

CONVEYING OF COARSE PARTICLES IN INCLINED PIPES

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Abstract: Basalt pebbles of mean diameter 11.5 mm conveyed by water were investigated on an experimental pipe loop with horizontal, vertical, and inclined pipe sections, consisting of smooth stainless steel pipes of inner diameter $D = 100$ mm. The local particle concentration distribution in pipe cross-section was carried out with the application of a gamma-ray densitometer. The paper is focused on studying the effect of the mixture velocity and overall concentration on the coarse particle-water mixtures flow behaviour and concentration distribution in the pipe cross-section. Mixture flow-behaviour and particles motion along the pipe invert were studied in a pipe viewing section. Presented results refer to the effect of mixture velocity, overall concentration, and angle of pipe inclination on chord-averaged concentration and local concentration distribution in the inclined pipe sections. The study revealed that the coarse particle-water mixtures in the horizontal and inclined pipe sections were significantly stratified. The solid particles moved principally close to the pipe invert in the inclined pipe sections, and for higher and moderate flow velocities particle saltation becomes the dominant mode of particle conveying.

KEY WORDS: coarse particle conveying; gamma-ray radiometry; concentration distribution; pipe inclination; mixture flow behaviour.

1. INTRODUCTION

Pipeline transport of coarse particles in the form of heterogeneous mixtures is of special interest in, e.g. dredging, mining and building industry, or poly-metallic nodules transport from the ocean bottom to the surface. The flow of heterogeneous solid-liquid mixtures in a pipe may be defined as the flow with an asymmetrical concentration and velocity distribution, where a Coulomb friction contributes significantly to the friction losses. A flow pattern with a bed layer and a skewed concentration distribution generally exist for these slurries (Wilson et al., 2006). The first mechanistic approach for coarse particle-water mixture flow was probably that of Newitt et al. (1955). They distinguished between fluid friction, and particle-wall frictions of the Coulomb type, and defined coarse particle conveyance as flow with a sliding bed and a skipping motion (saltation) of conveyed particles.

A slurry flow mechanism can be theoretically described by a set of differential equations for the conservation of mass, momentum and energy in the slurry flow, the so called microscopic model. Unfortunately, no experimental technique is able to provide enough information on the slurry flow mechanism at a microscopic level, and the model remains only theoretical. A compromise between the microscopic and empirical approaches is 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, where all particles are

supposed to be concentrated in the lower portion of the pipe with concentration approaching the loose-packed value, and the Coulombic contribution to particle-wall friction is dominant. In the upper layer only clear fluid is assumed.

Based on experimental data from the large test pipelines of the Saskatchewan Research Council the so called SRC two-layer model, based upon force balance for the upper and lower horizontal layers, was introduced (Shook and Roco, 1991). Progress in the theoretical description of heterogeneous slurry flow is limited due to the lack of experimental data describing the flow behaviour and an inner structure of slurry flow since study of the inner structure of settling mixtures flow is relatively difficult.

The present paper describes the experimental investigation of coarse-grained particle-water mixtures. It is focused on evaluation of the effect of average mixture velocity, pipe inclination, and overall concentration on slurry flow behaviour and local concentration distribution.

2. EXPERIMENTAL EQUIPMENT AND MATERIAL

The experimental pipe loop of inner diameter $D = 100$ mm, consisting of smooth stainless steel pipes and glass viewing section, was used to study the flow behaviour and local concentration distribution in horizontal, inclined and vertical pipe sections (Vlasak et al., 2014a). To measure vertical profiles of chord-averaged local in-situ volumetric concentration c_v and 2D-concentration maps, the loop is equipped with γ -ray density meters. The studied mixtures consist of graded basalt pebbles with a narrow particle size distribution (particle diameter, d , ranging from 8 to 16 mm, density $\rho_p = 2895$ kg/m³). Water was used as the carrier liquid.

To avoid the effect of degradation, degraded basalt pebbles were used and the particle size distribution (PSD) was checked after individual measurements. Due to degradation the basalt pebbles with original value of mean diameter $d_{50} = 12$ mm changed slightly, after measurement the mean diameter was about $d_{50} \approx 11.5$ mm, see Figure 1, where the effect of pumping on PSD is illustrated.

