Energy Conversion and Management 88 (2014) 15–26

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Conjugate conduction and convection underneath a downward facing non-isothermal extended surface: A numerical study

Biplab Das, Asis Giri *

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

A R T I C L E I N F O

Article history:
Received 22 January 2014
Accepted 7 August 2014
Available online 2 September 2014

Keywords:
Downward facing fin
Conjugate conduction–convection
Grashof number
Nusselt number

A B S T R A C T

The analysis of the conjugate conduction and mixed convection heat transfer in a downward facing channel constituted by two non-isothermal extended surfaces, a base and an adiabatic shroud is numerically performed. The effect of fin conductivity, Grashof number, dimensionless clearance (C^*) and dimensionless inter fin spacing (S^*) is carried out through the evolution of the temperature, heat transfer and fluid flow fields. Computed results reveal that buoyancy induced cross-stream flow enhances flow by-pass through the clearance, especially for higher fin spacing. Moreover, it reveals that isothermal surface (infinite conductivity) leads to a significant overprediction of heat transfer as high as 134%, especially at lower fin spacing ($S^* = 0.1$). In addition, enhancing dimensionless fin conductance parameter by 200%, an increase of heat transfer as good as 62% is noted for $S^* = 0.1$. At higher fin spacing ($S^* = 0.3$ and 0.5), effect of Grashof number on heat transfer found to be more profound at higher Grashof number ($>10^5$). Zero clearance turns out to be the superior configuration.

1. Introduction

Augmentation of heat transport is frequently achieved by attaching extended surfaces in many applications like thermoelectric devices, nuclear reactor, automotive vehicle, solar heat transport, etc. Absolute magnitude of heat transport depends very much on the fluid flow direction as well as on the orientation of extended surface. Easily reproducible and most commonly used rectangular extended surfaces aligned vertically, parallel to gravity, may be considered to be the best configuration under natural convection. But this does not rule out other types of installations, which may be inevitable due to some other constraints. A case of such configurations is identified as the extended surfaces projecting downwards from a horizontal base. The present effort is directed to estimate the cooling capability of rectangular fin arrays projected downward from a horizontal base. Natural convection cooling of engineering equipment has the advantage of little noise. But the paucity of heat transport from natural convection limits its use. Thus, combined mode of free and forced convection may be a viable option.

Existing literatures indicates that there are several articles on vertical extended surfaces projected upwards from a horizontal surface. Natural convection from such configuration was reported in a number of literatures [1–13]. Starner and McManus [1] examined laminar natural convection from rectangular fin arrays glued to a rectangular base orienting the base to horizontal, vertical, and inclined 45^0 to horizontal direction to find the effects of fin height and fin spacing on heat transfer. Vertical orientation was turned out to be the superior. Immediately after Starner and McManus [1], Welling and Wooldridge [2] experimentally visited the natural convection from a vertical rectangular near isothermal fin array, in which fin heat transfer are found to lie between the results of vertical plate and the square duct/infinite parallel plate. In 1967, Harahap and McManus [3] highlighted experimental findings of free convection heat transfer from a vertical fin array on a horizontal base, where fluid motion was observed using Schlieren-shadowgraph technique. Results indicated single chimney flow drawing air from both the ends, while larger fin length induced many chimney flow introduced by the flow reversal in the intermediate section along the length of fin. Similar experimental studies of fin heat transfer on a horizontal base was made by Jones and Smith [4] to find an optimum fin spacing.

Sobhan et al. [5] experimentally revisited natural convection from fin array on horizontal base using differential interferometer technique and proposed Nusselt number correlation. A comprehensive experimental study of simultaneous natural convection and radiation from horizontal fin arrays is found in Rao and Venkateshan [6]. Heat transfer correlation for both fin and base are also provided in terms of governing dimensionless parameters.

---

* Corresponding author. Tel.: +91 360 2257401x6191; fax: +91 360 2258533.
E-mail address: measisgiri@rediffmail.com (A. Giri).

http://dx.doi.org/10.1016/j.enconman.2014.08.011
0196-8904/

Nomenclature

A_c	cross-sectional area of fin geometry, $0.5 \times S(H+C)$ (m^2)
C	fin tip to shroud clearance (m)
C^*	dimensionless tip clearance, C/H
g	gravitational acceleration (m/s^2)
Gr	thermal Grashof number, $g\beta QH^3/\nu^2k$ (dimensionless)
h	heat transfer coefficient (W/m^2 K)
H	fin height (m)
k	thermal conductivity of fluid (W/m K)
k_f	thermal conductivity of fin (W/m K)
Nu	Nusselt number (dimensionless)
p	pressure, (Pa)
Pr	Prandtl number, ν/α (dimensionless)
Q	heat input per unit axial length, (W/m)
Re	Reynolds number, $w_{av}H/\nu$ (dimensionless)
S	fin spacing (m)
S^*	dimensionless fin spacing, S/H
t	fin thickness (m)
T	temperature (K)
u, v	cross-stream velocities in x- and y-direction respectively (m/s)
U, V	dimensionless cross-stream velocities in X- and Y-direction respectively, uH/ν, $\upsilon H/\nu$
w	velocity component in z-direction (m/s)
W	dimensionless velocities in Z- directions, $-w\mu/(H^2(dp/dz + \rho g))$
x,y,z	cross stream and axial coordinates (m)
X,Y,Z	dimensionless cross stream and axial coordinates, x/H, y/H and $(z/H)/(w_{av}H/\alpha)$

