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Experimental Study of Turbulence Characteristics of Three-Dimensional Turbidity Currents

EXPERIMENTAL STUDY OF TURBULENCE CHARACTERISTICS OF THREE-DIMENSIONAL TURBIDITY CURRENTS

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ABSTRACT

The present study investigates the turbulence characteristic of turbidity current experimentally. The three-dimensional Acoustic-Doppler Velocimeter (ADV) was used to measure the instantaneous velocity and characteristics of the turbulent flow. The courses of experiment were conducted in a three-dimensional channel for different discharge flows, concentrations, and bed slopes. Results are expressed at various distances from the inlet, for all flow rates, slopes and concentrations as the distribution of turbulence energy, Reynolds stress and the turbulent intensity. It was concluded that the maximum turbulence intensity happens in both the interface and near the wall. Also it was observed that turbulence intensity reaches its minimum where maximum velocity occurs.

Keywords: turbidity currents, turbulence, laboratory experiment

1. INTRODUCTION

Spectacular turbidity currents are usually seen in natural such as in the oceans, lakes, atmosphere and etc. Turbidity currents are continuous currents which move down slope due to different density. In the turbidity currents, the density difference can arise from suspended solids such as kaolin or clay. These affect the gravity which is an actual driving force of such flows.

Many investigations were performed on velocity structure of turbidity currents such as Ellison & Turner (1959), Simpson (1972) and Garcia (1994). Kneller et al. 1999 performed the study of structure and turbulence in two-dimensional of density currents experimentally and developed a relation for velocity profile. Kneller concluded that the maximum amount of turbulent occurs near the upper edge of the flow and length scale of eddies is about the flow thickness. Best et al. (2001) investigated turbulence structure of semi-steady density currents in a horizontal channel. Buckee et al. (2001) studied vertical distribution of turbulence in density currents. Best et al. (2001) studied the turbulent structure of semi - steady density currents in a channel. Yu and Lee (2000) performed experimental studies of the behavior and turbulence intensity of the density currents. Although many studies have been performed in the turbidity currents, the turbulent structures of the turbidity currents are not clear. In order to understand the turbulence characteristics of turbidity currents, it is necessary to investigate turbulence structure of these currents experimentally.

In this study, turbulence structure of turbidity current is investigated in the three-dimensional channel in the different discharge flows, concentrations, and bed slopes at Sharif University lab. The instantaneous velocities and turbulence characteristics were measured by an Acoustic Doppler Velocimeter (ADV). Results will be expressed at various distances from the inlet, for all flow rates, slopes and concentrations as the distribution of turbulence energy, Reynolds stress and the turbulent intensity.

2. EXPERIMENTAL SETUP

A laboratory apparatus was built to study three-dimensional flows resulting from the release of turbid water on a sloping surface in a channel of fresh water 12 m long, 1.5 m wide and 0.6 m high. One side of this channel was constructed of glass for observation. As seen in Figure 1, the channel was divided into two parts in the longitudinal direction by a separating Plexiglas sheet. The shorter upstream section was an accumulator for dense water with an outlet in the middle bottom of separating Plexiglas sheet with a rectangular cross section and was controlled by a gate. In all experiments, the opening of the gate was set to 1 cm high. The ratio of the inlet gate opening ($h_{in} = 1cm$) to the above water depth at the inlet was about 0.02 $(1cm / 50cm)$ or less during the experiments in order to avoid the large recirculation due to depth limitation.

The remaining part of the channel was previously filled with fresh water and its temperature kept as the laboratory temperature. As the test began, the dense water continuously left the reservoir through the outlet and moved along the channel bed. The slope of the channel could be adjusted in the range of 0% to 3.5%. The salt-solution gradually spread under the fresh water. To avoid the return flow, a 25cm step was constructed at the end of the channel. Sixty-four valves with a flow rate about 0.2 lit/min were installed at the bottom of the step. The number of the opening valves was dictated by the inlet flow to set the discharge rate a little more than the inflow rate to let the entrained water out of the channel. To prevent loosing fresh water, we resupplied the fresh water at the end of the channel so that the total height of fresh water was kept constant during the experiments. The channel overflow prevents over resupplying the fresh water.

A reservoir tank with a maximum capacity of 2 m^3 was used to prepare the mixture of the dense water. This tank was made of stainless steel and installed at an elevation of 2.5 m from the ground. A supplying pipe fed the dense water from the reservoir into the accumulator and a gate valve controlled the feed rate. The feed rate was measured by an ultrasonic flow meter and fixed at a desired rate. Thus, the current was in a quasi-steady condition.

