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Conjugate mixed convection in the entrance region of a symmetrically heated vertical channel with thick walls

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A B S T R A C T

Conjugate mixed convection with buoyancy assisted laminar flow in the entrance region of a vertical channel is considered numerically. The problem is solved by a finite volume method for a thick walled, two-regional channel which has constant and uniform outside wall temperatures. The effects of wall thermal conduction as well as assisted buoyancy force on the flow and heat transfer are discussed in detail. Results are presented for a Prandtl number of 0.7, solid-to-fluid thermal conductivity ratios of $1 \le k^* < \infty$, wall thickness-to-channel length ratios of $0 \le l^* \le 5$, Reynolds numbers of $200 \le \mathrm{Re} \le 1000$, and for various Grashof numbers. The critical buoyancy parameter (Gr/Re), above which the flow reversal occurs, increases linearly with the increasing l^*/k^*, while it is independent on the Reynolds number.

1. Introduction

Mixed convection heat transfer in vertical pipe and channel flows has been extensively studied in the past few decades due to its importance in industrial and engineering applications, such as heat exchanger systems, nuclear reactors, electronic cooling, fluid transport, building works and so on. It has been recognized that, when the flow velocity is low and the temperature difference between the channel wall and the fluid is large, the direction and magnitude of the buoyancy force may significantly affect the flow structure and heat transfer characteristics in the channel.

Most of the previous literatures concerned with the mixed convection flow and heat transfer in a vertical channel with imposed heat flux or temperature at the channel wall, neglected wall thermal conduction [1,2]. The flow reversal, which occurs when the buoyancy parameter exceed a threshold value, was one of the most extensively investigated subjects, as it determined the flow structure in the channel and, consequently, heat transfer, pressure drop, fluid friction and entropy generation, etc. The regime of such buoyancy induced reversed flow has been presented comprehensively by researchers for fully developed or developing flow, accounting for cases of symmetric or asymmetric heated boundary conditions [3–10]. In a recent study, Desrayaud and Lauriat [11] numerically investigated the flow reversal phenomenon for laminar mixed convection of air in a vertical parallel-plate channel. The effects of the assisted buoyancy on the flow pattern and temperature profiles were discussed in detail, and the regime of reversed flow was identified for high values of the Péclet number in a Pe-Gr/Re map. Their study was thereafter extended to three dimensional mixed convection flow by the present authors [12,13], who investigated the flow reversal and heat transfer in a three dimensional symmetrically heated rectangular duct.

However, in most practical situation, such as for hot/cold fluid transport and heat exchangers, the boundary conditions of the fluid zone are not known initially but depend on the coupling between convection and wall conduction at the fluid–solid interface, and the effect of wall conduction is even pronounced in the thermal entrance region [14]. The earlier studies of conjugate heat transfer problems were mainly concerned with the coupling of wall conduction and pure forced convection flow or the coupling of wall conduction with natural convection. For laminar convection flows in parallel plates or in circular pipes, the effect of axial wall conduction was examined by many authors such as Davis and Gill [15], Mori et al. [16,17], Faghri and Sparrow [18], etc. The wall conduction was considered as one dimensional in these studies. Bilir [19] numerically analyzed the conjugate heat transfer problem within thermal developing laminar pipe flow, involving two dimensional (axial and radial) wall and axial fluid conduction. Adelaja et al. [20]

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Nomenclature

c_p	specific heat of the fluid, J/(kg K)
f	friction factor
g	gravitational acceleration, m/s^2
Gr	Grashof number
H	height of the duct, m
k	thermal conductivity, W/(m K)
l	thickness of the solid zone, m
L	length of the fluid zone, m
N	grid number
Nu	Nusselt number
p	pressure, Pa
P	non-dimensional pressure
Pe	Péclet number
Pr	Prantdl number
Re	Reynolds number
Ri	Richardson number
T	temperature, K
U, V	dimensionless velocity
X, Y	dimensionless coordinate system

Greek symbols

β	coefficient of volumetric expansion, 1/K
θ	dimensionless temperature
μ	dynamic viscosity of the fluid, Pa s
ν	kinematic viscosity of fluid, m^2/s
ρ	density of the fluid, kg/m^3

