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STRATIFICATION EFFECTS ON TURBULENT OPEN CHANNEL FLOWS

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Abstract. Transport and mixing processes in stratified open channel flows has many applications on environmental engineering and industrial area. In order to investigate stratification effects on flow behavior and solute transport, detailed measurements of velocity and salinity were conducted using Laser Doppler Anemometry (LDA) and Laser Induced Fluorescence (LIF) techniques, respectively. The experiments were carried out in a narrow rectangular open channel with different stratification levels and the main flow characteristics, such as the corner flow and velocity dip, were affected by stratification. The same conditions used in the experiments were also simulated using Computational Fluid Dynamics (CFD) and the main flow characteristics were reproduced accordingly, showing the potential of this tool to evaluate stratified flow conditions. Once calibrated, a CFD model is useful for understanding the effects of stratification on the turbulent flow behavior and it can contribute to diminish environmental pollution and improve the performance of industrial processes in which stratification is present.

Keywords: stratified flow, secondary current, mixing processes, turbulence, open channel

1. INTRODUCTION

The expansion of cities and the implementation of new industries to satisfy the demands of population have lead to an increasing concern about the use of water and the final destination of effluents. Therefore, new policies concerning the management of water bodies, such as rivers, estuaries and coastal waters, have been introduced so that a more effective use of these resources can be made.

An important contribution to the management of water bodies is the understanding of transport and mixing mechanisms in turbulent flows but the flow is quite complex and in many cases of practical importance, the situation can become even more complex due to stratification, which is typically induced by river discharge or, in some cases, by cooling water discharge from a thermal power plant.

Stratification effects on mixing processes have been reported in some works available in the literature (Salehipour and Peltier, 2015; Horner-Devine, Hetland and MacDonald, 2015; Bartello e Tobias, 2013). Stratification reduces the vertical mixing of solutes and ecologically important variables such as phyto-plankton, heat and nutrients and also increases the vertical shear. Consequently, the longitudinal dispersion coefficient may be considerably enhanced.

Even for a non-stratified flows, secondary flows, induced by anisotropy of turbulence, have been found to exist in rectangular open channels [Cokljat and Younis, 1995; Ishigaki et al., 2001] but in stratified flows, the effect of secondary flow on the mixing process is not well known.

The present study simultaneously measured velocity and concentration using the laser Doppler anemometer (LDA) and laser induced fluorescence (LIF) techniques, in order to clarify the transport and mixing mechanisms in stratified flows. This data can also be used as benchmark to calibrate three-dimensional numerical models for the improvement of

their prediction capability. A preliminary CFD study was also performed to evaluate the capability of the model to predict stratified flow conditions.

2. STRATIFIED FLOW EQUATIONS

For stratified flow conditions, the flow equations are:

Continuity equation:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho_r} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j} - \overline{u_i u_j}\right) + g_i \frac{\rho - \rho_r}{\rho_r} \tag{2}$$

Solute transport equation:

$$\frac{\partial C}{\partial t} + U_i \frac{\partial C}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial C}{\partial x_i} - \overline{u_i c}\right) + S_C \tag{3}$$

where U_i, P, C and ρ are time averaged velocity, pressure, concentration and density, ρ_r is the reference density and u_i and c are the fluctuating velocity and solute concentration, respectively. Since no assumption has been made about the terms in these equations, they are exact and describe precisely the flow behaviour. However, due to the Reynolds decomposition process, unknown correlations between the fluctuating velocities ($\overline{u_i u_j}$) and between velocity and concentration fluctuations ($\overline{u_i c}$) have been introduced and the number of unknowns is now bigger than the number of equations. As reported by Rodi (1993), when multiplied by density, these correlations represent the transport of momentum and mass due to the fluctuating (i.e. turbulent) motion. $-\rho \overline{u_i u_j}$ is the transport of x_i - momentum in the direction x_j (or vice versa); it acts as a stress on the fluid and is therefore called turbulent or Reynolds stress. $-\rho \overline{u_i c}$ is the transport of mass due to turbulence in the direction x_i and is therefore a turbulent mass flux.

3. EXPERIMENTAL AND COMPUTATIONAL PROCEDURES

This work presents both experimental and computational results. In order to better describe the procedures that were used, the section is divided in two parts, experimental setup and computational method.

