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The effect of mixed convection on the structure of channel flow at low Reynolds numbers

Ahmed Elatar, Kamran Siddiqui *

Department of Mechanical and Materials Engineering, University of Western Ontario, London, Ontario, Canada

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ABSTRACT

An experimental study was conducted to investigate the effect of bottom wall heating on the flow structure inside a horizontal square channel at low Reynolds numbers (Re) and high Grashof numbers (*Gr*). The flow field was found to be complex and three-dimensional due to the interactions of buoyancy-induced rising plumes of warm fluid, falling parcels of cold fluid and the shear flow. The mean streamwise velocity profiles were altered by bottom wall heating; and back flow was induced in the upper half of the channel when $Gr/Re^2 > 55$. The bottom wall temperatures were found to have more significant influence on the turbulent velocity magnitudes than the flow rate. The Reynolds stress became negative in the channel core region indicating the momentum transfer from the turbulent velocity field to the buoyancy field. The POD analysis revealed the presence of convective cells primarily in the lower half of the channel.

1. Introduction

Mixed convection heat transfer where both forced as well as free convection modes exist, can be found in several industrial applications. Two main factors that control the heat transfer mechanism and consequently the flow behavior are Grashof number (*Gr*) and Reynolds number (*Re*). Grashof number is the ratio between buoyancy and viscous forces, and the Reynolds number is the ratio between inertial and viscous forces (Incropera et al., 2006). Mixed convection at low Reynolds numbers is important in electronics cooling, food process industry, chemical and nuclear reactors, and biomedical applications. Recently, a new application of low Reynolds number mixed convection is emerging in the green energy sector where the solar thermal systems that convert solar energy into heat operate at low Reynolds numbers and high Grashof numbers.

Several studies investigated the low Reynolds number mixed convection inside channels. Different channel geometries, orientations and boundary conditions were examined. Generally, the main focus of these previous studies was on quantifying the bulk properties such as Nusselt number or coefficient of friction and investigating its variation along the channel heating section (e.g. Mahaney et al., 1987; Maughan and Incropera, 1987). Some studies were focused on flow visualization and identification of different flow patterns emerged due to convection (e.g. Lin and Lin, 1996 and Wang et al., 1996). The low Reynolds number flow in the laminar regime when exposed to heat, generates turbulence and hence, the investigation of turbulent flow behavior is crucial to understand the underlying physical processes associated with the mixed convection. To the best of authors' knowledge, no previously reported studies had conducted a detailed investigation of the turbulent flow behavior in low Reynolds number channel flows during mixed convection.

Gajusingh and Siddiqui (2008) experimentally studied the effect of wall heating on the flow characteristics in the near wall region inside a square channel. Their main focus was on the region immediately adjacent to the bottom heated surface. They studied how heat transfer would affect flow dynamics in the near wall region for originally laminar and turbulent flows. They found that the turbulence was generated due to buoyancy for originally laminar flow while for originally turbulent flow, buoyancy dampened turbulence. They argued that in originally turbulent flow, the turbulence dampens due to working against buoyancy. They quantified the instability due to stratification using Richardson number. They argued that for originally laminar flow, the instability produced by heating enhances turbulence while for originally turbulent flow, instability due to heating would reduce turbulence magnitude.

Several studies investigated the effect of bottom wall heating on the Nusselt number in a horizontal rectangular channel (Lin and Lin, 1996; Mahaney et al., 1987; Maughan and Incropera, 1987; Osborne and Incropera, 1985a, 1985b; Ozsunar et al., 2002) and a horizontal tube (Choi and Choi, 1994) at low Reynolds numbers. They all observed enhancement of Nusselt number for mixed convection compared to forced convection along the channel length and attributed this to the secondary flow enhancement which

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* Corresponding author. Tel.: +1 519 661 2111x88234; fax: +1 519 661 3020.
E-mail address: ksiddiqui@eng.uwo.ca (K. Siddiqui).

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disrupts the thermal boundary layer. Decay in Nusselt number was observed at the channel entrance region (Lin and Lin, 1996; Maughan and Incropera, 1987; Ozsunar et al., 2002) where the forced convection was the dominant mode as the buoyancy-driven secondary flow was not developed yet. Osborne and Incropera (1985a,b) experimentally investigated the effect of buoyancy on convection heat transfer inside horizontal channels with top and bottom heated walls for laminar, transient and turbulent flow regimes. Their main focus was to quantify Nusselt number adjacent to the top and bottom walls. At the top wall, forced convection was dominant in all flow regimes and the Nusselt number values were lower than that for the bottom wall. They argued that for the transient regime at the top wall, the flow "laminarization" due to stably stratified temperature distribution is responsible for the decrease in the Nusselt number values. For laminar flow regime, forced convection was dominant in the top wall region and a thermally stable boundary layer was formed preventing ascending plumes from the bottom wall to penetrate this region. They proposed a correlation to quantify Nusselt number. They concluded that the magnitude of heat flux at one wall has no influence on the convection heat transfer at the other wall. It has been reported in the previous studies that an increase in the Grashof number accelerates the onset of the secondary flow and consequently the mixed convection, while an increase in the Reynolds number delays the onset of secondary flow and consequently the mixed convection (Maughan and Incropera, 1987; Osborne and Incropera, 1985b; Ozsunar et al., 2002).

