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A numerical study of entry region laminar mixed convection over shrouded vertical fin arrays

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ABSTRACT

A computational study of laminar mixed convection over a shrouded vertical rectangular fin array attached to a vertical base has been performed. Maintaining the base-fin system above the surrounding temperature, a fan velocity is imposed to enhance the heat transfer through the mixed convection process. Present study finds the effects of clearance spacing, fin spacing, fin length, Reynolds number and Grashof number on the thermal performance of the base-fin system. Mixed convection inlet velocity is decoupled to forced and natural convection velocity components and the resulting pressure drop across the duct length arises purely due to the forced convection velocity component. Thus, Reynolds number is estimated based on forced convection velocity component as the inlet velocity does not vanish even in pure natural convection. Computed local Nusselt number shows sharp drop near the entrance and reaches a fully developed value after a certain streamwise distance from the entrance. Further, fully developed local Nusselt number shows a clear maximum at the clearance spacing of 0.075 and 0.15 for the inter-fin spacing of 0.3 and 0.5 respectively. Pressure drop across the duct, induced natural convection velocity and overall Nusselt number are well correlated with the governing parameters of the problem.

1. Introduction

Rapid heat removal from heat generating components is essential for the safe operation of equipment such as gas cooled nuclear reactors, automobile and aerospace vehicles, and electronic systems. Further, with the development of advanced technology the demand for miniaturization of engineering components is increasing day by day. But the miniaturization of components and higher packaging densities invariably result in higher heat fluxes. Thus, the components are elevated to higher temperature, thereby degrading the performance and reliability of such equipment. Hence there is an ever increasing need for the rapid and reliable heat removal for the safe operation of the components. In many cases, cooling of electronic equipment is accomplished by blowing air at moderate velocities. All the above factors normally result in laminar convection involving low values of heat transfer coefficients. In such situations, it is a common practice to add fins to augment the heat transfer, since fins increase the available surface area.

Extensive studies on heat transfer from extended surfaces have been reported in the classic publications such as Harper and Brown [1], Elenbaas [2] and Gardner [3]. Heat transfer due to natural convection from vertical and horizontal fin arrays are investigated by several researchers, for instance, Starner and McManus [4], Welling and Wooldridge [5], Harahap and McManus [6], Jones and Smith [7], Karki and Patankar [8]. Recent experimental studies by Rao and Venkateshan [9], and Yüncü and Anbar [10] on vertical fin with horizontal base consider simultaneous free convection and radiation. Additional experimental evidence on natural convection from shrouded vertical fin with vertical base can be seen in Fisher and Torrance [11], in which chimney effect was discussed. Yazicioğlu and Yüncü [12] presented optimum fin spacing in the case of natural convection from vertical fin with vertical base.

Sparrow et al. [13], Sparrow and Beckley [14], Sparrow and Kadle [15], and Kadle and Sparrow [16] performed investigation on the effect of heat transfer in the presence of fin-tip clearance under forced convection situation. Results obtained from these investigations showed a close relation between heat transfer coefficient ratio and fin-tip clearance to fin-height ratio, but found hardly any dependence on the air flow rate and fin height. A comprehensive experimental study on forced convection was made by El-Sayed et al. [17] from shrouded fin arrays under very high Reynolds number, in which Nusselt number was correlated with the fin thickness, fin length, fin height and Reynolds number of the problem. In another investigation, Elshafei [18] investigated the performance of fin heat transfer from a shrouded fin arrays both experimentally and theoretically under forced flow situation.

