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Effect of aspect ratio and assisted buoyancy on flow reversal for mixed convection with imposed flow rate in a vertical three dimensional rectangular duct

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ABSTRACT

A numerical investigation is carried out to understand the effect of aspect ratio, as well as assisted buoyancy on flow and heat transfer characteristics in a vertical duct with rectangular cross section. Results are obtained for mixed convection flow with imposed inlet flow rate in a symmetrically heated duct with uniform wall temperature. The flow and thermal patterns are presented and discussed for various aspect ratios and buoyancy parameters. The critical value of buoyancy parameter (Gr/Re), above which the flow reversal starts to occur, decreases with increasing aspect ratio (L/W) for $0 < L/W < 0.75$, and increases with increasing aspect ratio for $0.75 < L/W < 1$. The position of the stagnation point and the profile of the recirculation cells for the flow reversal are significantly affected by the aspect ratio of the rectangular cross section. The influence of aspect ratio and buoyancy force on the local and average Nusselt number of the walls is also investigated.

1. Introduction

The problem of mixed convection flow and heat transfer in vertical ducts has received considerable attention because of its practical applications in heat exchangers, electronic cooling, fluid transport, building works, etc. Especially, the flow reversal phenomenon induced by assisted buoyancy has been extensively reported in the past several decades, due to its profound influence on flow instability, friction factor, temperature distribution and heat transfer.

The vast majority of the literature reviews correspond to the mixed convection flow in circular tubes or in vertical channels. As has been recognized by many researchers, the fluids near the channel walls are accelerated by the assisted buoyancy force and those near the center are decelerated as governed by the conservation of mass. When the buoyancy effect is strong, the centerline axial velocity reverses itself and the fluid near the centerline moves opposite to the inlet flow, and thus the reversed flow occurs. Hanratty et al. [1] might be the first to observe the flow reversal in vertical circular tubes by experiment. Their study revealed the reversed flow patterns in buoyancy assisted mixed convection flows at low Reynolds number. Thereafter, many researchers investigated the regime of the reversed flow and provided critical buoyancy parameters (Gr, Ra, Gr/Re, or Ri) for the occurrence of flow reversal numerically, analytically or experimentally. The solutions for fully developed flow either in parallel plates or in circular tubes are provided by Aung and Worku [2] and Cheng et al. [3], etc. They found the reversed flow occurred if the buoyancy force exceeded a certain critical value. On the other hand, the flow reversal phenomenon in developing flows has also been extensively studied, such as Ingham et al. [4], Gau et al. [5,6], Moutsoglou and Kwon [7] and Wang et al. [8], etc. Among these studies, various boundary conditions are considered, accounting for cases of symmetric or asymmetric heating with uniform wall temperatures and uniform or non-uniform heat fluxes. Zghal et al. [9] extended the research by investigating the effect of heating zone lengths on the flow characteristics for heating lengths ranging from 10 to 50 tube diameters. Their results showed that the values of Prandtl number, Reynolds number, Grashof number and heating length determined whether the flow reversal occurs, whether the flow is developing or fully developed and whether upstream diffusion of heat and momentum are significant. Azizi and Benhamou [10] numerically investigated the effects of buoyancy force on both assisted and opposed flow of air in a vertical parallel-plates channel wet by a thin liquid water, considering phase changes. The flow reversal was predicted in their study. Desrayaud and Lauriat [11]

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Nomenclature

AR	aspect ratio of the duct, $=L/W$
c_p	specific heat of the fluid, J/(kg K)
g	gravitational acceleration, m/s^2
Gr	Grashof number
H	height of the duct, m
k	thermal conductivity of the fluid, W/(m K)
L	length of the rectangular cross section, m
Nu	Nusselt number
p	pressure, Pa
P	non-dimensional pressure
Pr	Prandtl number
Re	Reynolds number
T	temperature, K
$\vec{V}$	dimensionless velocity vector
W	width of the rectangular cross section, m
X, Y, Z	dimensionless coordinate system

