Investigation of slurry flows in rectangular pressurized pipe flow by means of ultrasonic velocimetry

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Ultrasonic velocimetry was used to study flow and turbulence characteristics in both clear water and slurry flows with different sediment transport regimes. The velocity and turbulence profiles were investigated in the vertical plane at the centreline of a rectangular channel. Reference measurements in clear water delivered the vertical distribution of velocity components and turbulence characteristics in rectangular cross section. Strong symmetrical secondary currents were observed and evaluated. Those flow structures affect the velocity and the Reynolds stress vertical distribution as presented. Experiments with solid particles provided the information about the influence of solids concentration on flow and turbulence properties at different transport regimes. An attenuation of the velocity fluctuation with increasing solids concentration was observed. A critical aspect of experiments seems to be an attenuation of ultrasonic signal by solid particles especially at higher concentration rates.

Keywords: Pressurized flow; Reynolds stress; slurry flow; ultrasonic velocimetry; velocity distribution

1 INTRODUCTION

Intense sediment transport at high bed shear is a phenomenon associated with flows in open mobile-bed channels and pressurized industrial slurry pipes. For instance, flood flows in steep mountain streams can carry sediments at high concentration over the upper plane bed. Lately, increasing research attention has been focused to high concentrated flows in natural channels [1-3] and laboratory conduits. The well-controlled laboratory flows have been subject to both mathematical [4-5] and physical modelling in either steep flumes [5-6] or pipe loops [7-8].

Investigation of slurry flows by means of velocity and turbulence measurements is mostly associated with acoustic methods while the applicability of the optical methods such as Laser Doppler anemometry or Particle Image Velocimetry is difficult or impossible [9]. Most of experiments with suspensions in pipe loops based on ultrasonic velocimetry were conducted with non-Newtonian systems [10-11].

The paper deals with a Newtonian system in turbulent flow regime with the uniform particle size phase of glass spheres and a wide range of solids concentrations.

2 METHODS

2.1 Experimental loop

Experiments were carried out on a closed pipeline circuit (Fig. 1) placed in the Water Engineering Laboratory of the Czech Technical University in Prague. Differential pressures were measured on sections 1, 2 and 3. Differential pressures in the upward pipe (section 1) and in the downward pipe (section 2) were measured in order to determine the density of flowing mixture (and thereafter concentration of the solid phase in the mixture). The differential pressures measured in Section 3 were used for determination of the hydraulic gradient in the horizontal plexiglass pipe of a rectangular cross section (of length 6 m, inner width 50.8 mm, inner height 51.6 mm). The flowrate was measured using an electromagnetic flow meter Krohne Optiflux 5000 installed at the vertical pipe. The flow of the mixture was obtained by a centrifugal pump. The speed of pump was smoothly regulated by a frequency converter. The temperature of the mixture was measured to determine of its viscosity and density. Data from all differential pressure transmitters, flow meter and thermometer were collected by an electronic data acquisition system. Besides the electronically collected data, the thickness of sediment deposits in the horizontal transparent plexiglass section was measured manually.

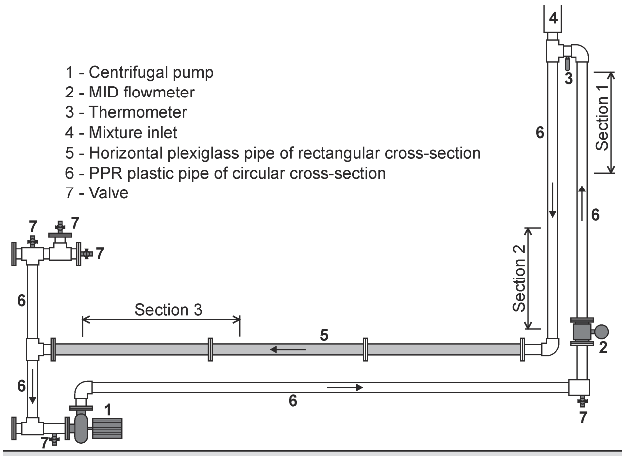

Figure 1: Scheme of experimental loop.