After mixing kaolin with fresh water in the reservoir tank, and before feeding into the accumulator, it was transferred to a weir by another circulation pump. The purpose of using this weir was to keep the dense water head constant and to prevent the impacts of fluctuations in mixing reservoirs on the feed rate. The velocity profiles were measured by the 10 MHz ADV (Acoustic Doppler Velocimeter) made by Nortek Company.

In the present work, the distance between the two sensors of ADV which were placed on a rail conveyor on the channel was 1m. By changing the vertical location of sensors, the velocity profile of any specific section was determined. The data acquisition took 35–40 sec. for each probe's position. The measurement started form the top part of the dense layer and continued into the lower part by dipping probes into the dense layer until all the desired positions were selected. The total duration of each experiment was about 80 minutes.

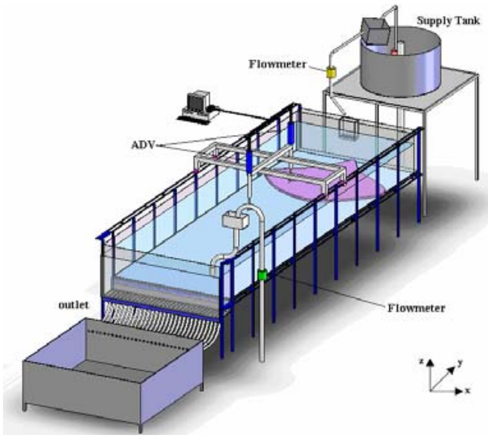

Figure 1. Schematic of the experiment setup

3. EXPERIMENTAL RESULTS

Table 1 includes the test dada. Each part of the test was performed twice in order to reduce the experiment errors. In all experiments the inlet height and width has been $z_0 = 1cm$ $b_0 = 10cm$, respectively. Buoyancy flux at the entrance of the channel, Richardson number and density can be derived using following equations.

$$B_0 = \frac{g}{b_0}\frac{\rho - \rho_w}{\rho_w} * Q_0 \tag{1}$$

$$Ri_0 = \frac{B_0 \times \cos\theta}{U_0^3} \tag{2}$$

In the above expressions, ρ_w , ρ_s , ρ , g , and Q_0, represent ambient water density, dry kaolin density, mixture density, gravity acceleration, and inlet discharge, respectively. These data is available in Table 1. Each part of the test is presented by a symbol for example S2Q10C2.5 which states slope of 2%, flow rate of $10\, {}^{lit}/_{\min}$, and concentration of $2.5\,\frac{gr}{lit}$. For all experiments Richardson number is smaller than one so the current is supercritical at the beginning of the channel. A Steady, continuous turbidity current is developing in the bed that has a constant, small slope. The x-coordinate is directed down slope tangential to the bed, and the z-coordinate is directed upward normal to the bed. The reduced gravitational acceleration is define by $g' = g(\rho - \rho_w)/\rho_w$. Layer-averaged current velocity U_d and the layer-averaged thickness h_d defined by Ellison and Turner (1959) are as follows

$$U_d h_d = \int_0^\infty U dz \tag{3}$$

$$U_d^2 h_d = \int_0^\infty U^2 dz \tag{4}$$

Table1. Inlet conditions for turbidity current experiments

Run	$\overline{U}_0$ (cm/s)	C_0 (gr/lit)	$S\%$	B_0 (cm^3/s^3)	Ri_0	Re_0	T_{in} (^0C)	T_{Fluid} (^0C)
S2Q10C2.5	16.7	2.5	2	41	0.008	1667	21	21
S2Q10C5.0	16.7	5	2	82	0.018	1667	21.5	21.5
S2Q10C7.5	16.7	7.5	2	123	0.027	1667	21	21
S2Q15C2.5	25.0	2.5	2	61	0.004	2500	21	21
S2Q15C5.0	25.0	5.0	2	123	0.008	2500	21	21
S2Q15C7.5	25.0	7.5	2	184	0.012	2500	21	21
S2Q20C2.5	33.3	2.5	2	82	0.002	3333	21	21
S2Q20C5.0	33.3	5.0	2	184	0.004	3333	21	21
S2Q20C7.5	33.3	7.5	2	245	0.007	3333	20.5	20.5
S3Q10C2.5	16.7	2.5	3	41	0.008	1667	21	21
S3Q10C5.0	16.7	5.0	3	82	0.018	1667	21	21
S3Q10C7.5	16.7	7.5	3	123	0.027	1667	21	21
S3Q15C2.5	25.0	2.5	3	61	0.004	2500	21	21
S3Q15C5.0	25.0	5.0	3	123	0.008	2500	21	21
S3Q15C7.5	25.0	7.5	3	184	0.012	2500	21	21
S3Q20C2.5	33.3	2.5	3	82	0.002	3333	21	21
S3Q20C5.0	33.3	5.0	3	184	0.004	3333	21	21
S3Q20C7.5	33.3	7.5	3	245	0.007	3333	21	21

