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FLOW OF HETEROGENEOUS SLURRY IN HORIZONTAL AND INCLINED PIPES

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Narrow particle size distribution heterogeneous slurries were investigated on an experimental pipe loop with the horizontal and inclined pipe sections of inner diameter 100 mm. The investigation was focused on the effect of the pipe inclination, average slurry velocity and overall concentration and on the local concentration distribution, pressure drop, deposition limit and carrier liquid-particle slip velocity. The local concentration distribution was studied with the application of a gamma-ray densitometer. Mixture flow-behaviour and particles motion were investigated in a pipe viewing section. The study revealed that the heterogeneous slurries in the horizontal and inclined pipe sections were significantly stratified, the solid particles moved principally close to the pipe invert, and particle saltation becomes the dominant mode of particle conveying for higher and moderate flow velocities. Carrier liquid-particle slip velocity depends not only on the mixture velocity, but also on particle position in the pipe cross-section. The effect of pipe inclination on the frictional pressure drop in inclined pipe sections depends on mixture velocity, in ascending pipe section decreases with increasing mixture velocity and in descending pipe section the frictional pressure drop gradually decreased with increasing pipe inclination.

KEY WORDS: Solid-Liquid Mixture, Pipe Inclination, Slip Velocity, Mixture Flow Behaviour, Concentration Distribution

1. INTRODUCTION

Freight pipelines are commonly used for transport of different particulate solids. Pipeline conveying of bulk materials in the form of heterogeneous mixtures is of special interest in, e.g. dredging, building, land reclamation or mining (Vlasak et al., 2012). A lot of theoretical or experimental studies have been carried out on transport of particle-water mixtures in horizontal pipes. However, a relatively little research has been done on hydraulic conveying of gravel or bigger particles, especially in vertical and inclined pipes. Pressure drops and operational velocity are most important parameters for pipeline transport design and operation. Friction losses in pipeline flow of heterogeneous solid particle-water mixtures are strongly dependent on the flow pattern (Matousek, 2002). If the operational velocity of the mixture is close to deposition limit, a granular bed forms at the pipe invert. The bed slide over the pipe invert at velocities above the deposition limit and it is stationary below the deposition limit. The contact bed is important contributor to solid friction in mixture flow.

The flow of heterogeneous solid-liquid mixtures in a pipe may be defined as the flow with an asymmetrical velocity and concentration distribution. Wilson proposed a two-layer model for settling slurries with fully stratified flow pattern. When the Reynolds number, friction factor and Coulomb type friction are defined for each layer as well as the interfacial friction factor, the flow parameters could be determined (Wilson, 1976, Wilson et al., 2006). Because the layers differ in the local solids concentration and velocity, there is a difference in the mean velocities of the particles and the liquid. Slip between the particles and the liquid results in a continuous transfer of energy from the fluid to the particle and from the particle to the pipe wall (Vlasak et al., 2017a).

The particles in the turbulent flow are supported by turbulent diffusion, and near the pipe wall a lift force, associated with slip velocity and concentration profile, contributed to particle lift-off, too. For the particles with size larger than the thickness of viscous sub-layer, Saffman force, induced due to the shear of the fluid, supports particle movement and together with Magnus force (due to the particle rotation) could reach a significant fraction of the total weight of particles (Wilson et al., 2010).

2. EXPERIMENTAL EQUIPMENT AND MATERIAL

The experimental investigation was carried out on the pipe loop of inner diameter D = 100 mm with horizontal [A] and inclinable [B] pipe sections, see Fig. 1. Measured solid-liquid mixture was pumped by a centrifugal slurry pump GIW LCC-M 80-300 [2]with variable speed drive Siemens 1LG4283-2AB60-Z A11 [3]. The pressure drops were measured by the differential pressure transducers Rosemount 1151DP [8]. Transparent viewing pipe sections [7] for visual observation were situated on the end of the horizontal pipe section [A]. The mixture flow was recorded using a high speed digital camera NanoSence MK III+ with a frequency up to 2 000 frames per second, image resolution 1280 × 1024.