3.1 Experimental setup

A schematic representation of the hydraulic circuit used to carry the stratified flow experiments is shown in Fig. 1. Water was supplied from a 100m³ reservoir (1) and pumped through a system of pipes to the ducts located at the inlet of the channel (2). A set of valves and flow meters were used to control the flow rate. To obtain different stratification levels, highly concentrated salty water (100ppt) was prepared in a 1m³ container (5) and pumped from a constant head reservoir into a pipe connected to the lower duct. A conductivity meter, placed in the lower duct at 1m from the inlet of the open channel, was used to monitor the salt concentration. A valve was also used to control the salt concentration so that the required stratification level could be achieved. A fluorescent dye (Rhodamine 6G), injected into the same tube, was used as a surrogate for salinity measurements in order to use the laser induced fluorescence technique. The dye was injected by gravity and a flow meter was used to monitor the amount of dye released. A third container (7) supplied seeding particles (Iriodin 111 Rutile Fine Satin) to the water. The purpose of the seeding particles was to improve the quality of the laser measurements. The particles were released either into the upper or lower duct, depending on the place where the readings were taken. After passing through the open channel (3), the water flows into a small reservoir where it was either discharged (if salt has been added to the water) or recycled to the system (if no salt has been added to the water). This recycling system was important, as the flume was let to run for about one hour, to assure uniform flow condition before commencing the experiments.
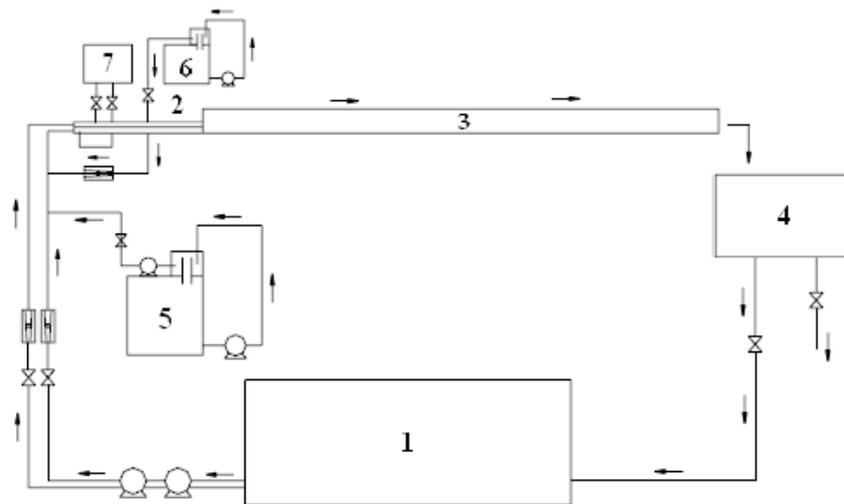
Figure 1. Schematic representation of the hydraulic circuit. 1) Water reservoir; 2) Channel inlet; 3) Main channel; 4) Recycling system; 5) Saline water tank; 6) Fluorescent dye tank; 7) Seeding particles tank.

To investigate the fundamental interaction between turbulence and stratification, measurements of velocity and concentration were taken in a narrow rectangular open channel with a bed slope of 1:2000 and a width to depth aspect ratio of one (B/H = 1). The channel consisted of a 12.0 m long flume, in which the first 2.5 m were adapted to create a two layer stratified flow. The flow rate in each layer was 1.25×10^{-3} m^3/s. The upper duct carried fresh water and the lower duct carried salty water in which the concentration depended on the stratification level considered. After 2.5 m the flow enters the open channel and the fluids from the two ducts start to mix. An outlet weir controlled the depth of the flow to obtain uniform flow condition with 0.1m depth. The channel was 0.1m wide 9.5m long. With the objective to analyze the flow development, measurements were taken at three different cross-sections: x/Dh = 12, x/Dh = 24 and x/Dh = 48. However, the majority of the analyses carried out at the last section, where the flow was more developed. Details of the hydraulic circuit can be found in Siqueira (2002) and a schematic view of the channel is given in Fig. 2.
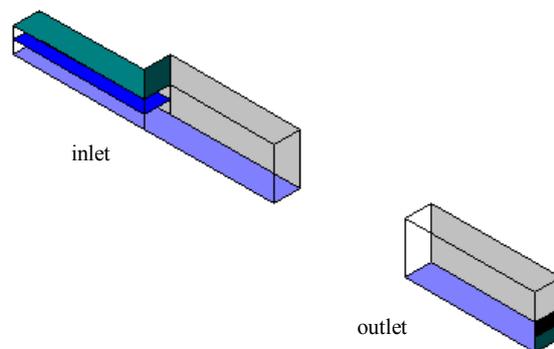

Figure 2. Schematic view of the rectangular channel.

