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The influence of bottom wall heating on the mean and turbulent flow behavior in the near wall region during mixed convection

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ABSTRACT

An experimental work is reported that studied the effect of mixed convection on the mean and turbulent flow structure in the near wall region inside a horizontal square channel heated from below at low Reynolds numbers (Re) and high Grashof numbers (Gr). The Gr/Re^2 values ranged from 9 to 106 indicating that natural convection was dominant over forced convection for all studied cases. Velocity fields were measured using particle image velocimetry (PIV) in the vertical mid plane and two horizontal planes close to the heated wall. The results show that the bottom wall heating altered the mean velocity field and induced turbulence. Both mean and turbulent velocity magnitudes showed partial dependency on the Gr/Re^2 ratio. In the higher range of Gr/Re^2, mean streamwise velocity showed larger magnitude whereas, in the lower range of Gr/Re^2, streamwise and spanwise turbulent velocities have larger magnitudes. The streamwise and spanwise turbulent velocity magnitudes were also found to be largest close to the heated wall. It was observed that in the vicinity of the heated wall, the warm fluid converges along the streaks which initiate the rising plumes while the falling parcels of cooler fluid disperse in the spanwise plane.

1. Introduction

Buoyancy is known for its influence on the hydraulic and thermal behavior of the flow. Mixed convection heat transfer is the process where buoyancy through natural convection coexists with forced convection. Mixed convection can occur at both low and high Reynolds number flows. Grashof number (Gr) to Reynolds number (Re) ratio (Gr/Re^2) determines the relative contribution of natural and forced convection modes in the mixed convection regime [1]. The Grashof number is the ratio between buoyancy forces and viscous forces while, Reynolds number is the ratio between the inertial forces and viscous forces. Hence, the Gr/Re^2 represents the ratio between the buoyancy and inertial forces. Low Reynolds number mixed convection can be found in several industrial applications such as: electronic cooling, chemical and nuclear reactors, food process industry and biomedical applications. Mixed convection heat transfer has been studied extensively over the past few decades. However, majority of the previous work was focused on evaluating overall heat transfer behavior by quantifying the Nusselt number (Nu).

Gajusingh and Siddiqui [2] experimentally studied the effect of wall heating on the flow characteristics in the near wall region inside a square channel. They found that the buoyancy generates turbulence for originally laminar flow while for originally turbulent flow, buoyancy dampens turbulence. They argued that for turbulent flow, turbulence is dampened due to working against buoyancy. Mahaney et al. [3] studied mixed convection inside rectangular duct with bottom heated wall and adiabatic side and top walls. They found that the secondary flow induced by natural convection was in the form of vortices due to the interactions between ascending plumes near the side walls and falling of cooler fluid. Nusselt number was found to increase downstream of the channel due to buoyancy-driven secondary flow enhancement. Osborne and Incropera [4,5] experimentally investigated the effect of buoyancy on convection heat transfer inside horizontal channels with heated top and bottom walls. For turbulent flow regime, they observed forced convection near the top wall and mixed convection near the bottom wall [4]. For laminar flow, they observed the presence of thermally stable boundary layer at the top blocking the thermal plumes originating from the bottom wall to reach the top wall [5].

Wang et al. [6] identified different flow patterns for mixed convection along the heated test section of a horizontal square channel with a bottom heated wall through flow visualization. They found that the flow passes through four different flow regimes along the channel heated section: laminar forced convection, laminar mixed convection, transient mixed convection and turbulent free convection. Ozsunar et al. [7] experimentally studied

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Nomenclature

c_p	specific heat, kJ/kg °C
D_h	hydraulic diameter, m
g	gravitational acceleration
Gr	Grashof number
Gz	Graetz number
h	heat transfer coefficient, (W/m^2 °C)
k	thermal conductivity, (W/m °C)
L	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
q''_s	surface heat flux, kW/m^2
Q_o	kinematic heat flux, m °C/s
Ra	Rayleigh number
Re	Reynolds number
T	temperature, °C
U	mean streamwise velocity, cm/s
u_*	fractional velocity, cm/s
u'	streamwise turbulent velocity, cm/s
v'	vertical turbulent velocity, cm/s
W	mean spanwise velocity, cm/s
w'	spanwise turbulent velocity, cm/s
w_*	convective velocity, cm/s
y_*	length scale, cm

Greek symbols

ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
β	coefficient of thermal expansion, 1/°C