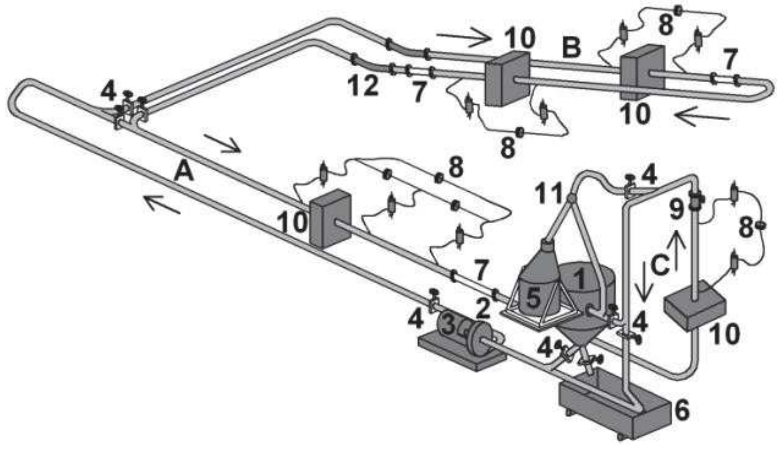

Fig. 1 Experimental test loop D = 100 mm (IH AS CR, v. v. i., Prague)

Slurry velocity was measured by a Krohne OPTIFLUX 5000 magnetic flow meter [9], the flow divider [11] and the sampling tank [5] allow measuring of the flow rate and delivered concentration. The loop is equipped with gamma-ray density meters [10] placed on a special support controlled by the computer (Vlasak et al., 2014c). The studied mixtures consist of basalt pebbles (particle diameter, d, ranging from 8 to 16 mm, the mean diameter $d_{50} \approx 11.5$ mm, particle density ρ_p=2 895 kg m^{-3}) and water, the overall volumetric concentration, c_v, ranged from 3 to 15%.

3. MIXTURE FLOW BEHAVIOUR AND SLIP VELOCITY RATIO

Particles slide and roll along the pipe invert for the mixture velocities even below the deposition limit. With the increasing mixture velocity formations similar to dunes are originated, and individual particles roll and jump across the dunes, see Fig. 2. For velocity interval from 1.5 to 2.5 m/s (i.e. close to deposition limit) dunes disaggregated, the thickness of bed formations decreased, with increasing velocity sliding bed layer originated. This flow pattern resulted in pressure drops fluctuation. For higher slurry velocities most of particles lifted off the pipe bottom and moved in saltation mode or even in suspended mode.

Velocities of the saltating particles were significantly higher than that moving in contact with the pipe wall. However, most of the particles remained concentrated in the lower portion of the pipe, Vlasak et al. (2014a). For moderate and high flow velocities the particle saltation became dominant mode of the particle movement. The relatively high value of slip velocity between particles and carrier liquid, mutual particle-particle and particle-pipe interactions and collisions resulted in significant increase of the total pressure drops. The particle velocities increased with increasing distance from pipe invert (Vlasak et al., 2012; Vlasak et al., 2014c).

Fig. 2 Particles movement along the pipe invert (V_s = 0.96 and 2.15 m/s)

Slip velocity in two-phase flow is defined as the velocity difference between the solid and liquid phase. It is one of mechanism of particle movement in two-phase flow. In the homogeneous model of two-phase flow the slip velocity V_{slip} is by definition assumed to be close to zero (no slip). For heterogeneous slurry flow it was experimentally observed that the slip velocity depends on the flow pattern (e.g. suspended flow, stratified flow, slug flow). Due to slip velocity, there is difference between delivery (transport c_d) and spatial (in situ c_v) concentrations, and the slip ratio ($c_d / c_v = V_{slip} / V_s$) is the parameter describing flow stratification in a pipe. In vertical two-phase flow the slip velocity can be approximated by hindered settling velocity. The slip-velocity will be determined from comparison of the mean in situ and mean transport concentration.