Flow visualization provides an insight into the nature of the secondary flow induced by the wall heating in low Reynolds number mixed convection. The reported flow visualization studies were focused on the visualization along the channel length (Osborne and Incropera, 1985a,b; Sakamoto et al., 1999; Toriyama and Ichimiya, 2010; Wang et al., 1996) and in the cross stream direction (Koizumi and Hosokawa, 1993; Lin and Lin, 1996; Sakamoto et al., 1999). Wang et al. (1996) identified four different flow patterns for mixed convection along the heated test section of a horizontal square channel with bottom heated wall using shadowgraph technique. Grashof number ranged from 2.8×10^6 to 2.5×10^7, Reynolds ranged from 100 to 1000. They found that the flow patterns changed with the Reynolds number and Grashof number. Based on the flow patterns they argued 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. Lin and Lin (1996) experimentally investigated the unsteady mixed convection for air in a bottom heated horizontal rectangular channel in the cross stream direction using smoke tracer. The Reynolds numbers in the range from 9 to 186 and Grashof numbers up to 5×10^6 were considered. They found that increasing Grashof number and/or decreasing Reynolds number alter the flow structure from periodic into quasiperiodic and even chaotic.

Nandakumar et al. (1985) investigated the flow structure in the cross stream direction for different horizontal channel geometries heated from below for Grashof numbers up to 5×10^5. 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 the channel aspect ratio. Huang and Lin (1994) numerically investigated laminar mixed convection in a horizontal rectangular duct heated from below. Their main focus was on studying the effect of buoyancy-inertia ratio on the cross-stream flow behavior. They found that with an 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 $Gr/Re^2 > 25$.

Despite several studies, there is a scarcity of detailed investigation of the turbulent flow structure in mixed convection channel flows at low Reynolds numbers. Such studies are important as they provide a better insight into the underlying physical processes that occurs in such flows. The present study is focused on experimentally investigating the impact of bottom wall heating on the flow structure inside a horizontal square channel at low Reynolds and high Grashof numbers. A detailed qualitative as well as quantitative analysis of both mean and turbulent flow fields have been conducted to obtain better understanding of the fundamental flow processes associated with the mixed convection channel flow.

2. Experimental setup

A 7 cm × 7 cm square channel was built for the experiments. The channel consists of three sections as shown in Fig. 1(a). The inlet section has a ½ inch diameter inlet followed by a divergent section that transitions into the 7 cm × 7 cm square cross section. The length of the inlet section was 70 cm. A honeycomb was placed inside the square section to straighten the flow and damp any disturbance before entering the test section. The inlet section was made of aluminum and contains a bleed valve to remove any air trapped inside the channel and a pressure gauge to monitor the inlet fluid pressure. The inlet section was connected to the test section using two aluminum flanges. The test section was 150 cm long and has a 7 cm × 7 cm square cross section. The top and side walls were made of ½ inch non-tempered glass for visual access to the channel and the bottom wall was made of ½ inch aluminum plate. The aluminum bottom surface was colored in black with a marker to eliminate any light reflection during the experiments.

The test section was supported by two 5 cm high and 1.3 cm thick aluminum plates. Two strip heaters (1500 W – 250 V) 1.3 m in length were installed in parallel directly underneath the bottom aluminum surface 10 cm downstream of the test section entrance. The temperature of the bottom wall was controlled by a temperature controller (ZESTA-ZCP513) through a feedback loop from a thermocouple embedded in the bottom wall close to the measurement location. For a given controlled temperature, the variation of the surface temperature along the entire test section length was checked and was found to be normally within 1 °C i.e. 2–3% of the wall temperature, which is reasonable to consider wall temperature uniformity.

The end section was 30 cm in length and connected to the downstream end of the test section by two aluminum flanges. The end section contains a bleed valve to remove any trapped air in the channel and a pressure gauge to monitor the exit fluid pressure. It has a convergent end section with a 1/2 inch diameter exit.

Clean tap water was used as the working fluid. As the water was being continuously heated through the channel in a closed loop, the water temperature tended to build up with time. Four barrels, 200 L each, were coupled together in series and used as a water reservoir; This reservoir can supply water at room temperature throughout the experiment without a need to recycle i.e. water was circulated one time only during a given set of experiments. Due to a constant room temperature, the inlet water temperature maintained a constant value of around 24.5 °C. Air bubbles present in the tap water had to be removed to obtain good quality results. Therefore, water was stored in the barrels for 2 days with periodic stirring to remove air bubbles. A magnetic pump (Little Giant, 5 MD) installed downstream of the barrels was used to circulate water through the loop. A flow meter with a control valve (FL4205, Omega Engineering) was installed between the pump and the channel to control the water flow rate (see Fig. 1(a)).

Four mass flow rates 0.0210, 0.0315, 0.0420 and 0.0525 kg/s were used in the experimental runs. The Reynolds numbers correspond to these flow rates in the absence of heating are 300, 450, 600 and 750 for reference. At each flow rate, experiments were conducted at different bottom wall temperatures which were 30,