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CONCENTRATION DISTRIBUTION AND SLIP VELOCITY OF COARSE-PARTICLE-WATER MIXTURE IN HORIZONTAL AND INCLINED PIPE SECTIONS

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Abstract: *Narrow particle size distribution basalt pebbles of mean particle size 11.5 mm conveyed by water in the pipe sections of different inclination were investigated on an experimental pipe loop of inner diameter D = 100 mm. Mixture flow-behaviour and the concentration distribution were studied in a pipe viewing section and with the application of a gamma-ray densitometer. The study refers to the effect of mixture velocity, overall concentration, and angle of pipe inclination on chord-averaged concentration profiles and local concentration maps. The study revealed that the coarse particle-water mixtures in the inclined pipe sections were significantly stratified, the solid particles moved principally close to the pipe invert, and for higher and moderate flow velocities particle saltation becomes the dominant mode of particle conveying.*

Keywords: **Hydraulic Conveying,, Concentration Distribution, Pipe Inclination, Gamma-Ray Radiometry, Mixture Flow Behaviour.**

1. Introduction

Pipeline conveying of bulk materials in the form of heterogeneous mixtures is of special interest in, e.g. mining, dredging, building or land reclamation (Vlasak et al., 2012). 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. 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). A lot of theoretical or experimental studies have been carried out on transport of sand or fine particles 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.

The flow of heterogeneous solid-liquid mixtures in a horizontal pipe may be defined as the flow with an asymmetrical concentration and velocity distribution. Based on macroscopic modelling, where the conservation equations are formulated using averaged quantities over the control volume, Wilson proposed a two-layer model for settling slurries with fully stratified flow pattern (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, which results in a continuous transfer of energy from the fluid to the particle and from the particle to the pipe wall (Vlasak et al., 2017).

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_s is by definition assumed to be close to zero. For heterogeneous slurry flow it was experimentally observed that the slip velocity depends on the flow pattern (e.g. 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 ($c_d / c_v = V_s / V_a$) is the parameter describing flow stratification in a pipe.

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2. Experimental Equipment and Material

The experimental investigation was carried out on the pipe loop of inner diameter D = 100 mm with horizontal and inclinable pipe sections. Glass viewing sections were used to study the slurry flow behaviour. 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. Slurry velocity was measured by a Krohne OPTIFLUX 5000 magnetic flow meter, the flow divider and the sampling tank allow measuring of the flow rate and delivered concentration. The loop is equipped with gamma-ray density meters placed on a special support controlled by the computer. 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. Local Concentration

Distribution of the local concentration in the pipe cross-section is important for understanding the mechanism of the heterogeneous mixture flow; it has a great effect on both the mixture's flow behaviour and pressure drop. The local concentration distribution was measured using a γ-ray densitometer (Krupicka and Matousek, 2014; Matousek et al., 2015). The effect of mean concentration, mixture velocity and angle of pipe inclination on chord-averaged vertical profiles of local concentration was studied. The measured chord-average concentration profiles for different transport concentration c_d confirmed the stratified flow pattern of the coarse particle-water mixture in inclined pipe sections. The chord-average concentration profiles can be divided into three parts similarly as in horizontal pipe sections (Vlasak et al., 2014a; 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 and mean transport concentration. A nearly linear concentration distribution was observed in the central portion of the pipe cross-section. Local concentration reached maximum near the pipe invert, however, in inclined pipe sections never reached value close to the loose-packed value for studied conditions.