Effect of mean mixture velocity and pipe inclination on slip ratio in horizontal, inclined, and vertical ascending ($V_{slip.up}/V_s$) and descending ($V_{slip,down}/V_s$) pipe sections, determined from measured basalt pebbles-water mixture concentration are indicated in Tab. 1 for mean mixture velocity about V_s = 2.85 m/s and in Tab. 2 for mean mixture velocity about V_{as} = 3.85 m/s and transport concentration $c_d \approx 0.06$.

Table 1.
Slip ratio in horizontal, inclined, and vertical ascending and descending pipe sections

V_s[m/s]	α	$c_{v,\ \mathrm{up}}$	$c_{v,\ \mathrm{down}}$	c_d	$V_{slip.up}/V_s$	$V_{slip,down}/V_s$
2.85	0°	0.0360	0.0415	0.0385	1.06944	0.92771
2.83	15°	0.0425	0.0374	0.0397	0.93412	1.06150
2.84	30°	0.0469	0.0333	0.0390	0.83156	1.17117
2.85	45°	0.0541	0.0308	0.0392	0.72458	1.27273
2.88	75°	0.0530	0.0288	0.0372	0.70189	1.29167
2.85	90°	0.0518	0.0286	0.0370	0.71429	1.29371

Table 2.
Slip ratio in horizontal, inclined, and vertical ascending and descending pipe sections

V_s[m/s]	α	$c_{v,\ \mathrm{up}}$	$c_{v,\ \mathrm{down}}$	c_d	$V_{slip.up}/V_s$	$V_{slip,down}/V_s$
3.82	0°	0.0637	0.0587	0.06110	0.9592	1.0409
3.84	15°	0.0703	0.0588	0.06410	0.9118	1.0901
3.85	30°	0.0677	0.0545	0.06050	0.8936	1.1101
3.87	45°	0.0633	0.0481	0.05470	0.8641	1.1372
3.89	60°	0.0639	0.0464	0.05380	0.8419	1.1595
3.87	75°	0.0591	0.0443	0.05065	0.8570	1.1433
3.86	90°	0.0621	0.0468	0.0533	0.8580	1.1390

4. LOCAL CONCENTRATION

Local concentration distribution is important for understanding the mechanism of the heterogeneous mixture flow, it has a great effect on both the mixture pressure drop and flow behaviour. Various methods have been used for measurement of the local concentration, e.g. isokinetic sampling, electrical resistance and capacity or radiometric methods (Krupicka and Matousek, 2014; Matousek, 2002; Matousek et al., 2015; Przewlodcki et al., 1979; Pugh and Wilson, 1999; Sobota J., Plewa F., 2000; Sobota et al.,2009).

The volumetric concentration distribution was measured using a γ-ray densitometer. The effect of the pipe inclination α, mixture velocity V_s on local concentration distribution in vertical profiles is illustrated in Fig. 3 and 4. The measured chord-averaged concentration profiles for different transport concentration c_d confirmed the stratified flow pattern of the coarse particle-water mixture in inclined pipe sections. The concentration profiles can be divided into three parts similarly as in horizontal pipe sections (Vlasak et al., 2014b; 2016). The local concentration c_v approaches practically zero in the upper portion of the pipe, this region increases for the descending flow with decreasing mixture velocity V_s and mean transport concentration c_d. A nearly linear concentration distribution was determined in the central portion of the pipe cross-section. Solids concentration reached maximum near the pipe invert, however, in inclined pipe sections never reached value close to the loose-packed value for studied conditions.