3.2 Computational method

The same system described above was modeled using the CFD code Ansys CFX® 16.0. Following the work of Al-Qaessi and Abu-Farah (2009), the homogeneous multiphase model was used to calculate the velocity and pressure fields. More details of the model can be fount at Al-Qaessi (2007).

The contour conditions used are non-slip walls, prescribed velocity at the inlet, zero mean relative pressure at the outlet and prescribed tension at the free surface, as shown in Fig. 3. The shear distribution used for the simulation was measured during the experiments (Siqueira, 2002).
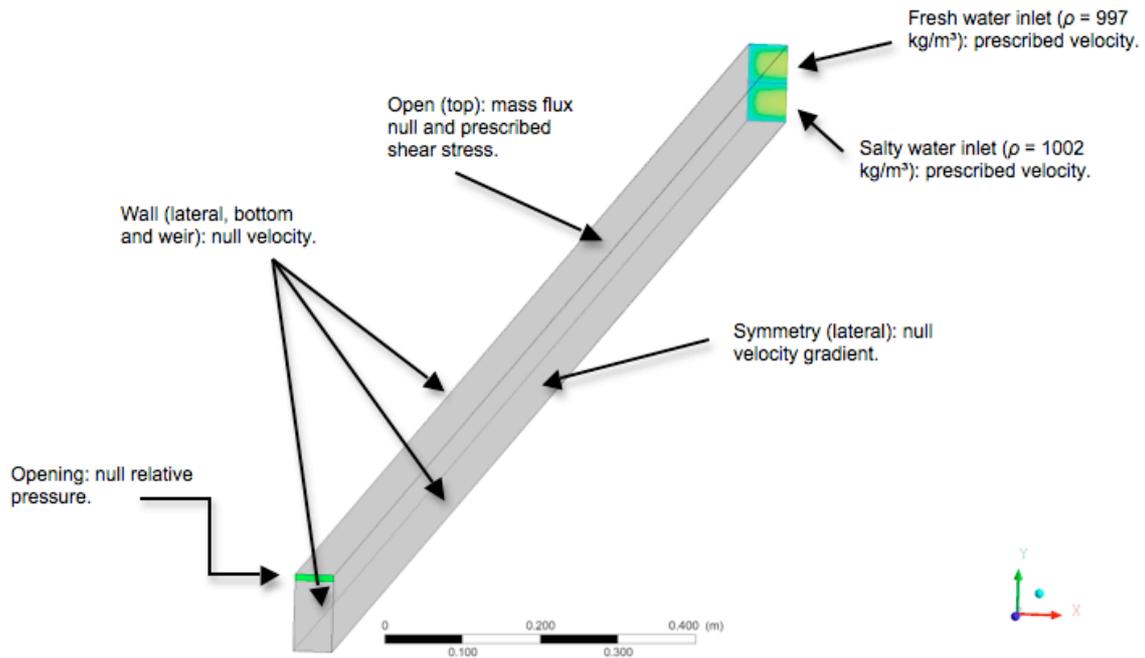
Figure 3. Geometry and contour conditions.

The weir height was set to 0,095 m in order to keep the uniform flow condition with flow depth of 0,100 m. For the stratified flow case, the specific mass of the fluid was 1002 kg/m³ to represent a density difference of 5 kg/m³ (DDi = 5 kg/m³), since the fresh water specific mass was 997 kg/m³.

The Reynolds Tensor SSG turbulence model was used in order to capture the turbulence anisotropy effects (Ansys, 2014; Davidson, 2004) and the convergence criterion for the residuals was RMS values smaller than 10^{-6} for mass, momentum and closure equations.