4. RESULTS

Let we define the parameter of turbulence in this research. The instantaneous value for example for the horizontal component of velocity be $U = \overline{U} + u$ where $\overline{U}, u$ is turbulent mean value and a turbulent fluctuation, respectively, Similarly for vertical and lateral component of velocity and particle concentration. The root mean square value of a turbulent fluctuation for example for longitudinal direction be given by u' and the turbulence flux covariance terms instance for vertical transport of horizontal momentum be given by $\overline{uw}$.

Profiles of velocity, concentration, turbulent kinetic energy and Reynolds stress for different concentrations and different discharges are shown in Figure 2, 3, and 4, respectively. In all experiments concentration profile smoothly increases moving toward the bottom and reaches the maximum value near the bed. These concentration profiles are seen when concentration is low or in saline density currents (B. Kneller & C. Buckee 2001). At constant inlet concentration, when discharge rate increases concentration of dense layer increases. It shows that in higher discharges lower amount of kaolin deposits. As profile of turbulent kinetic energy shows this result is understandable because when turbulent kinetic energy increases it means that the dense layer is more turbulent and more of kaolin particles are suspended in the flow. Increase in concentration has the opposite effect on the turbulent kinetic energy. All profiles of turbulent kinetic energy show minima around the maximum velocity which almost is compatible with the level of minimum shear stress. Maximum turbulent kinetic energy occurs both near the bed and between the $z_{U_{\max}}$ and the $z_{1/2}$ which is about $z/h = 0.6$ .Reynolds stress is positive in heights below the $z_{U_{\max}}$ and it reaches to the zero over this location and it has negative amounts in the upper layer of the dense layer. Negative amounts of Reynolds stress is a sign of mixing of fresh water into the current.

Figure 5 shows the velocity distribution for turbidity current near the wall. The log-law is compatible with experimental values for this current. In these currents, we need to know the von Karman constant κ and the integral constant A . The most reliable data shows that $\kappa = 1/2.42$ and $A = 1.52$.

$$U^+ = \ln(z^+)/\kappa + A \tag{5}$$

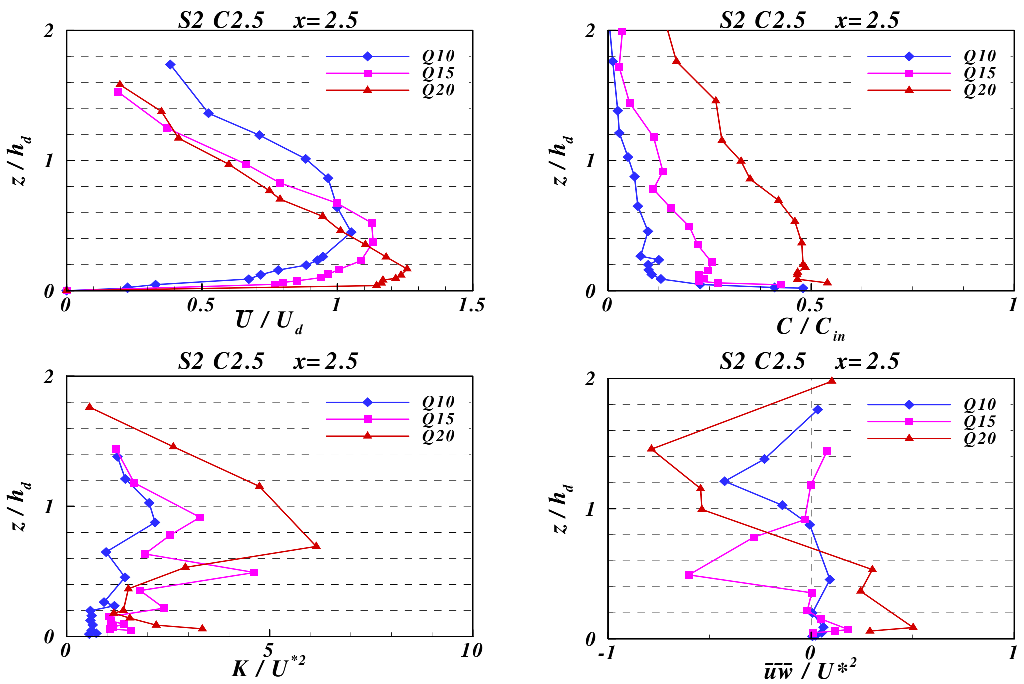

Figure 2. Velocity, Concentration, turbulent kinetic energy and Reynolds stress profiles in Slope=2% and Concentration =2.5g/lit