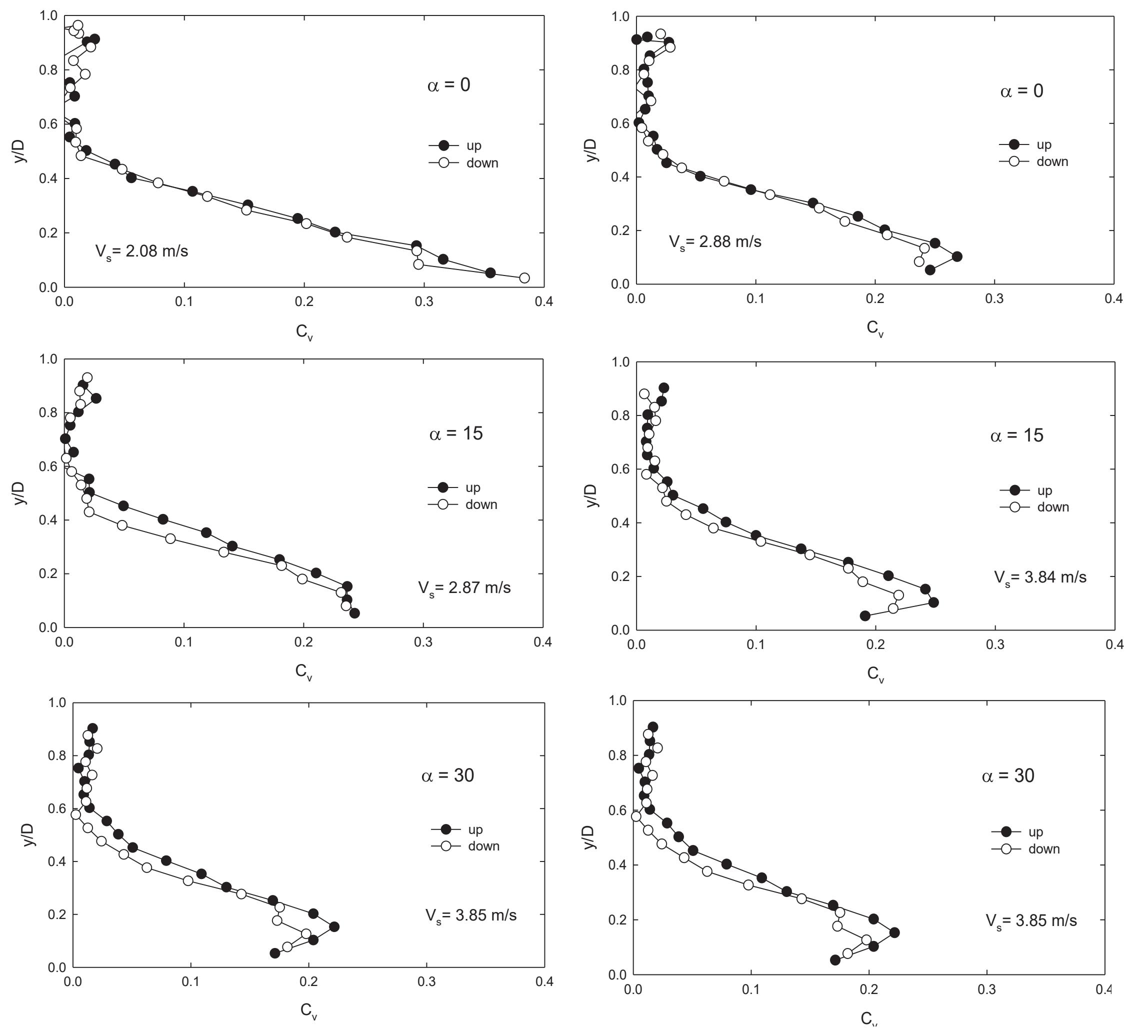

Fig. 3 Chord-averaged profiles of local concentration, c_v, effect of the inclination angle α and the mean mixture velocity V_s; low inclination values (transport concentration $c_d \approx 0.06$)