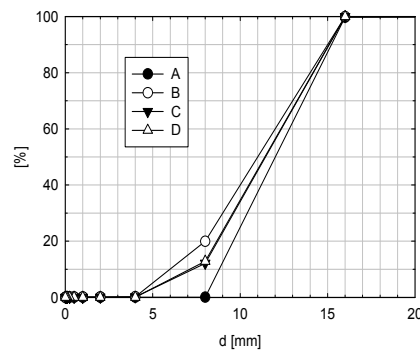


Fig.1 Effect of pumping on particle size distribution of graded basalt pebbles (A – original sample; B – $c_d = 3\%$, C – $c_d = 6\%$, D – $c_d = 9\%$, after measurement)

3. MIXTURE FLOW BEHAVIOUR

From visualization and high speed camera records we found, that particles slid and rolled along the pipe invert for flow velocities at about the deposition limit (e.g. $V_s \approx 0.9$ m/s). With increasing mixture velocity individual particles passed to the saltation mode and bottom formations similar to dunes originated. For velocity interval from about 1.5 to

2.5 m/s dunes disaggregated, thickness of the bed formations decreased, and a continuous sliding bed layer was observed. This flow pattern resulted in pressure drop fluctuations.

For low mixture velocities (e.g. $V_s \approx 1.1$ m/s) a stationary bed was observed, close to pipe invert particles were motionless; see e.g. particle No. 1 in Figures 2a and 2b. In the upper layer particle No. 2 and others in the bed were slowly moving, and above the “compact” bed, particles moved relatively quickly in saltation mode. With increasing velocity (e.g. $V_s \approx 1.5$ m/s), even particles close the pipe invert started slowly to move, see particle No. 1 in Figures 2c and 2d. below. For moderate and higher mixture velocities more and more particles lifted off the pipe bottom and moved in saltation with intensive rotation, or even suspended mode.

The particle saltation became the dominant mode for particle movement. Velocities of the saltating particles were significantly higher than that of the sliding or rolling particles, moving in contact with the pipe wall. The particle velocities

increased with increasing distance from the pipe invert, (Vlasak et al., 2014b).

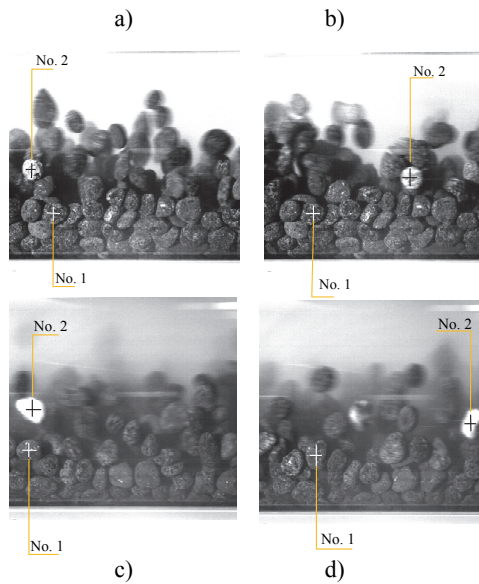


Fig.2 Movement of particles in bed layer ($V_s = 1.04$ and 1.35 m/s, respectively)

4. CONCENTRATION DISTRIBUTION

Distribution of the local concentration in the pipe cross-section has a great effect on both the mixture’s flow behaviour and pressure drop. Various methods have been used for measurement of the local concentration, e.g. isokinetic sampling, different visualization techniques, electrical resistance and capacity or radiometric methods. The volumetric concentration distribution in the inclined pipe sections was measured using a γ -ray densitometer by Krupicka and Matousek (2014).

4.1. CHORD AVERAGED CONCENTRATION PROFILES

The effect of different flow parameters on local concentration distribution in chord-averaged vertical profiles in pipe sections with different angle of inclination α was studied for three values of concentration and three mixture flow velocities. The measured concentration profiles for different transport concentration c_d confirmed the stratified flow pattern of the coarse particle-water mixture in inclined pipe sections, see Figures 3-6. The chord averaged concentration profiles can be divided into three parts similarly as in horizontal pipe sections (Vlasak et al., 2014a). The local volumetric concentration c_v approaches practically zero in the upper portion of the pipe. The zero-

concentration region increases for the descending flow direction, with decreasing mixture velocity and mean transport concentration. A nearly linear concentration distribution can be recognized in the central portion of the pipe. Near the pipe invert, solids concentration reached maximum, and for the higher mixture velocity a thin layer with nearly constant local concentration formed; however, for studied conditions the bed concentration in inclined pipe sections never reached values close to the loose-packed value; it demonstrates that bed particles moved along the bed of the pipe (slide, roll or in saltation mode) for given flow condition (i.e. for velocities higher than the deposition limit).