Greek Symbols

β	coefficient of volumetric expansion, 1/K
δ	cell size of the control volume
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
Ω	buoyancy parameter, Ω = Gr/Re

Subscripts

av	average value
cr	critical value
∞	free-stream or inlet condition
x, y, z	Cartesian coordinates

Superscript

$'$	dimensional variable

investigated flow reversal phenomena for laminar mixed convection of air in a vertical parallel-plate channel, which was symmetrically heated with uniform wall temperatures. The critical buoyancy parameter (Gr/Re) for the occurrence of flow reversal was found to be independent of the Péclet number for Pe > 200. Bazdidi-Tehrani and Shahini [12] numerically analyzed laminar ascending flow and combined mixed convection-radiation heat transfer within a symmetrically heated vertical parallel plates, considering the radiation effects (i.e., emitting, scattering and absorbing) both for walls and the participating medium. Their results indicated that the onset of flow reversal was considerably affected by wall emissivity and scattering albedo.

In practical applications, vertical ducts often occur with rectangular cross sections of various aspect ratios. Cheng et al. [13–15] investigated the buoyancy assisted flow reversal and heat transfer in vertical rectangular ducts. Physical situations investigated in their study included cases with various asymmetric heating conditions over wide ranges of parameters. Barletta and his co-workers [16–18] analytically studied laminar and fully developed mixed convection in a vertical rectangular duct. Various boundary conditions of channel walls were considered in their study, but their discussions were limited to fully developed flow, and the flow reversal under symmetrically heated isotherm walls was not put in evidence. In our earlier study [19], the flow reversal as well as entropy generation in a vertical channel of square cross section with uniform and constant wall temperatures was investigated. Different from flows in two dimensional channels or in circular tubes, the fluids in the vicinity of the corners between neighboring walls were found to be strongly accelerated by the assisted buoyancy in the rectangular duct.

The objective of this investigation is to study the effect of aspect ratios ($AR = L/W$) of the rectangular cross section, as well as the effect of the assisted buoyancy (Ω = Gr/Re) on the flow reversal phenomenon and heat transfer characteristics in a three dimensional vertical rectangular duct for various buoyancy parameters and aspect ratios. In this work, the distributions of velocity and temperature, the profiles of the flow reversal zones and the heat transfer characteristics are presented and discussed in detail.

2. Physical description and governing equations

The geometry and the relevant dimensions considered for analysis are schematically shown in Fig. 1. Newton fluid with constant inlet temperature T_∞ and uniform inlet velocity flows in a vertical duct from bottom to top. The duct has a finite height of H, and a rectangular cross section of $L \times W$. The no-slip walls of duct are maintained to a constant and uniform temperature of T_w greater than the temperature of the inlet fluid. Our previous work [19] has proved that the channel length has little effect on the flow reversal phenomenon in the vertical square duct of $H \geqslant 10L$. In order to get some detailed information of the fluids downstream the flow reversal region, the height of $H = 30L$ is adopted in the present study. All geometrical lengths are scaled with the length of the rectangular cross section L, and the various degree of aspect

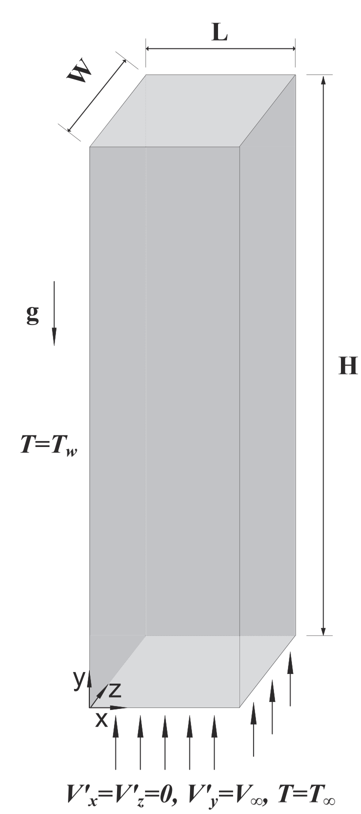

Fig. 1. Schematics of the upward flow in a heated three dimensional vertical rectangular duct.