The effect of pipe inclination for low values of inclination angle α (see Fig. 3 - up to about 30°) is not significant, similarly as it was observed for pressure drop (Vlasak et al., 2014c; 2017a). Local concentration c_v at the pipe invert slightly decreased with increasing pipe inclination. For inclination angle α higher than 45°, a decrease in concentration close to the pipe invert was observed. For the vertical pipe a nearly constant concentration distribution was observed, see Fig. 4. Bed layer with thickness of about 20% of the pipe diameter were formed for moderate and higher mixture velocities. Local concentration in the bed layer decreased with increasing velocity and with increasing inclination angle α. No maximum of local concentration was observed for descending flow direction and inclination angle α = 15°, concentration profiles were nearly linear in the lower portion of the pipe.

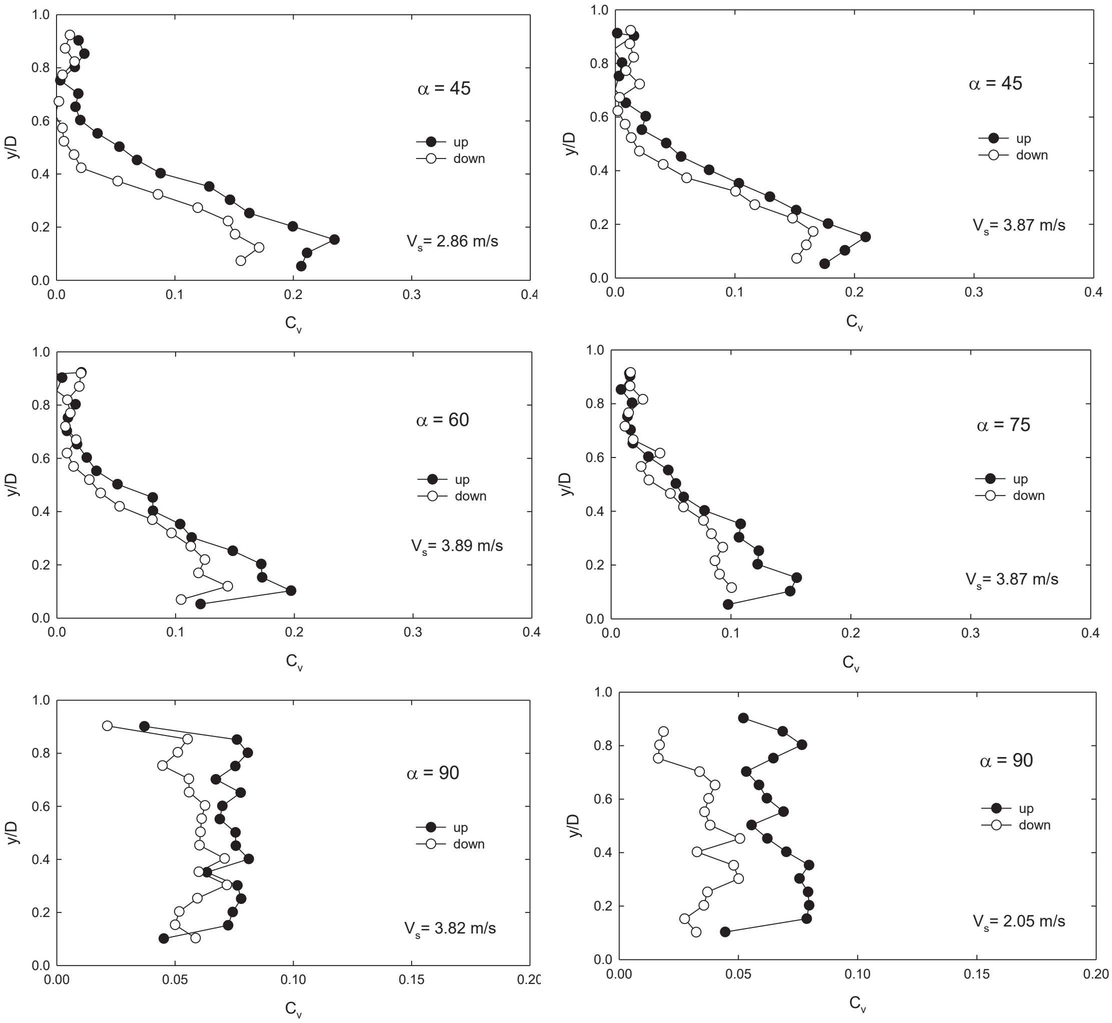

Fig. 4 Chord-averaged profiles of local concentration, c_v, effect of the inclination angle α and the mean mixture velocity V_s; high inclination values (transport concentration $c_d \approx 0.06$)

The effect of up and down flow is clearly illustrated in Figs. 3 and 4, for different mixture velocities (V_s =2.05, 2.85, and 3.85 m s^{-1}), and inclination angle α in range from 0° to 90°. The local concentration in ascending pipe section is always higher than that in descending pipe section. It is valid also for vertical up-ward and down-ward flow, where difference between the concentration values corresponds to particle slip velocity.