Subscript

c	channel
rms	root mean square

mixed convection inside a bottom heated rectangular channel with side insulated walls. Their results showed that the development of mixed convection mechanism is strongly affected by Re and Gr values. They found that an increase in the Grashof number accelerated the development of mixed convection due to the generation of secondary buoyancy-driven flow, while, an increase in the Reynolds number delayed it. Huang and Lin [8] numerically investigated laminar mixed convection in a horizontal rectangular duct heated from below. They studied the effect of buoyancy-inertia ratio on the cross stream flow behavior. They found that with the increase of Gr/Re^2, the cross stream flow behavior shifts from a steady vortex flow at Gr/Re$^2 < 4$ into a chaotic flow at the channel exit at Gr/Re$^2 > 25$. Lin and Lin [9] visualized the air flow structure in a cross stream plane inside a bottom heated horizontal rectangular channel and found that the flow structure changes from periodic to quasiperiodic or chaotic with an increase in Gr or decrease in Re.

Nandakumar et al. [10] also focused on visualizing the flow structure in the cross stream direction for different horizontal channel geometries heated from below. Longitudinal vortex patterns of two or four vortices were observed and the bifurcation of the vortices was found to depend on the Grashof number and channel aspect ratio.

In spite of numerous studies on mixed convection at low Reynolds numbers, the structure of turbulence and its role on the transport of heat inside the channel fluid domain in the mixed convection mode still lack fundamental understanding. In particular, the flow dynamics in the region close to the heated bottom wall, which plays a very crucial role in regulating the buoyancy-induced secondary flow and the heat transfer rate, has not been thoroughly investigated and characterized. Furthermore, due to the complex interaction of the buoyancy-induced secondary flow and the shear flow, flow measurements in multiple planes provide a better characterization of the turbulent flow structure, which is likely three-dimensional in this case. The present study provides a qualitative as well as quantitative analysis of the flow near the heated wall in multiple planes with the aim of characterizing the three-dimensional mean and turbulent flow behavior.

2. Experimental setup

Experiments were conducted in a 7 cm × 7 cm square channel comprised of three sections; inlet section, test section and end section, as shown in Fig. 1(a). The inlet section 0.7 m long was made of aluminum and had a ½ inch diameter inlet, which housed a honeycomb to straighten the flow and damp any disturbances. The test section (1.5 m in length) has top and side walls made of ½ inch non-tempered glass and an aluminum bottom plate. Two strip heaters (1500 W–250 V) 1.3 m in length were installed directly underneath the bottom aluminum plate in parallel. The upstream ends of the heaters were located 10 cm downstream of the test section inlet. Five thermocouples were embedded in the bottom wall along the channel to monitor the uniformity of the bottom heated wall. It was observed that the bottom wall has good temperature uniformity with the variations within ±1 °C. To control the bottom wall temperature, a temperature controller (ZESTA-ZCP513) was used through a feedback loop from a thermocouple embedded in the bottom wall close to the measurement location. The end section was 30 cm in length and had a ½ inch diameter exit. Both inlet and end sections have bleed valves to remove any air trapped inside the channel, and pressure gauges to monitor the inlet and outlet fluid pressure.

Clean tap water was used as the working fluid. Four, 200 L storage tanks (barrels) were used to store the water at the room temperature, which allowed supplying the water at the same inlet conditions throughout a given experimental run. In the present study, the inlet water temperature was maintained around 24.5 °C. The water was stored in the barrels for two days with periodic stirring to remove air bubbles present in the tap water. To circulate the water through the loop, a magnetic pump (Little Giant, 5 MD) was used. The flow rate of water was controlled via a flow meter with a control valve (FL4205, Omega Engineering) (see Fig. 1(a)).

Four mass flow rates 0.0210, 0.0315, 0.0420 and 0.0525 kg/s were considered (corresponding Reynolds numbers in the absence of heating are 300, 450, 600 and 750, respectively, for reference). At each flow rate, experiments were conducted at different bottom wall temperatures which were 30, 35, and 40 °C. The corresponding Grashof numbers ranged from 6.37×10^6 to 1.57×10^7. To allow steady state to be reached, for each set of experiments, the measurements were taken 30 min after adjusting the flow rate for a given bottom wall temperature.

Particle image velocimetry (PIV) technique was used for measuring two-dimensional velocity fields in one vertical and two horizontal planes (see Fig. 1(b)). The PIV system comprised of a 120 mJ Nd:YAG laser (SoloPIV 120XT 532 nm) as the light source, a 2336 × 1752 pixels CCD camera (VA-4M32, Vieworks) to capture the images in the measurement plane along with an image