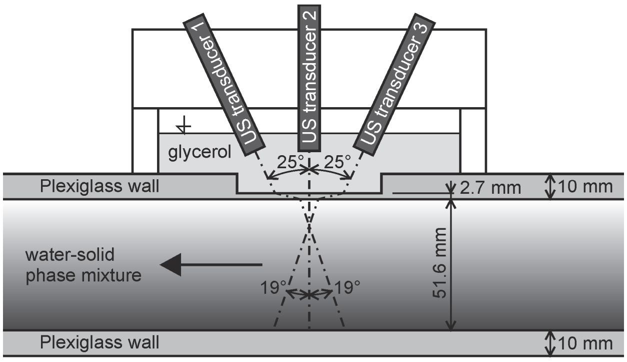

Figure 2: Arrangement of US transducers on the plexiglass pipe of rectangular cross section.

2.2 Velocity and turbulence measurements

Instantaneous velocity profiles were measured using Ultrasonic Velocity Profile (UVP) monitor (Met-Flow SA) in the vertical longitudinal plane passing through the centre in Section 3. US transducers of basic frequencies of 4 MHz, 2 MHz and 1 MHz were used in dependence on the mixture concentration and the velocity magnitude of the mixture. For higher concentrations of the solid phase lower basic frequencies were used. Sampling frequency was kept at constant level of 20 Hz (Δt = 50 ms) for all experiments and the full range of basic frequencies.

Three various positions of the probes were used (Fig. 2). Transducers angle to the main flow's normal (transducer 1 and 3) was 25°. However, the resulting active angle was estimated by 19° due to different acoustic impedance of glycerol and water. The velocity was decomposed under the same assumptions as in previous studies [12-13]. Thus, the point time-averaged quantities of the longitudinal and the vertical velocity and the Reynolds stress can be expressed as follows:

$$\bar{u} = \frac{\overline{V_{R1}} - \overline{V_{R3}}}{2\sin\alpha} \quad (1)$$

$$\bar{v} = \frac{\overline{V_{R1}} + \overline{V_{R3}}}{2\cos\alpha} \quad (2)$$

$$-\overline{u'v'} = -\frac{\overline{V'_{R1}} - \overline{V'_{R3}}}{2\sin 2\alpha} \quad (3)$$

where V_R are radial components measured by individual transducers 1 – 3.

2.3 Flow conditions, sediment transport modes and solid phase characteristics

A wide range of flow conditions was simulated in the experimental track. An average velocity in the cross section varied from 0.2 to 3.5 m/s. Reynolds numbers Re in clear water flows were between $1.6\text{x}10^4$ - $1.0\text{x}10^5$, Re in slurry flows was of a magnitude smaller. The volumetric concentration varied from 5 to 40%, which is given by volume of the solid phase and fluid in the experimental loop. Flow conditions and volumetric concentration naturally influence a delivered concentration which was measured continuously during each experiment (range of c_{vd} = 3 – 29%). Those data are consistent with the mode of slurry flows – upper plane bed (UPB), stratified flow (SF) and heterogeneous flow (HF). A stable plane bed with intense sediment transport upwards with a high concentration gradient is a typical characteristic of the UPB regime. The nature of SF flows is similar, however all particles are in motion. The time-averaged suspension concentration is considered to be quasy-constant in HF flow runs (Fig. 3).

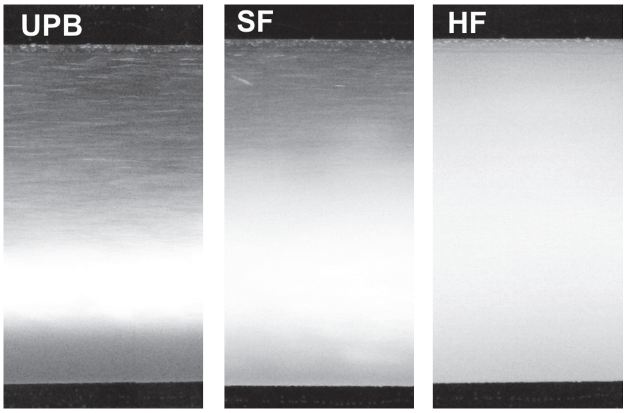

Figure 3: Visual comparison of studied transport regimes.