Greeks

α	thermal diffusivity (m^2/s)
β	thermal volumetric expansion coefficient, $-(1/\rho_w)(\partial \rho/\partial T) = 1/T_w$ (1/K)
ΔT	scaling temperature difference, Q/k (K)
ν	momentum diffusivity (m^2/s)
Ω	thermal conductance parameter, $k_f(t/2)/(kH)$
ϕ_f	dimensionless fin temperature based on excess temperature of base wall and bulk fluid, $\left(\frac{T_w-T_f}{T_w-T_b}\right)$
ρ	density (kg/m^3)
θ	dimensionless temperature, $(T_w - T)/(Q/k)$

Subscript

av	average quantity
b	bulk
c	convection
f	fin
l	local quantity
s	shroud
w	base
0	ambient/reference

Superscript

*	dimensionless quantity

An experimental study of buoyancy induced convective heat transfer from vertical rectangular fin array on a horizontal rectangular base is reported in Yüncü and Anbar [7], where useful correlation is provided for heat transfer. A numerical study of natural convection heat transfer from an array of rectangular vertical fin on horizontal surface is carried out by Baskaya et al. [8].The overall heat transport is found to enhance with the increase in fin-height, while the same is decreased with the fin-length. In addition, it observes optimum value of fin spacing for which heat transfer is maximum. Moreover, Nusselt number is correlated by following the correlation provided by Harahap and McManus [3]. A three dimensional numerical study on natural convection heat transfer from longitudinal horizontal rectangular fin array is performed by Mobedi and Yüncü [9]. As depicted by the authors, the increase of fin spacing increases heat transfer coefficient, since fresh fluid enters through the middle in addition to the possibility of reduced boundary layer interference. Rao et al. [10], Sashikumar and Balaji [11], and Rakshit and Balaji [12] studied simultaneous natural convection and radiation from vertical fin array on horizontal base, while Dogan et al. [13] studied combined modes of natural convection and radiation from different shape fin on a horizontal base.

As mentioned earlier, heat transport by free convection is limited. Therefore, forced convection in combination with natural convection may provide a resort to enhance the upper limit of heat transport. An effort towards this may be seen in Sparrow et al. [14], wherein laminar forced convection was reported from non-isothermal vertical fin array projected upwards from a horizontal base. Fudholi et al. [15] studied the forced convection heat transfer performance of finned double pass solar collector. Isothermal vertical fin array protruding upward from a horizontal base undergoing mixed convection was examined by Acharya and Patankar [16] for a specific case. Both experimental and numerical investigations of mixed convection from an array of vertical fins glued upward to a horizontal base were made by Maughan and Incropera [17,18]. Recently, Dogan and Sivrioglu [19–21] performed a series of tests both experimentally and computationally under mixed convection from a shrouded vertical fin protruding upward from a horizontal base for high and low Archimedis number.

On the other hand, the case of vertical fins protruding downward is limited. Since the arrangement is not a convenient one, this configuration is ignored long. But the requirements of architectural design demands such hidden cooling devices. There remain a handful of literatures on heat transfer from a horizontal surface facing downward as seen in Fujii and Imura [22], Aihara et al. [23] and Su et al. [24]. But the present case considers a configuration, which relates closely to the studies of Dayan et al. [25,26], Mittleman et al. [27], Kwak and Song [28], and Acharya and Patankar [16]. Dayan et al. [25,26] and Mittleman et al. [27] recently investigated vertical fin projecting downward undergoing natural convection both analytically and experimentally. They provided a tool of estimating heat transport under natural convection. Kwak and Song [28] experimentally examined downward facing vertical fin array undergoing natural convection. Recently Pakdaman et al. [29] studied natural convection from finned solar air heater, in which fins are projected downwards. Laminar mixed convection from isothermal vertical fin projecting downwards reported by Acharya and Patankar [16] for limited parameters.

A comprehensive survey of archival literature directs that heat transfer studies from downward facing vertical fin are indeed inadequate. Only pure natural convection studies under such configuration are reported recently by Dayan et al. [25,26], Mittleman et al. [27], Kwak and Song [28] and Pakdaman et al. [29]. The sole prior study known to authors on mixed convection under such configuration is reported in Acharya and Patankar [16] for restricted parameters involving large fin spacing and large clearances. Moreover, Acharya and Patankar [16] consider a case of isothermal fin, which considerably overestimates the heat transfer [30]. Further, computed heat transfer coefficient data presented