The effect of the transport concentration c_d for inclination angle α = 30° and the mixture velocity V_s = 2.85 m s^{-1}, is illustrated on Fig. 5, both for ascending and descending flow directions. Practically no maximum of local concentration was observed for descending flow direction. In the lower portion of the pipe concentration profiles were nearly linear. The zero concentration part of the concentration profile was significantly more extended than that for the ascending flow direction due to the braking effect of gravity force on ascending flow and accelerating effect of gravity force on descending flow (Vlasak et al., 2017b).

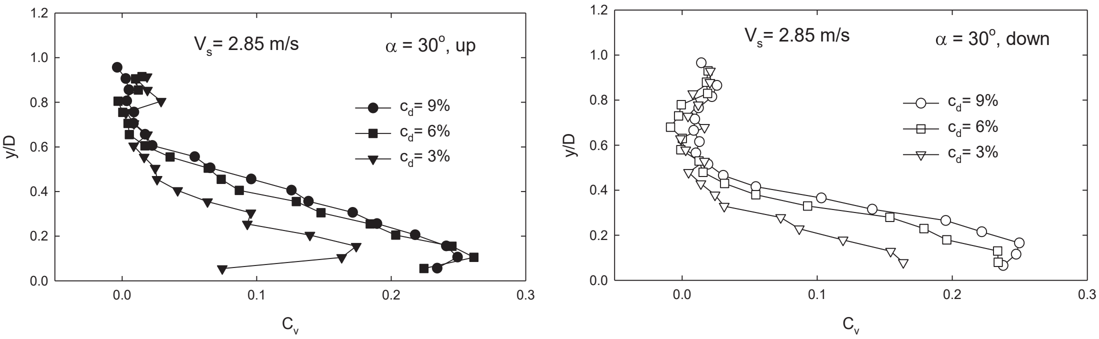

Fig. 5 Effect of the transport concentration c_d and flow direction on chord-averaged profiles of local concentration, c_v,

5. CONCLUSIONS

The effect of slurry velocity and mean concentration on a coarse particle (basalt pebbles) – water mixtures flow behaviour in the turbulent regime was studied in horizontal and inclined smooth pipe sections of inner diameter D = 100 mm.

The visualization and local concentration measurements revealed the stratified flow pattern of the coarse particle-water mixture in inclined pipe sections. The particles moved mostly near to the pipe invert. For velocities close to deposition limit dune formations or sliding bed were formed. For moderate and higher mixture velocities, particle saltation became the dominant mode of sediment transport.

The in situ concentration reached higher values in the ascending section than in the descending section. In the inclined pipe sections, similarly to horizontal one, the chord averaged concentration profiles can be divided in three parts: a region with a maximum concentration near the pipe invert, the central portion of the pipe with a nearly linear concentration distribution, and the zero-concentration region in the upper portion of the pipe.

For inclination angle α lower then about 30°, the effect of pipe inclination on local concentration distribution is not significant.

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