Similarly as it was confirmed for pressure drop, the effect of pipe inclination for low values of angle α (up to about 30°) is not significant, especially in the upper and central portions of the pipe, see Figure 3. Local concentration c_v slightly decreased with increasing pipe inclination at the pipe bottom. For higher values of angle α , a decrease in concentration close to the pipe invert is observed; local concentration in the central portion of the pipe increased and for the vertical pipe a nearly constant concentration distribution was observed. The effect of inclination was similar for both higher mixture velocities, for low mixture velocity ($V_s = 2.05$ m/s) a bed layer was observed.

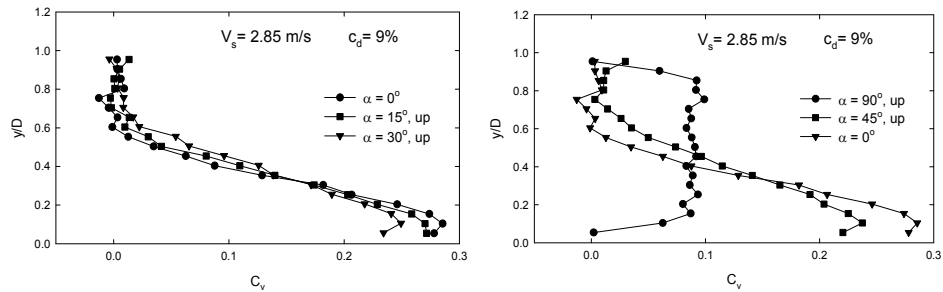


Fig.3 Vertical profiles of chord-averaged local volumetric concentration, c_v , effect of the inclination angle α for constant mean transport concentration c_d and mean mixture velocity V_s

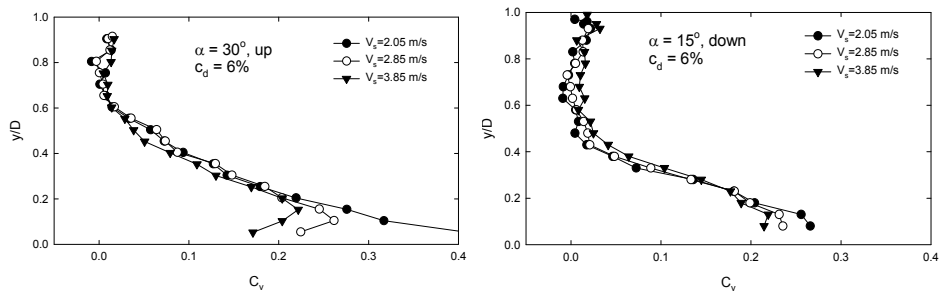


Fig.4 Vertical profiles of chord-averaged local volumetric concentration, c_v , effect of the mean mixture velocity V_s for constant mean transport concentration c_d and inclination angle α

The same was observed from Figure 4, which illustrated the effect of mean mixture velocity V_s for low values of pipe inclination angle $\alpha=15^\circ$ and 30° , and mean transport concentration $c_d = 6\%$. For moderate and higher mixture velocities bed layers with thickness of about 20% of the pipe diameter were formed. Concentration in the bed layer decreased with increasing velocity; probably due to increasing saltation intensity more particles reach higher portion of the pipe. This effect increased with increasing inclination angle.

The effect of the mean transport concentration c_d is illustrated in Figure 5 for inclination angle $\alpha = 30^\circ$, both ascending and descending flow directions, and the mean mixture velocity $V_s = 2.85$ m/s. With increasing mean transport concentration the local concentration in the bed layer, as well as in central proportion of the pipe increased, and in ascending flow direction the bed layer was distinct even for low concentration value. For descending flow direction no maximum of local concentration was observed, concentration profiles are nearly linear in the lower portion of the pipe, and the zero concentration part of the pipe cross-section is significantly bigger than 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 and negative effect of gravity decreases and increases, respectively, the particle-liquid slip velocity.