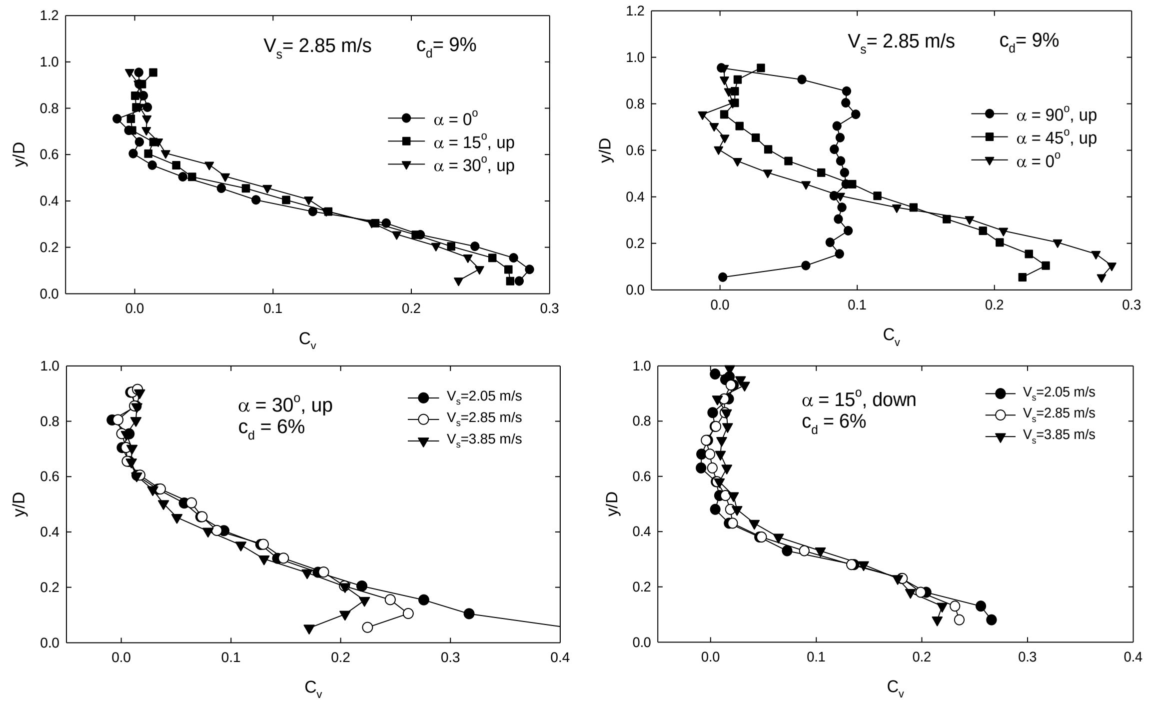


Fig. 1: Effect of inclination angle α and mean mixture velocity V_s on profiles of local concentration c_v.

Similarly as it was confirmed for pressure drop, the effect of pipe inclination for low values of inclination angle α (up to about 30 °) is not significant (Vlasak et al., 2014b). Local in situ concentration c_v at the pipe invert slightly decreased with increasing pipe inclination. For higher inclination angle α, a decrease in concentration close to the pipe invert was observed. For the vertical pipe a nearly constant concentration distribution was observed, see Fig. 1. 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; this effect increased with increasing inclination angle α. Fig. 2 (upper panels) illustrates the effect of the transport concentration c_d for inclination angle α = 30 ° and the mixture velocity V_s = 2.85 m s^{-1}, both for ascending and descending flow directions. No maximum of local concentration was observed for descending flow direction, concentration profiles were nearly linear in the lower portion of the pipe, and the zero concentration part of the chord-averaged 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. The positive effect of gravity decreases and the negative effect of gravity increase the particle–liquid slip velocity.

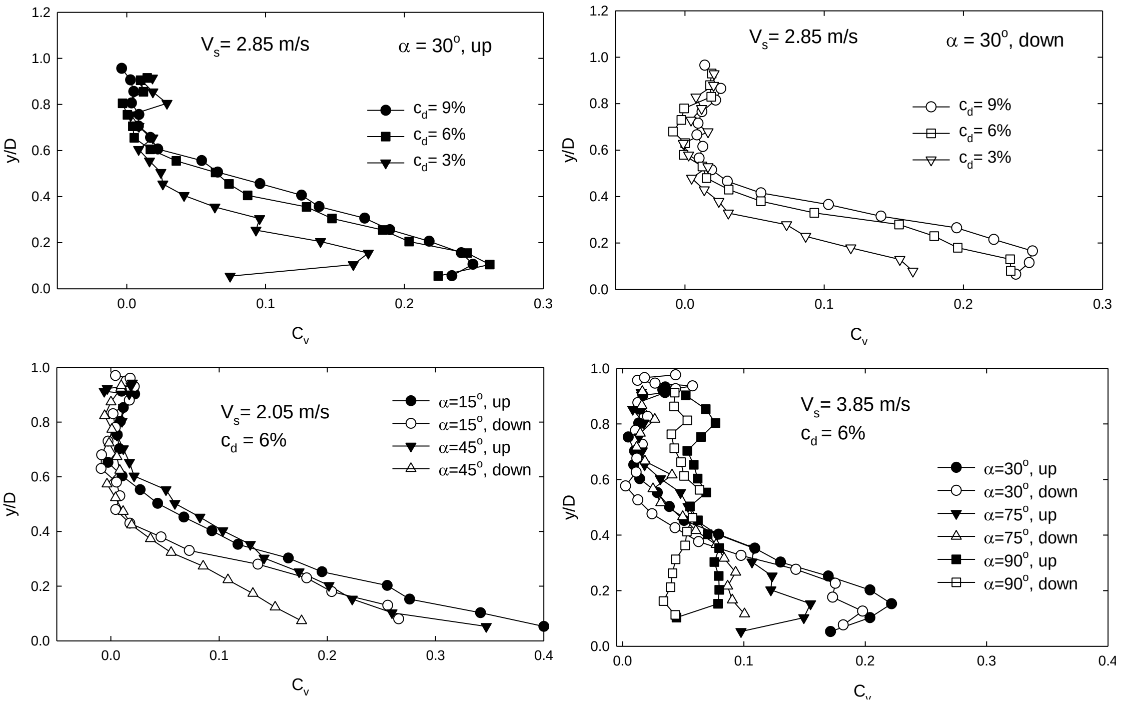
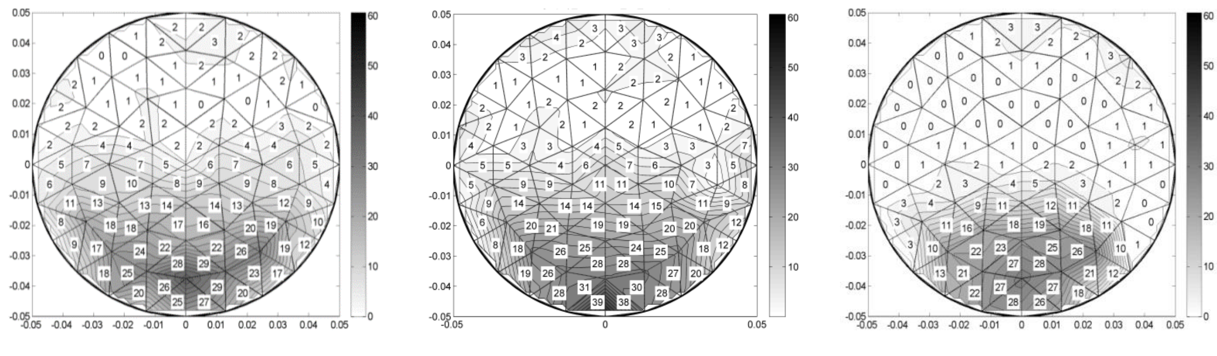