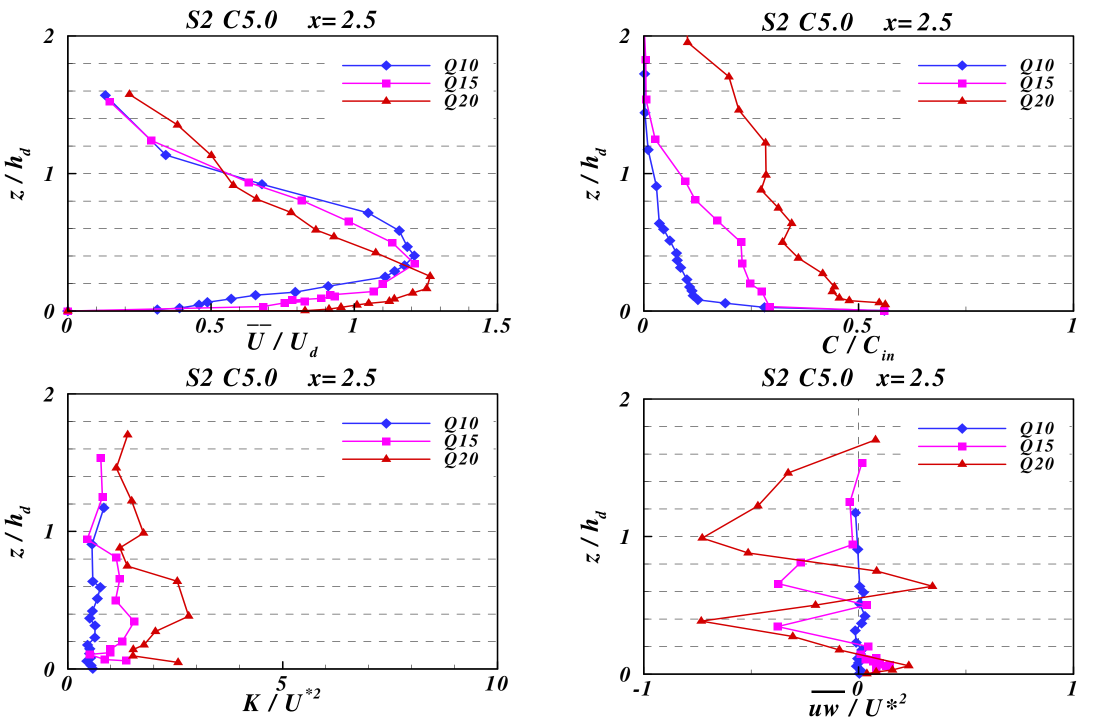

Figure 3. Velocity, Concentration, turbulent kinetic energy and Reynolds stress profiles in Slope=2% and Concentration =5.0 g/lit

