (A. Giri).

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Nomenclature

A_c	half cross-sectional area of fin geometry, $S(H+C)/2$ (m^2)
C_P	specific heat at constant pressure (J/kg-K)
Ec	Eckert number ($\nu^2/(H^2C_p\Delta T)$) (dimensionless)
Gr	Grashof number, $g\beta(T_w - T_o)H^3/\nu^2$ (dimensionless)
h	heat transfer coefficient (W/m^2-K)
k	conductivity of fluid (W/m-K)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, (hH/k) (dimensionless)
N	local volumetric rate of non-dimensional total entropy generation ($\dot{S}_{gen}H^2/k$)
$\bar{p}$	average pressure defect over the cross section (Pa)
p_f	cross stream pressure
P^*	dimensionless axial pressure defect, $\bar{p}H^2/\rho_0\nu^2$
P	dimensionless cross stream pressure, $p_fH^2/\rho_0\nu^2$
$\dot{Q}$	rate of total heat flux from base-fin system (W)
Re	Reynolds number, $W_{in,force}H/\nu$ (dimensionless)
$\dot{S}_{gen}$	local volumetric rate of entropy generation (W/m^3-K)
$\dot{S}_t$	rate of total entropy generation (W/K) $\left(\int_0^L\int_0^{0.5S}\int_0^{H+C}\dot{S}_{gen}dxdydz\right)$
T	temperature (K)
T_0^*	dimensionless ambient temperature ($T_0/\Delta T$)
u,v,w	velocity component in x-, y- and z-direction (m/s)
U,V,W	dimensionless velocities in X-, Y-, and Z- directions, uH/ν, vH/ν and wH/ν
x,y,z	cross stream and axial coordinates (m)
X,Y,Z	dimensionless cross stream and axial coordinates, x/H, y/H and z/H

Greeks

α	thermal diffusivity (m^2/s)
β	thermal volumetric expansion coefficient, $-(1/\rho_0)(\partial\rho/\partial T) = 1/T_0$ (1/K)
ΔT	scaling temperature difference, $T_w - T_0$ (K)
ρ	density (kg/m^3)
θ	dimensionless temperature, $(T - T_0)/(T_w - T_0)$
ν	momentum diffusivity (m^2/s)
ψ	total entropy generation (dimensionless)

Subscript

f	forced
in	inlet
mix	mixed convection

Superscript

*	dimensionless quantity

base, so that an optimal design might be found. This optimal condition is not achieved by the usual mathematical optimization techniques; rather it is an outcome of direct scanning of finite CFD solution set.

1.1. Mathematical model

Present situation (Fig. 1) considers an array of equally spaced (S) vertical rectangular fins attached to vertical base, which is elevated to a uniform high temperature (T_w) than the surrounding fluid temperature (T_0). A rectangular vertical adiabatic shroud is placed over the fin-tip maintaining a clearance, C. Fin, having thickness (t), is treated to be thin compared to its height, H. Thus, the whole system constitutes an array of channels, each of which is geometrically identical having a dimension of $L \times S(H+C)$ and symmetric about the midplane passing through midpoint of base and parallel to the fin surface. Therefore, only half section of the channel is considered for the analysis (Fig. 1b). It is assumed further that base and fin are made of the same material of high thermal conductivity with no contact resistance between them. To enhance the heat transfer, forced flow is superimposed on the induced flow due to elevated thermal condition. The physical model depicted above is governed by the equations of mass, momentum and energy conservation. Oberbeck–Boussinésq approximation is incorporated in the momentum equations. The radiation effect is considered negligible. Further, negligible diffusion is considered along the stream-wise directions of the momentum and energy equation. With the above assumptions, governing equations of mass, momentum, and energy in dimensionless form can be cast as [12]:

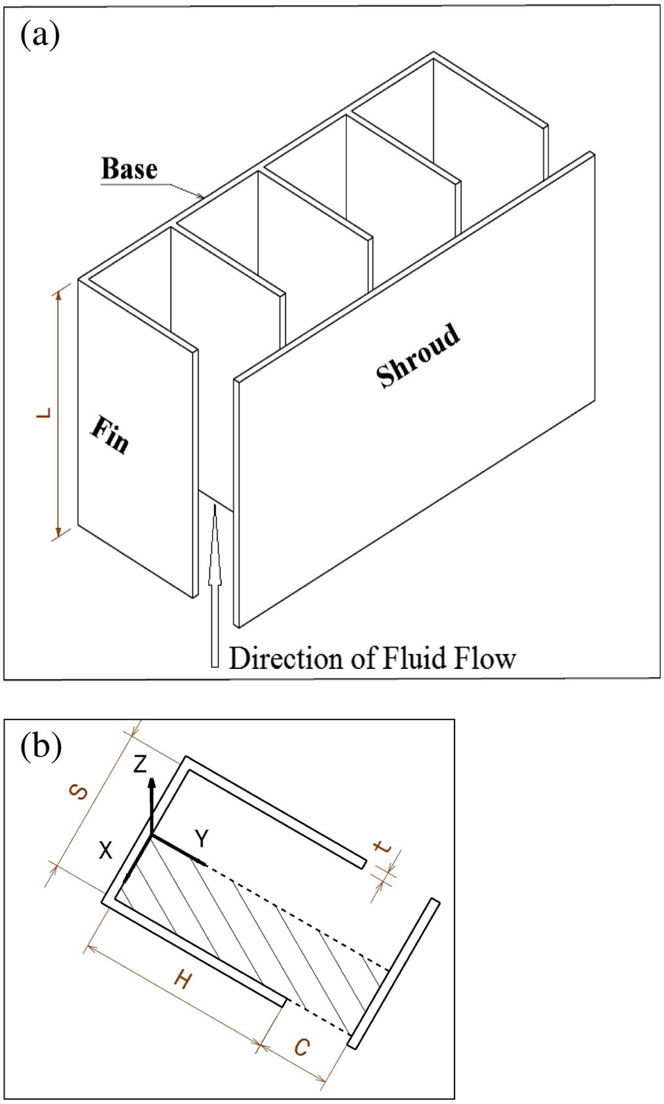

Fig. 1. (a) Schematic of mixed convection heat transfer from the vertical plate-finned heat sink. (b) Computational domain.

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} + \frac{\partial W}{\partial Z} = 0 \qquad (1)$$