4. RESULTS

Figure 4 shows the longitudinal velocity field for the non-stratified (DDi = 0) and stratified flow conditions (DDi = 5 kg/m³). DDi is the Density Difference at the inlet of the open channel. According to this figure, the velocity dip is mitigated with stratification and the position of the maximum velocity tends to be closer to the water surface. Although not shown in this figure, the results also demonstrated that the flow development is retarded by the increase in the stratification level due to a weak vertical mixing caused by the action of buoyancy forces.
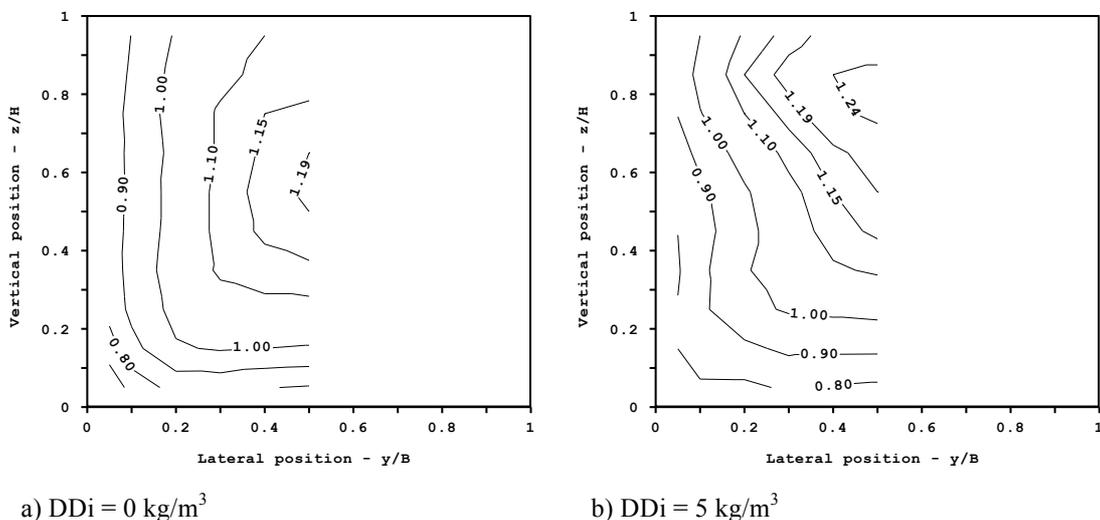
a) DDi = 0 kg/m³   b) DDi = 5 kg/m³

Figure 4. Longitudinal velocities at x/Dh = 48.

Concerning to the secondary currents, the following features can be observed in Figure 5: for the non-stratified flow (Figure 5a), a pair of vortices is formed in the lower corner. The upper vortex extends from the bottom to the water surface, and the secondary flow carries low momentum fluid from the wall towards the center of the channel near the water surface. At the center of the channel, the direction of the flow changes again and carries high momentum fluid from the water surface region downwards, causing the so-called velocity dip. When DDi increases to 5kg/m³, as shown in Figure 5b, a pair of vortices is observed in each corner of the channel and the wall bisectors limit their size. This pattern shows a strong influence of the inlet configuration and confirms that the higher DDi the less developed the flow.
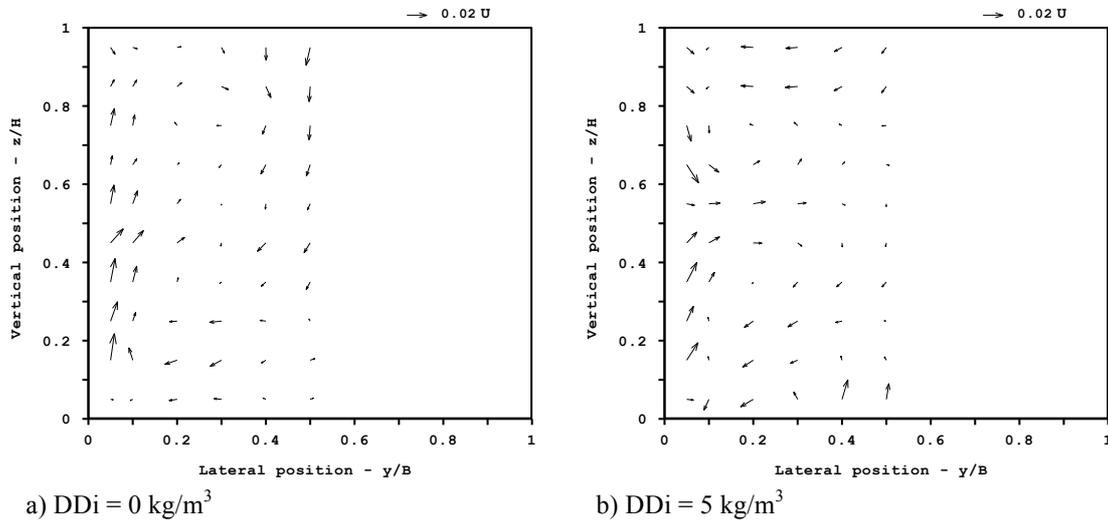
a) DDi = 0 kg/m³   b) DDi = 5 kg/m³

Figure 5. Secondary flow profiles at x/Dh = 48.

