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Entropy generation in a rectangular channel of buoyancy opposed mixed convection

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ABSTRACT

Mixed convection flow, heat transfer and entropy generation in a three dimensional rectangular channel under the influence of opposed buoyancy are investigated numerically. Results are obtained for various buoyancy parameters of $-500 \leqslant Gr/Re \leqslant 0$ at a constant Prandtl number of 0.7 in a symmetrically cooled channel with uniform wall temperature. The flow reversal is found to occur at the four corners between neighboring walls in the entrance region when buoyancy parameter exceeds a certain critical value, which strongly affects the temperature field, local and average Nusselt number, and local and global entropy generation. Such critical buoyancy parameter increases with the increasing aspect ratio of the rectangular cross section for $0.25 \leqslant AR \leqslant 1$ and is independent of Reynolds number for $100 \leqslant Re \leqslant 500$. The opposed buoyancy force decreases the global entropy generation by heat transfer in the channel, but the entropy generation by fluid friction drastically increases with the increasing opposed buoyancy force.

1. Introduction

Combined natural and forced convection (mixed convection) in a vertical channel is one of the most extensively investigated heat transfer problems because of its application in electronic cooling, heat exchangers, building works, nuclear reactors, solar systems, etc. A summary of the computational and experimental studies for mixed convection in a vertical tube was provided by Moutsoglou and Kwon [1] in 1993. As is acknowledged by many researchers, for flows in a symmetrically heated or cooled vertical channel, the flow reversal occurs in the central region of the channel under the effect of assisted buoyancy and at the channel walls under the effect of opposed buoyancy, both when the buoyancy parameter (|Gr/Re|) exceeds a certain value [2–4]. In the past twenty years, many researchers have investigated the effect of such flow reversal on the flow structures, stability, pressure drop and heat transfer analytically, numerically and experimentally [5–9].

Most of the existing studies concerned the results for two dimensional geometries. However, many channels encountered in engineering fields have a rectangular cross section, where the flow structure is inherently three dimensional. But the relevant 3D investigation is limited. To the best of our knowledge, the numerical and analytical solutions performed by Cheng et al. [10,11], Barletta et al. [12–14] and Yang et al. [15,16] compose the only published reports dealing with mixed convection flows in three dimensional rectangular ducts. Cheng et al. [11] investigated buoyancy assisted flow reversal and convective heat transfer in the entrance region of a vertical rectangular duct with various asymmetric heating conditions over wide rages of parameters. The criteria for the flow reversal to occur were predicted for fully development flows in their study. Barletta [12,13] and Barletta et al. [14] presented analytical solutions for laminar fully developed mixed convection flows in a rectangular duct. They considered various boundary conditions of channel walls, but their discussions were limited to fully developed flow and the flow reversal under symmetric heated isotherm walls was not put in evidence. Yang et al. [15,16] numerically investigated the mixed convection flow and heat transfer in a vertical rectangular duct under the effect of assisted buoyancy. The fluids in the vicinity of the four corners between neighboring walls were found to be strongly accelerated by the assisted buoyancy, and those at the centerline were decelerated. However, no works has been reported for thermal developing flow in a three dimensional rectangular with opposed buoyancy force, which is also often encountered in engineering applications. Therefore, the revealing of the regime of opposed buoyancy induced flow reversal, and the investigation

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Nomenclature

AR	aspect ratio of the rectangular cross section, L/W
Be	Bejan number
c_p	specific heat of the fluid, J/(kg K)
g	gravitational acceleration, m/s^2
Gr	Grashof number
H	height of the channel, m
k	thermal conductivity of the fluid, W/(m K)
L, W	width of the cross section of the channel, m
N_s	dimensionless entropy generation
Nu	local Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature, K
$\vec{V}$	dimensionless velocity vector
X, Y, Z	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
φ	irreversibility ratio
ρ	density of the fluid, kg/m^3
Ω	buoyancy parameter, Ω = Gr/Re

Subscripts

av	average value
b	bulk value
∞	ambient or inlet condition
fr	fluid friction
ht	heat transfer
tot	total
w	wall
x, y, z	Cartesian coordinates

Superscript

$'$	dimensional variable

of flow and heat transfer characteristics under the effect of opposed buoyancy in a rectangular duct, is of great theoretical and practical importance.