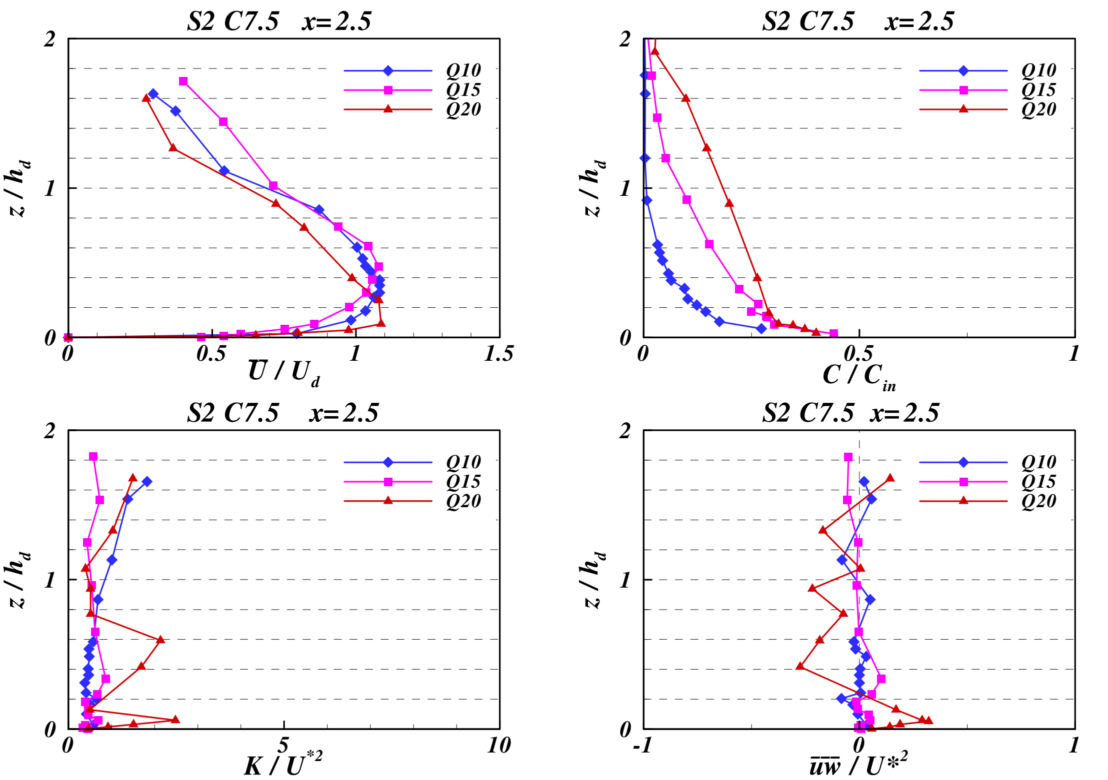

Figure 4. Velocity, concentration, turbulent kinetic energy and Reynolds stress profiles in Slope=2% and Concentration =7.5g/lit

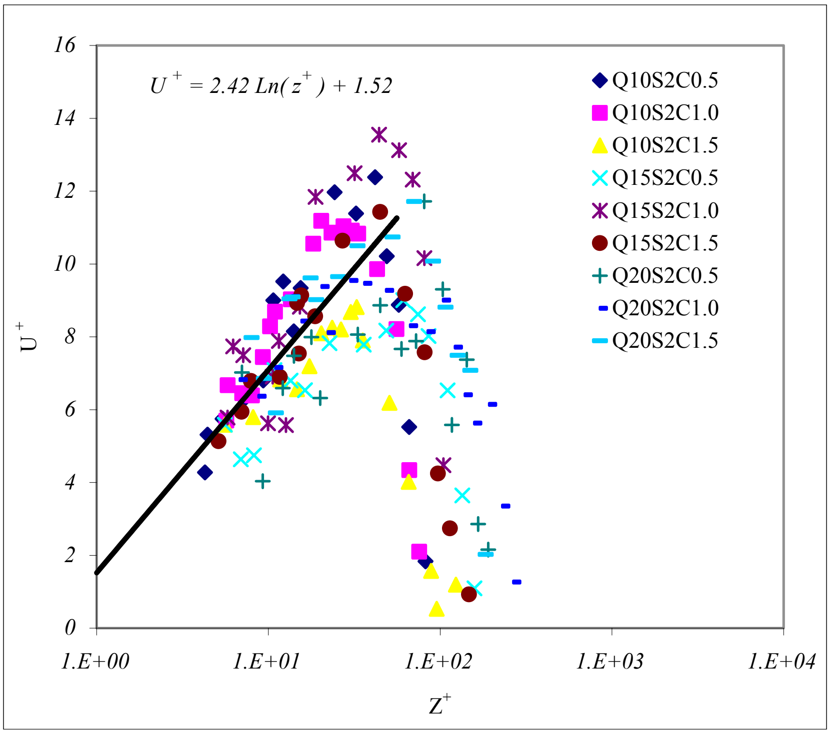

Figure 5. Log-law plots of mean velocity for turbidity current

Figure 6 shows a comparison between the data for $u'/U^*, v'/U^*, w'/U^*$ plotted against z^+ in the near wall region. High $u'/U^*, v'/U^*, w'/U^*$ occurred close to the bed in all experiment. Fluctuations of the longitudinal velocity in x=0.5, 1.5 m is about 30%-50% of the mean velocity. In x=2.5 to 5.5 m the portion of u', v' and w' in turbulent kinetic energy is 44%,39% and 17%. Moving away from the inlet section, fluctuations are reduced because of the viscosity and spreading in y direction. Consequently u' in x=2.5, 3.5 m, is about 20%-30% and in x=4.5, 5.5 m is about 10%-20% of the mean velocity. In all stations (except $x = 0.5, 1.5\text{m}$) $u' \approx v' \neq w'$. In stations $x = 0.5, 1.5\text{m}$ $\frac{v'}{u'} \approx 0.7$, $\frac{w'}{u'} \approx 0.5$ and in other stations $x > 1.5\text{m}$, $\frac{v}{u} \approx 0.9$, $\frac{w}{u} \approx 0.4$. At inlet section turbulence intensity has the highest level and in all directions turbulence is not isotropic because of the inlet effects and hydraulic jump. In $x > 3.5\text{m}$ results show that $u' \approx v' \cong 1.5U^*$ and $w' \cong 0.4U^*$. When discharge increases, turbulence length scale reduces. As a result turbulence intensity increases. Figure 7 and 8 show that when discharge increases or concentration increases, longitude turbulent intensity increases. At inlet section longitude turbulence intensity has the highest level and in all directions turbulence is anisotropic because of the inlet effects and hydraulic jump. Figure 9 shows the effect of change in bed slope on turbulence intensity. There is no visible difference in normalized turbulence intensity as bed slope changes.