Figure 6 shows the density distributions and secondary currents for DDi = 5kg/m³. It is very clear from this figure that the secondary flow affects the density distribution. Near the wall the secondary flow carries momentum from the lower part to the upper part of the channel and denser fluid is mixed with the les dense fluid on the top layers increasing the density of the water in this region. The tilting of the density difference contour lines is a direct effect of secondary flow motion.
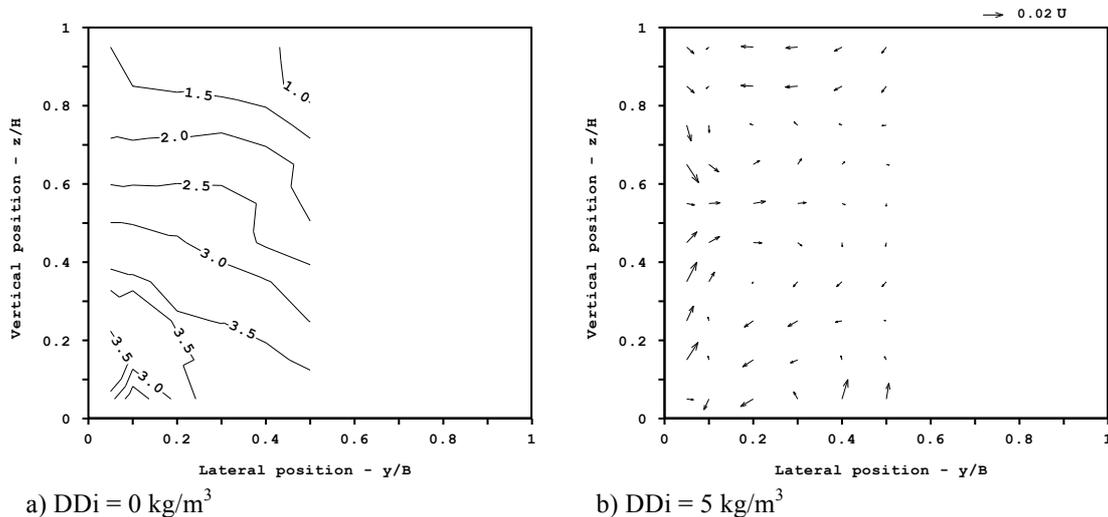
a) DDi = 0 kg/m³   b) DDi = 5 kg/m³

Figure 6. Effects of secondary flow on density profile at x/Dh = 48.

The longitudinal velocity contours and the secondary flow profiles obtained for the non-stratified and stratified flow condition are shown in Figure 7. It can be seen that the velocity distribution bulges towards the bottom corner. The bulging in the velocity distribution caused by the corner flow is similar to the obtained experimentally being more pronounced for the non-stratified flow case (Figure 7a) when compared to the stratified flow case (Figure 7b), indicating once again that stratification retards the flow development. The longitudinal velocity distribution corresponds well to the secondary flow profile, which shows that high momentum fluid is carried by the secondary currents from the water surface region to the center of the channel and from the center towards the corner. From the above flow characteristics, the velocity dip is the most remarkable one and occurs specially in narrow channel flow.
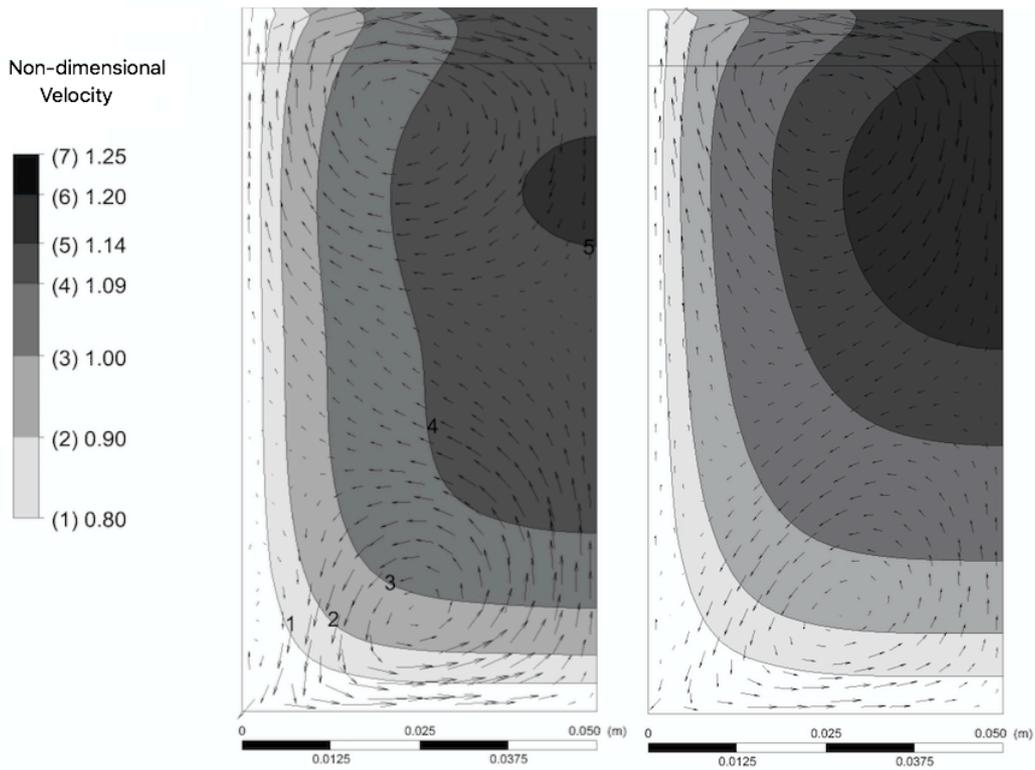
Figure 7. Effects of secondary flow on velocity profiles for (a) non-stratified and (b) stratified flow cases at x/Dh = 48.