Fig. 2: Effect of the transport concentration c_d and flow direction on profiles of local concentration c_v.

The effect of up and down flow is illustrated in Fig. 2 (lower panels) for inclination angle α in range from 15 ° 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–liquid slip velocity, which can be approximated by hindered settling velocity.



ascending flow, α = 0 °, c_d = 9 %   *horizontal flow*, α = 0 °, c_d = 10.2 %   *descending flow*, α = 30 °, c_d = 9 %

Fig. 3: Maps of local concentration c_v in inclined and horizontal pipe sections (V_s = 2.8 m.s^{-1}).

The concentration maps measured in inclined pipe sections (see Fig. 3) confirmed that coarse particles tended to occupy the bottom part of the pipe. However, with increasing mixture velocity and concentration, even the coarse particles lifted off the pipe bottom and moved up to the central area of the pipe, similarly as it was found in the horizontal pipe section (Vlasak et al., 2014b). Some differences were found for ascending and descending flow direction due to the effect of gravity force on particle movement and slip velocity. In descending pipe sections the observed local concentration near lateral walls of the pipe was slightly less than that in the ascending pipe sections, where especially for higher mean concentration significantly higher local concentration values were reached close to the pipe invert, probably due to the higher slip velocity and breaking effect of the gravity force acting on the particles.

Effect of mean mixture velocity and concentration on values of slip ratio in horizontal (V_s / V_a) and vertical ascending ($V_{s,a} / V_a$) and descending (V_{sd} / V_a) pipe sections, determined from measured basalt pebbles-water mixture concentration are indicated in Tab. 1.

Tab. 1: Slip ratio in horizontal and vertical ascending and descending pipe sections.

V_a [m/s]	c_v	c_d	V_s / V_a	V_a [m/s]	$c_{v,a}$	$c_{v,d}$	c_d	$V_{s,a}/V_a$	V_{sd}/V_a
2.0	0.136	0.105	0.77	2.05	0.063	0.037	0.049	0.78	1.32
2.8	0.102	0.075	0.74	2.85	0.071	0.048	0.059	0.83	1.23
3.8	0.121	0.105	0.87	3.85	0.067	0.053	0.061	0.91	1.15

4. Conclusions

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

The stratified flow pattern of the coarse particle-water mixture in inclined pipe sections was revealed. The particles moved mostly near to the pipe invert, where dune formations and for velocities higher than deposition limit a sliding bed layer were formed. For moderate and higher mixture velocities, particle saltation became the dominant mode of sediment transport.

Concentration distribution in ascending and descending vertical pipe section confirmed effect of fall velocity on particle-carrier liquid slip velocity and higher in situ concentration in ascending pipe section.

For inclination angle α (lower then about 30 °), the effect of pipe inclination on local concentration distribution is not significant. The zero concentration region increases for descending flow direction with decreasing mixture velocity and mean transport concentration and it is bigger than that for the ascending flow direction. With increasing mean mixture velocity the local concentration in the bed layer slightly decreased; this effect increased with increasing inclination angle.

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