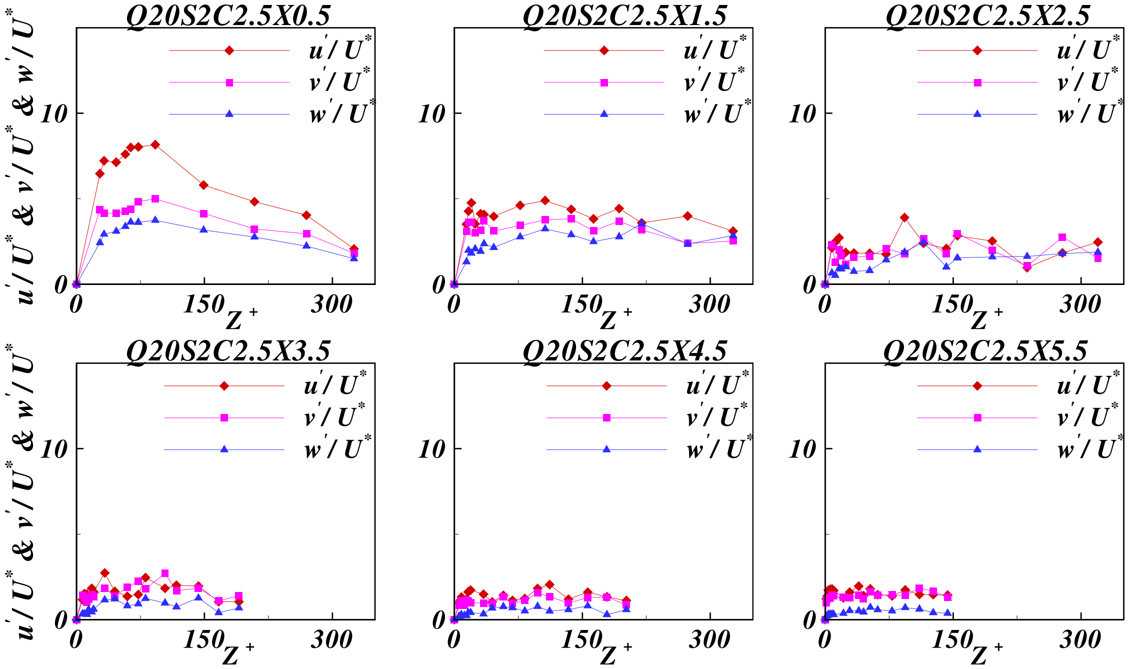

Figure 6. Effect of distance from inlet section on turbulence intensity

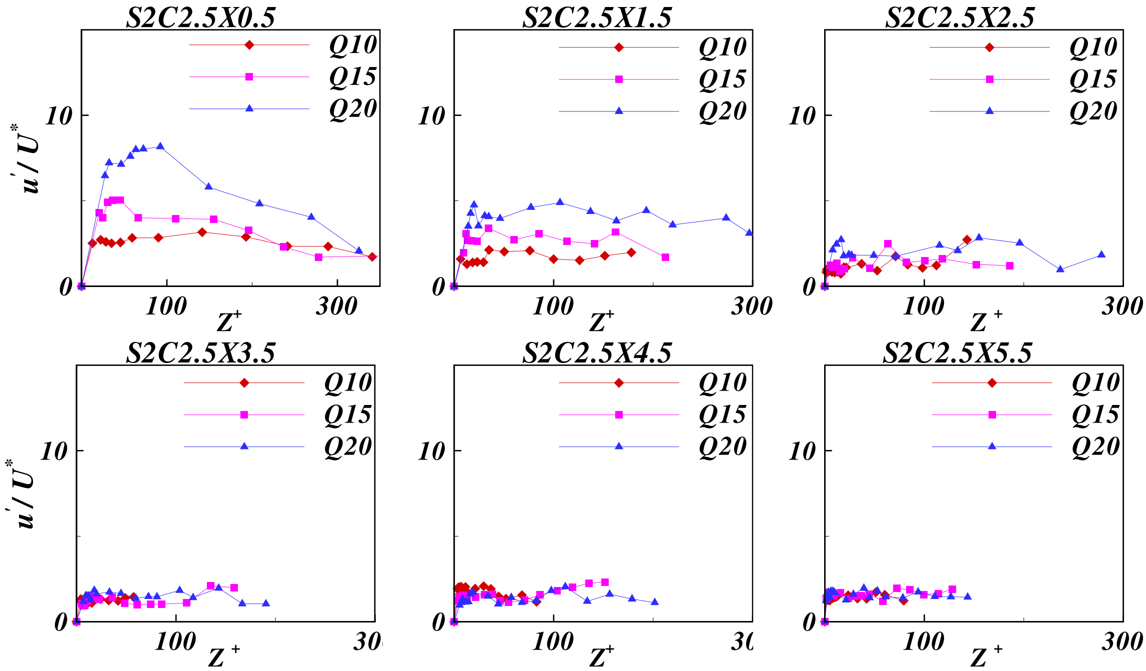

Figure 7. Effect of discharge on turbulence intensity

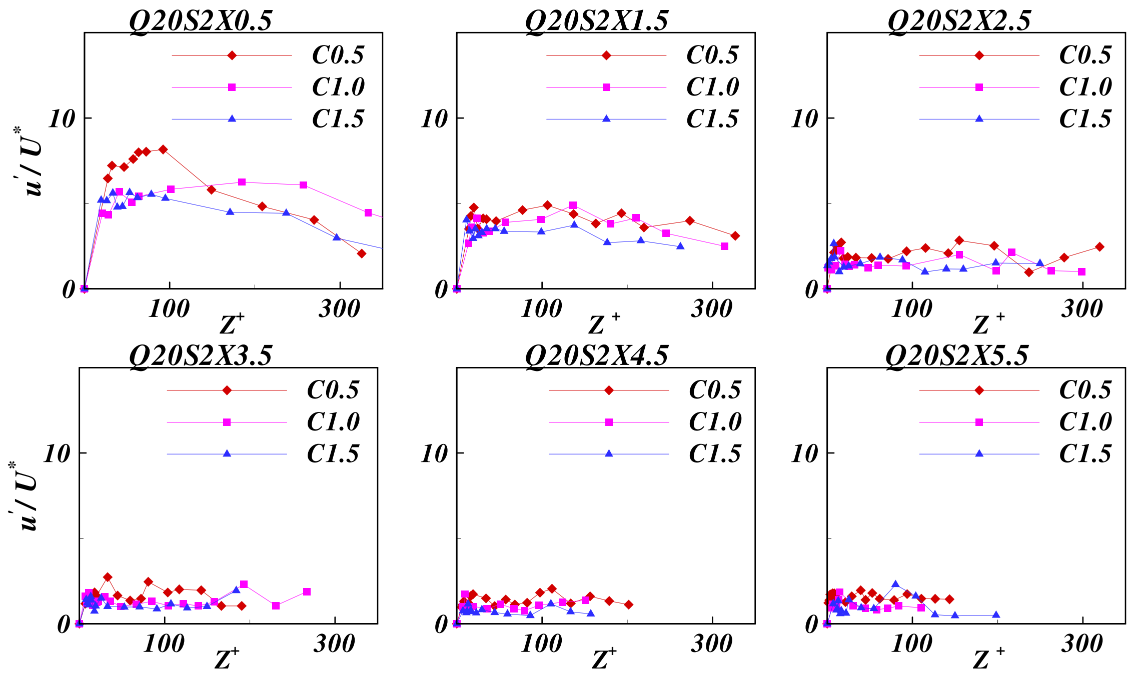

Figure 8. Effect of concentration on turbulence intensity

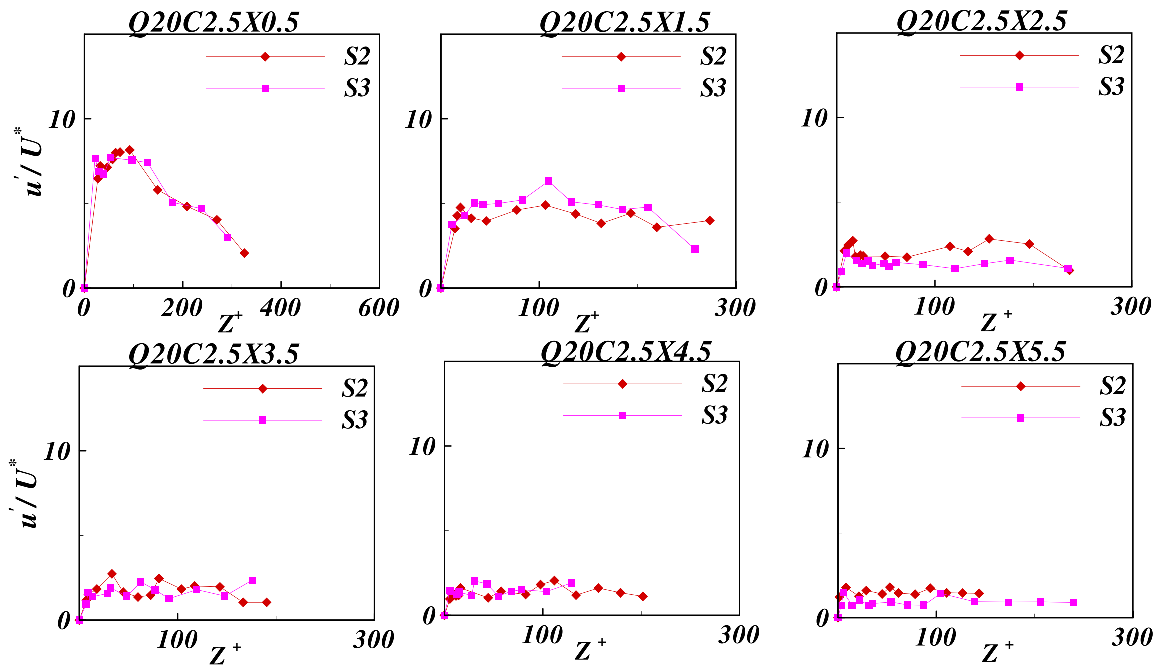

Figure 9. Effect of slope on turbulence intensity

The vertical distribution of gradient Richardson shows the stable and unstable regions of the stratified flows. This profile is shown in figure 10 for supercritical and subcritical flow along the x direction. The mean of Ri_g over the maximum velocity in x=0.5m (supercritical region) is about 0.11-0.32 in subcritical region (x>0.5m) $Ri_g = \frac{-g\left(d\rho/dz\right)}{\rho_0\left(dU/dz\right)^2}$ is larger than 1.

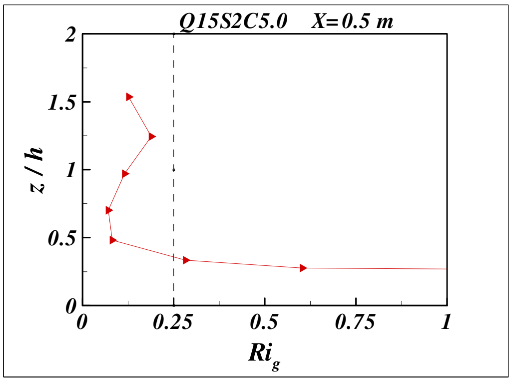