Subscripts

avg	average value
b	bulk value
cr	critical value
∞	free-stream or inlet condition
f	fluid
s	solid
w	wall
x, *y*	Cartesian coordinates

Superscript

$'$	dimensional variable
$*$	relative value

analytically studied the effect of two dimensional wall and fluid conduction for low Péclet number laminar flow heat transfer with convective boundary conditions of the third kind for the thermal entrance region problem. They found that an increase in the wall thickness resulted in reduced heat flux, while increases in the Biot number and the ratio of the wall-to-fluid thermal conductivity resulted in increased heat flux.

For studies considering the coupling of natural convection, forced convection and wall conduction (i.e. conjugate mixed convection), Chou and Lien [21] numerically studied the effect of wall conduction on laminar mixed convection in the thermal entrance region of horizontal rectangular channels. Results showed that the flow and heat transfer characteristics are affected significantly by the wall thermal conduction and the buoyancy-induced secondary flow. Bernier and Baliga [22] investigated the conjugate conduction and laminar mixed convection in vertical pipes for upward flow and uniform heat flux. Their results were presented for the conditions of Pr = 5, Gr = 5000, Re = 1 and 10, and different values of solid-to-fluid thermal conductivity ratios and wall thickness-to-pipe diameter ratios. Laplante and Bernier [23] presented a numerical study aimed at quantifying the effects of wall conduction on laminar mixed convection in vertical pipes for a downward flow and a uniform wall heat flux boundary condition. Results indicated that a significant amount of heat is redistributed upstream of the heated section when the solid-to-fluid thermal conductivity and/or the wall thickness-to-pipe diameter ratios are high. Omara et al. [24,25] numerically studied transient heat transfer for downward and upward mixed convection in a vertical thick pipe partially exposed to a constant heat flux, focusing on the transient distribution of heat flux and friction coefficient. However, most of these studies considered the boundary conditions of the solid wall surface as constant heat flux, and the buoyancy induced flow reversal regime in the vertical channel with thick walls of constant temperature was not clearly revealed.

The aim of the present study is to assess the combined effects of the wall conduction and assisted buoyancy on the flow and heat transfer characteristics in symmetrically heated vertical channels with isothermal thick walls, for the solid-to-fluid thermal conductivity ratios of $1 \le k^* < \infty$, wall thickness-to-channel length ratios of $0 \le l^* \le 5$, Reynolds numbers of $200 \le \text{Re} \le 1000$, a Prandtl number of 0.7 and for various Grashof numbers. The aim is achieved by numerically solving the governing equations in the fluid and solid regions. Another important objective of this study is to highlight the flow reversal mechanism in the vertical channel with conjugate mixed convection heat transfer.

2. Physical description and mathematical formulation

The physical model of mixed convection flow in a vertical channel with thermal conducting walls, along with the relevant dimensions considered in the present study is illustrated in Fig. 1. Newtonian fluids enter the channel with uniform velocity V'_∞ and temperature T_∞ from the bottom. The channel walls are of the thickness l ($0 \le l^* = l/L \le 5$) with the outer surface maintained at a

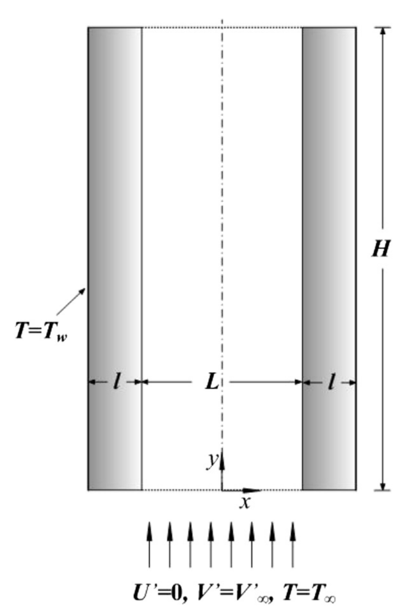

Fig. 1. Schematics of the upward flow in a parallel-plate channel with heated thick walls.