The tested granular fraction was an industrial ballotini (fraction B134, PRECIOSA) that is relatively narrow graded (d_{15} = 0.16 mm, d_{50} = 0.18 mm d_{85} = 0.24 mm) and has the density similar to natural sands and gravels (2450 kg/m^3). Our tests determined the sediment properties mentioned above and the settling velocity of the sediment, $w_t \approx$ 18 mm/s. Hence, the ballotini particle Reynolds number was $Re_p \approx 3.2$.

3 RESULTS

3.1 Clear water flows

The reference measurements of clear water turbulent flows delivered the vertical distribution of velocity components and turbulence characteristics. All experiments were carried out in smooth flow regime with Re = $1.6\text{x}10^4$ - $1.0\text{x}10^5$. Time-averaged longitudinal velocity profiles for different flow conditions are presented in Fig. 4. A symmetrical distribution with maxima in the centre of the rectangular duct can be observed. Comparing the shape of the distribution with theoretical models significant differences can be seen (Fig. 5). That can be explained by symmetrical secondary currents with vertical components oriented from walls to the center of the pipe. Those findings correspond well with the findings of Knight and Patel [14] who described secondary currents in rectangular ducts.

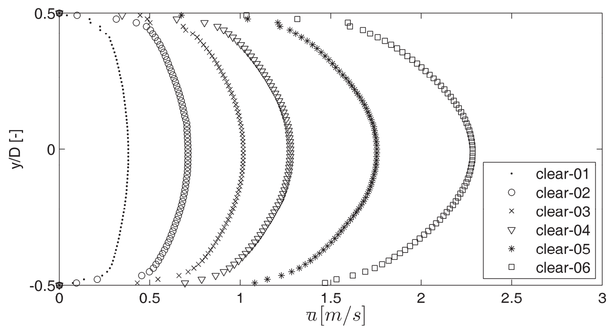

Figure 4: Vertical velocity distribution of time-averaged longitudinal components.

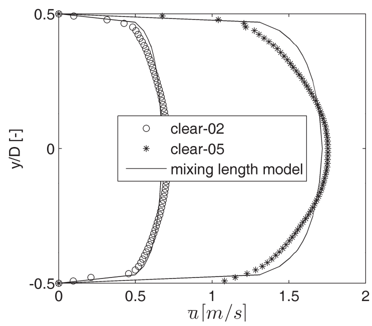

Figure 5: Comparison of measured and theoretical velocity distribution.

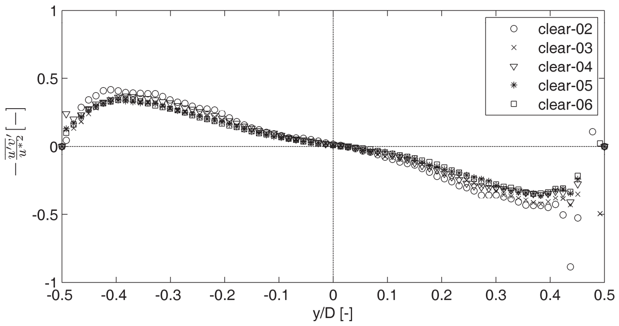

Figure 6: Normalized Reynolds stress distribution for Re = $2.9\text{x}10^4$ - $1.0\text{x}10^5$.

Theoretically, the normalized vertical distribution of Reynolds stress should be a linear function of flow depth with absolute maxima (±1.0) near the pipe walls and zero values at the centerline. Fig. 6 presents measured data sets for different flow conditions. The wall boundary shear tends to be round 50% of the shear given by the energy grade line i_e and hydraulic radius as $u_*^2 = gRi_e$. Such difference can be hardly explained by secondary currents as the vertical velocity components are about 1% of the average cross section velocity. Knight and Patel [14] reported a maximal decrease of the Reynolds stress to be 10% compared to the averaged shear rate along the wetted perimeter of pipe cross section.

3.2 Slurry flows

We present only results obtained in SF and HF transport modes as a concentration gradient above the plane bed in UPB mode is similar to SF transport mode. Typical normalized velocity and Reynolds stress distributions are presented in Fig. 7 (SF mode) and Fig. 8 (HF mode).

In SF mode the velocity distribution is affected by the varying concentration along the vertical. The maximal velocity is located in the upper part of the pipe with a lower concentration. The higher concentration of particles in the lower section results in a higher friction and velocity decrease. Higher concentration gradient results in a stronger asymmetry of the velocity profile.