From the viewpoint of energy utilization, the optimization of energy consumption in a mixed convection energy system is also greatly affected by the buoyancy force [17]. The method of thermodynamic optimization or entropy generation minimization has been used to analyze and optimize mixed convection problems in recent years [18–21]. Chen et al. [22] performed a numerical investigation of entropy generation within a mixed convection flow in a parallel plate vertical channel. The numerical results showed that the entropy generation rate had a minimal value near the centerline of the channel. Mokheimer [23] studied the effect of buoyancy effects on entropy generation in the entrance region of a two dimensional vertical channel. The optimum values of the buoyancy parameter (Gr/Re) at which the entropy generation assumes its minimum was obtained. As the increasing attentions on the research of energy optimization, the effect of buoyancy force on entropy generation in mixed convection has also been investigated combining with radiation effects, nanofluid, and MHD flows [24–26]. For mixed convection flow under the effect of assisted buoyancy force, Yang et al. [15] found the assisted buoyancy induced flow reversal significantly affected the entropy generation, but the results for the case under the opposed buoyancy have not been reported yet. So the combined study of the effects of opposed buoyancy on flow and heat transfer characteristics and the entropy generation can provide guidance for the energy optimization of relevant systems.

The objective of this investigation is to understand the flow and heat transfer characteristics of a buoyancy opposed mixed convection flow in a three dimensional rectangular duct, and to study the effect of the opposed buoyancy force on the entropy generation. Such aim is achieved by analyzing the flow structure, isotherm patterns, heat transfer and entropy generation rate for the buoyancy parameters of -500 ⩽ Gr/Re ⩽ 0, the Reynolds numbers of 100 ⩽ Re ⩽ 500, the aspect ratios of 0.25 ⩽ AR ⩽ 1, and the Prandtl number of Pr = 0.7. A comparison with solutions under assisted buoyancy [15] is also made, to comprehensively understand the effects of directions of the buoyancy forces on the flow, heat transfer and entropy generation in the vertical rectangular duct.

2. Problem description and numerical method

The geometry of the problem along with the relevant dimensions considered in present study is illustrated in Fig. 1. Newtonian fluids with Pr = 0.7 enter a channel with uniform velocity V_∞ and temperature T_∞ from bottom to top. The channel has a

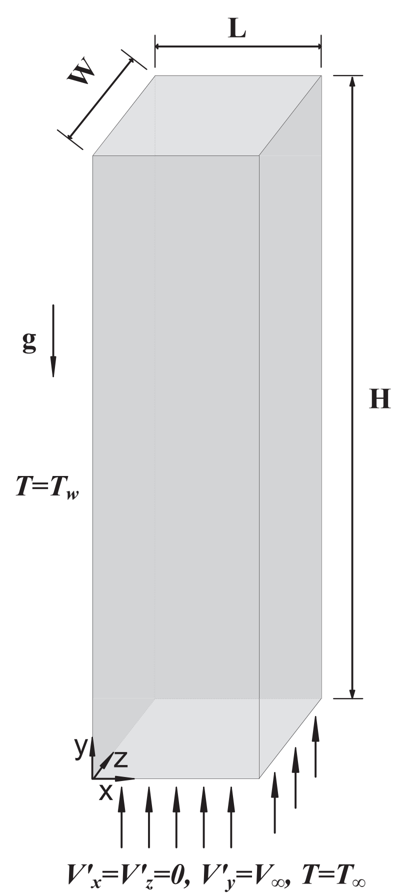

Fig. 1. Schematics of the upward flow in a cooled three dimensional vertical rectangular duct.