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Effects of a finite section with linearly varying wall temperature on mixed convection in a vertical channel

Tsai-Shou Chang

Department of Power Mechanical Engineering, National Formosa University, 64 Wun-Hua Road, Huwei, Yuenlin 63208, Taiwan ROC

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Abstract

Laminar mixed convection in a vertical channel with a finite section of a linearly varying wall temperature is numerically investigated. Dramatic variations of local velocity, temperature, local and average Nusselt numbers are plotted to demonstrate the influences of investigated parameters including Reynolds number, Grashof number and the degree of wall temperature variation. Particular attention is paid to reveal the effects of linearly varying temperature. The results suggest that the average Nusselt number $\overline{Nu}$ increases with Re and Gr. Moreover, $\overline{Nu}$ is higher with a linearly increasing wall temperature than that with a linearly decreasing wall temperature. Finally, an excellent correlation is proposed to predict $\overline{Nu}$ over the wide ranges of investigated parameters.

Keywords: Linearly varying wall temperature; Laminar mixed convection; Vertical channel

1. Introduction

Mixed convection flow through a heated channel has been extensively explored because of its occurrence in many practical applications such as the cooling of electronic equipment, heat exchangers, etc. Comprehensive reviews have been conducted by Incropera [1], Aung [2] and Gebhart et al. [3]. Most of the previous researches investigated the mixed convection with either uniform wall temperature or wall heat flux thermal boundary condition. However, these imposed thermal boundary conditions are not suitable in many practical applications such as heat exchangers [4,5], inject mold, transient setup and shutdown processes and non-equilibrium solidification processes. Furthermore, to meet the industrial requirements, a non-uniform thermal boundary is necessary. For example, Kim et al. [6] utilized a non-uniform temperature distribution to obtain a uniform thickness substance film in chemical deposition process. Therefore it is necessary to discover the influences of the non-uniform thermal boundary conditions on the heat transfer and flow characteristics in mixed convection flow. In the following, some of the published reports relevant to mixed convection and the effects of non-uniform thermal boundary are reviewed, respectively.

It is well known that buoyancy plays an important role on the forced fluid flow and heat transfer in a heated vertical channel. For an aiding flow with a sufficient high Gr/Re^2, the fluid near the heated walls is accelerated to a very high speed, causing the flow reversal in the central portion of the channel in order to maintain mass conservation. On the other hand, in general, a recirculating flow is observed near by the heated walls when the opposing buoyancy force is strong enough to reverse the forced flow locally. Consequently, understanding of mixed convection heat transfer becomes important and necessary. Tao [7] and Quintiere and Mueller [8] studied the steady fully developed and developing mixed convection. Habchi and Acharya [9] numerically investigated the aiding mixed convection of air. Their results show that the air temperature increases with Gr/Re^2 and the Nusselt number decreases monotonically. A similar study was performed by Aung and Worku

E-mail address: tschang@nfu.edu.tw

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Nomenclature

b	channel spacing
g	gravitational acceleration
Gr	Grashof number, $g\beta(T_m - T_e)b^3/\nu^2$
h	convective heat transfer coefficient
$\vec{i}, \vec{j}$	unit vector in X and Y direction, respectively
k	thermal conductivity of fluid
ℓ	length of the heated section
L	dimensionless length of the heated section
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
$\overline{Nu}_{cor}, \overline{Nu}_{num}$	$\overline{Nu}$ obtained from the proposed correlation and numerical simulation, respectively
p	pressure
P	dimensionless pressure, $(p - \rho g x)/\rho\overline{u}_e^2$
Pr	Prandtl number
Re	Reynolds number, $\overline{u}_e b/\nu$
T	temperature
T_e	inlet temperature
T_m	mean temperature of the heated section
u, v	dimensional velocities in x and y direction
u_e	inlet velocity
$\overline{u}_e$	average inlet velocity
U, V	dimensionless velocities in X and Y direction
$\vec{V}^*$	provisional velocity vector
x, y	Cartesian coordinate
X, Y	dimensionless Cartesian coordinate

Greek symbols

α	thermal diffusivity
β	volumetric thermal expansion coefficient
ν	kinematic viscosity
θ	dimensionless temperature, $\theta = (T - T_e)/(T_m - T_e)$
θ_1	dimensionless temperature at $X = 0$ and $Y = 0$
ρ	density of fluid

[10], indicating that buoyancy force can cause a severe distortion in the velocity profile especially under asymmetric heat condition. The mixed convection with a low Peclet number in a short channel was examined by Chow et al. [11]. Various axial length scales to distinguish regions of different convective mechanisms were discussed by Yao [12]. Cebeci et al. [13] investigated the recirculating flow and heat transfer in steady laminar opposing mixed convection in a vertical flat duct. Aung and Worku [14] and Lavine [15] proposed the criteria for the presence of reverse flow in vertical and inclined ducts, respectively. Ingham et al. [16,17] observed that poor heat transfer results for flow retarded by an opposing buoyancy force, but for a large and negative Gr/Re^2 heat transfer is rather effective. Actually, heat transfer may be greatly enhanced over the section containing a strong reverse flow.

It is a classical problem to consider the heat transfer of an infinite flat plate which has a power-law wall temperature distribution while the ambient being kept at a constant temperature [18]. Recently this problem has been re-investigated and combined with a few interesting features, for example, with a micropolar fluid [19], a thermally stratified porous medium [20], combined heat and mass transfer [21], linearly moving permeable surface [22] and MHD-free convection [23]. The effects of finite heating and/or cooling section are of interest, too. Effects of local cooling/heating surface in a thin vertical cylinder were studied by Kumari and Nath [24]. They assumed the variations of the wall temperature and wall heat flux are of the form, $(x - x_i)(x_j - x)/(x_j - x_i)^2$, where x is the axial coordinate and x_i, x_j are two pre-assigned positions. Ramos et al. [25] carried out the study on the effects of a sinusoidal wall temperature in an oscillatory flow. Their results show that the ambient velocity, the oscillatory frequency and the wave length of the sinusoidal wall temperature are the important parameters. Hernandez and Zamora [26] explored the effects of variable properties and non-uniform heating on the flow and heat behaviors in vertical channels. Particular attention is paid to the maximum mass flowrate in the channel inlet induced by natural convection when the wall heat flux was varied. Saeid and Yaacob [27] performed a computational work to study the influences of a sinusoidal side-wall temperature on the natural convection in a square cavity. They found that the imposed oscillatory amplitude and the wave number strongly affect the heat transfer. The maximum average Nusselt number occurs at a wave number about 0.7.

In addition to the spatial variation of thermal boundary conditions as reviewed above, it is also interested to consider the temporal variation. Turbulent channel flow with thermal stratification and wall temperature oscillation is studied numerically by Dong and Lu [28]. Large eddy simulation coupled with dynamic subgrid-scale models is employed to analysis the turbulent flow and heat transfer characteristics. The turbulent heat transfer is observed to be significantly affected by the forced wall temperature oscillation. The laminar mixed convection in an inclined channel was analytically investigated by Barletta and Zanchini [29]. Particular attention is focused on the effects resulted from the time-sinusoidal varying temperature distribution on the lower wall of the channel. A resonance frequency which corresponding to a maximum oscillatory amplitude of the Nusselt number is found for every Prandtl number. Malashetty and Basavaraja [30] examined the stability characteristics of a double diffusive convection in horizontal fluid layer by imposing symmetric or asymmetric temperature modulation on the top and bottom plates. Kwak et al. [31] investigate the effects of a time-dependent