At the inlet of the open channel, the flow is divided into two layers. The top layer carries fresh water ($\rho = 997$ kg/m^3) while the lower layer carries saline water ($\rho = 1002$ kg/m^3). The saline concentration varies from DDi = 0 to 5 kg/m^3 to create a two-layer stratified flow at the inlet of the open-channel. As the flow goes downstream, the fluids in these layers start to mix and change the density distribution.
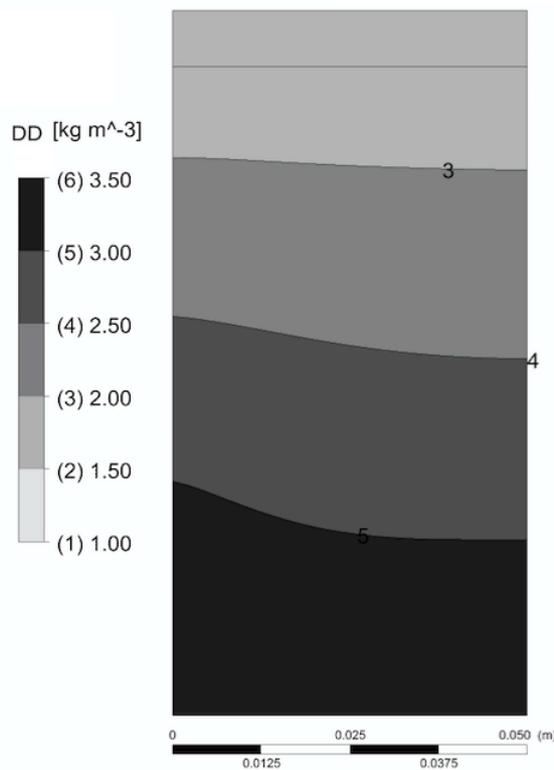

Figure 8. Effects of secondary flow on density profile at x/Dh = 48.

The density distribution is shown in Figure 8 and it is possible to observe that it is also influenced by the secondary flow pattern. At this stage of the flow development, the stratification is not only vertical but also lateral and it can affect the vorticity budget. From Figure 8 it is possible to see that the mixing process occurs mainly near the wall where the vortex generated move denser fluids towards the surface, causing the tilting in the density contours.

5. CONCLUSIONS

The most distinct flow characteristics of a narrow open channel are the bulging of the longitudinal velocity distribution towards the corner and the maximum velocity located below the water surface (i.e., the corner flow and velocity dip, respectively). These characteristics have been already reported in the literature and were also confirmed in this work. Stratification retards flow development and the corner flow is not so intense in this situation, diminishing the bulgings of the velocity contours towards the corner, usually observed for non-stratified flow cases. The velocity dip is also affected by stratification. These results were also observed in the simulations but the computational results are preliminary and needs validation. Once validated the CFD model can be used to predict other stratified flow conditions of environmental and industrial interest.

6. ACKNOWLEDGEMENTS

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