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Nomenclature

A_c	cross-sectional area of fin geometry, $S(H+C)$ (m^2)
g	gravitational acceleration (m/s^2)
H	fin height (m)
Gr	thermal Grashof number, $g\beta(T_w - T_0)H^3/\nu^2$ (dimensionless)
h	heat transfer coefficient (W/m^2 K)
L	fin length (m)
L^*	dimensionless fin length (L/H)
Nu	Nusselt number (dimensionless)
p	total pressure defect, $p_s - p_0$, (Pa)
$\overline{p}$	average pressure defect over the cross section (Pa)
p_f	cross stream pressure
p_s	static pressure (Pa)
p_0	ambient pressure, $\int_0^z \rho_0 g \partial z$ (Pa)
P^*	dimensionless axial pressure defect, $\overline{p}H^2/\rho_0\nu^2$
P	dimensionless cross stream pressure, $p_f H^2/\rho_0\nu^2$
Pr	Prandtl number, ν/α (dimensionless)
Re	Reynolds number, $W_{in,force}H/\nu$ (dimensionless)
S	fin spacing (m)
S^*	dimensionless fin spacing, S/H
T	temperature (K)
C	fin tip to shroud clearance (m)
C^*	dimensionless tip clearance, C/H
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)

Subscript

s	shroud
b	bulk
f	fin
w	base
0	ambient/reference
in	inlet
mix	mixed convection
force	forced convection
nc	natural convection
pnc	pure natural convection

Superscript

*	dimensionless quantity

Conclusion of this work indicated significant flow bypass through clearance between the fin-tip to shroud and thereby degrades the performance of fin heat transfer.

Acharya and Patankar [19] computationally studied combined free and forced convection from shrouded vertical fin attached to a horizontal base. Recent experimental study on mixed convection from longitudinal fin in a horizontal channel for both high and low Richardson number by Dogan and Sivrioglu [20,21] reveals optimum fin spacing for which heat transfer is maximum. A computational study of laminar combined free and forced convection from shrouded vertical fin attached to vertical base under fully-developed condition has been made by Zhang and Patankar [22] and later this problem was extended parametrically by Al-Sarkhi et al. [23] using the mathematical model developed by Zhang and Patankar [22]. Mixed convection studies by Zhang and Patankar [22] and by Al-Sarkhi et al. [23] are for fully-developed condition, which reduces the three dimensional problem into a two-dimensional problem. In practice, fully developed condition requires large length to achieve. Hence, these investigations are not applicable to fins having a smaller length. In addition, it may be appropriate to mention here that in most of the earlier studies on mixed convection over vertical channel, inlet velocity is considered as a characteristic velocity for Reynolds number evaluation. But under the situation of mixed convection for vertical fluid flow, contribution of inlet velocity is mainly due to two factors: one is the fan velocity and the other is the induced velocity resulting from buoyancy. In the analysis, these two velocities should be segregated by some suitable means. It should be remembered that induced velocity component due to buoyant force does not contribute significantly to the overall pressure drop across the ends of the duct. Therefore, it is important to decouple the two velocity components to find out the exact fan velocity which is required to evaluate fan power. Moreover, for a fixed inlet velocity, induced natural convection velocity component increases with the increase in length of the fin due to chimney effect. Hence pressure drop across the length of the duct consisting of base-fin and shroud decreases with the duct length until it reaches zero value, in which case it becomes a pure natural convection problem. So, friction factor with the increase in length of the fin never reaches a fully-developed value, as evaluated and depicted by the previous investigators [22,23] and also it does not depend on the Rayleigh number of the problem. Thus, vertical length of the duct in mixed convection is an important parameter.

Literature reveals that studies on heat transfer from rectangular fins have, for the most part, considered natural or forced convection. However, vertical fin arrays attached to vertical base operating under combined natural and forced convection heat transfer have received less attention, especially on the entry region of flow. Further, as mentioned above, it is important to segregate the natural convection velocity component from the inlet velocity. In the present work, an attempt has been made to study the entry region mixed convection over shrouded vertical rectangular fin arrays attached to a vertical base by decoupling the inlet velocity into two components, i.e., the fan velocity and the induced velocity resulting from buoyancy. Finally, pressure drop across the duct, induced velocity and overall Nusselt number have been correlated with the governing parameters of the problem. Description of the physical model is presented in the following section.

2. Analysis

2.1. Physical model

Fig. 1 shows the physical model of the problem considered here. Rectangular plate fins having length L, thickness t, and