Figure 10. Vertical distribution of gradient Richardson

5. CONCLUSIONS

The three-dimensional Acoustic-Doppler Velocimeter (ADV) was used to measure the instantaneous velocity and characteristics of the turbulent flow. The courses of experiment were conducted in a three-dimensional channel for different discharge flows, concentrations, and bed slopes. Results are expressed for all flow rates, slopes and concentrations as the distribution of turbulence energy, Reynolds stress and the turbulent intensity. All profiles of turbulent kinetic energy show minima around the maximum velocity which almost is compatible with the level of minimum shear stress. Maximum turbulent kinetic energy occurs both near the bed and between the $z_{U_{max}}$ and the $z_{1/2}$ which is about $z/h = 0.6$. Also increased discharge will result in increased turbulence kinetic energy. It should be mentioned that increased concentration will result in decreased turbulent kinetic energy which may be because of the increase in damping due to viscous force. Reynolds stress is positive in heights below the $z_{U_{max}}$ and it reaches to the zero over this location and it has negative amounts in the upper layer of the dense layer. The second constant of log-law is not compatible with experimental values for this current. All three component of turbulence intensity are decreased gradually as z^+ increases. In $x > 3.5$m results show that $u' \approx v' \cong 1.5U^*$ and $w' \cong 0.4U^*$. There is no visible difference in normalized turbulence intensity as bed slope changes. The amounts of Ri_g is about 0.11-0.32 in the supercritical region (x=0.5m) and it reveals that the outer region of the current is unstable.

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