Velocity data correspond well with the Reynolds stress distribution. The maximal velocity and zero Reynolds stress occurs at the same flow depth y/D. The maximal values of Reynolds stress are reported near by the top wall and the bed.

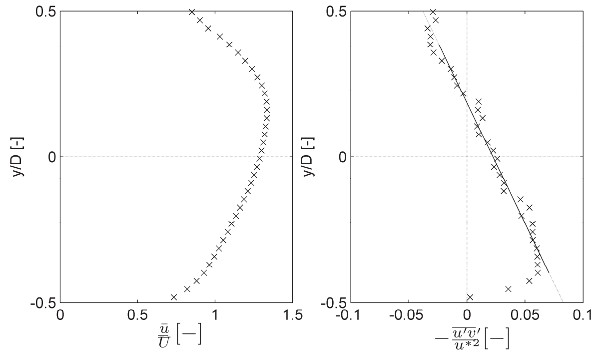

Figure 7: Normalized velocity (left) and Reynolds stress (right) distribution for SF mode with delivered concentration of 29% and Re = $7.1\text{x}10^3$.

When the concentration of the mixture becomes quasy-constant, the velocity distribution starts to be symmetrical. That is valid also for the Reynolds stress distribution with zero value in the centre of the rectangular duct (Fig. 8).

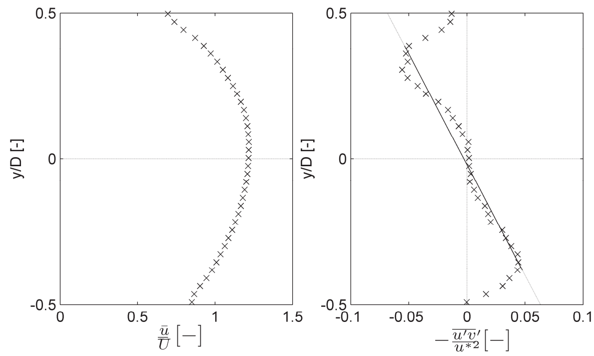

Figure 8: Normalized velocity (left) and Reynolds stress (right) distribution for HF transport mode with delivered concentration of 29% and Re = $1.9\text{x}10^4$.

In fact, the measured instantaneous velocity components in slurry flows represent the speed of solid particles (ballotini). Velocity fluctuation of the particles seems to be strongly attenuated even for small delivered concentration c_{vd} (Fig. 9).

Comparing the run with the lowest concentration (c_{vd} = 3%) and the clear water (Fig. 6) shows that the decrease in normalized Reynolds stress is more than double. With increasing concentration further decrease of normalized Reynolds stress can be observed.

Presented data show slight difference between the Reynolds stress in bottom (y/D = -0.5 - 0) and upper region (y/D = 0 – 0.5), which can be caused by a concentration gradient. Similar to clear water flows the maximal values of normalized Reynolds stress were found to be very low compared to the calculated wall shear stress based on the energy grade line.

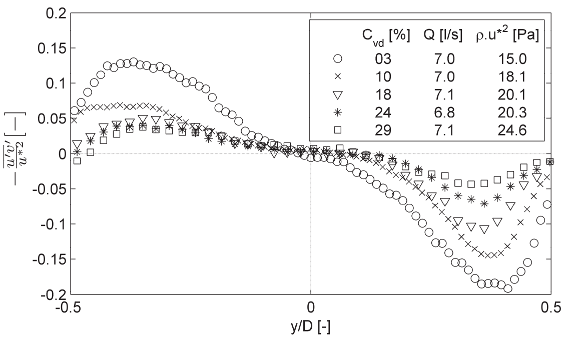

Figure 9: Normalized Reynolds stress distribution for HF mode with delivered concentrations from 3 to 29% and Re = 1.9×10^4.

6 SUMMARY

The presented study introduces results of an ultrasonic velocimetry investigation on water/solid–water mixture flows in a rectangular pipe.

Reference measurements of clear water turbulent flows provided expected distributions of longitudinal and vertical velocity components. However, the level of normalized Reynolds stress seems to be significantly underestimated in comparison with theoretical considerations.

Investigation of slurry flows brings the information about the influence of the sediment transport regime on the velocity distribution in the pipe. Further, a strong attenuation of the velocity fluctuation under the presence of the suspended particles is reported.

ACKNOWLEDGMENTS

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