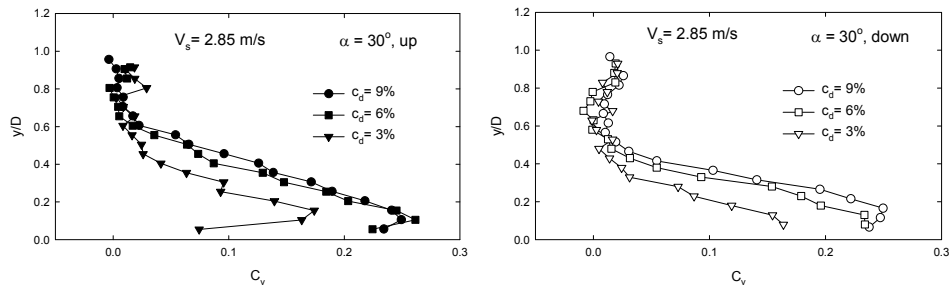


Fig.5 Vertical profiles of chord-averaged local volumetric concentration, c_v , effect of the mean transport concentration c_d for constant mixture velocity V_s and inclination angle α

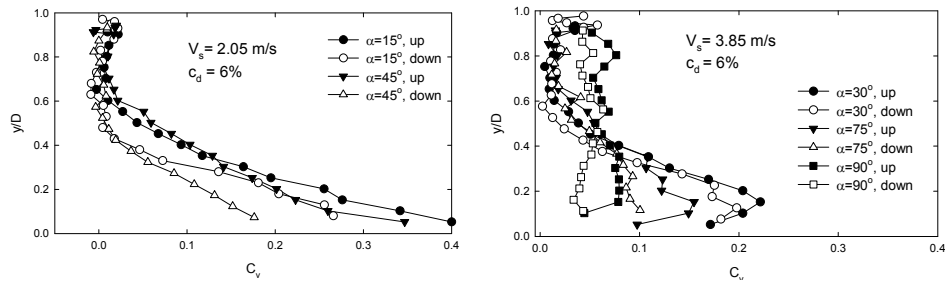
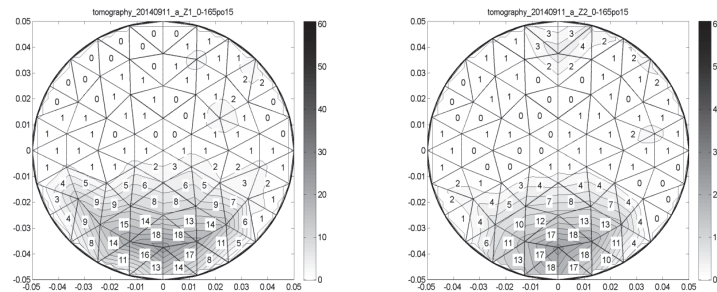


Fig.6 Vertical profiles of chord-averaged local volumetric concentration, c_v , effect of the up and down flow for constant mean transport concentration c_d mixture velocity V_s

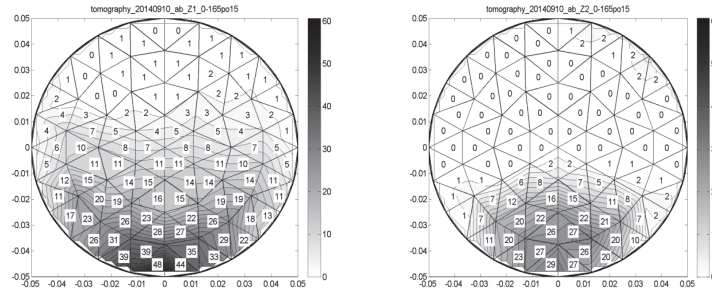
The effect of up and down flow is clearly illustrated in Figure 6, for low and high mixture velocities ($V_s = 2.05$ and 3.85 m/s), and wide range of inclination angle α , from 15° to 90° . The local concentration in ascending pipe sections is always higher than that in descending pipe sections; it is valid also for vertical up-ward and down-ward flow, where difference between the concentration values corresponds to particle slip velocity.

4.2. LOCAL CONCENTRATION MAPS

The concentration maps measured in inclined pipe sections, see Figure 7, confirmed that coarse particles tended to occupy the bottom part of the pipe. However, with increasing mixture velocity and concentration, even the measured 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., 2014a). Some differences were found for ascending and descending flow direction due to the effect of gravity force on particle movement. 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.



mean transport concentration $c_d = 3\%$, mixture velocity $V_s = 2.85$ m/s, inclination angle $\alpha = 30^\circ$



mean transport concentration $c_d = 9\%$, mixture velocity $V_s = 2.85$ m/s, inclination angle $\alpha = 30^\circ$

ascending flow direction

descending flow direction

Fig.7 Maps of local volumetric concentration c_v distribution in inclined pipe section

Local concentration maps in the ascending and descending vertical pipe section illustrated effect of particle fall velocity on mixture concentration see Figure 8. The in situ concentration reached higher values in the ascending section than in the descending section, since the fall velocity decreased the absolute particle velocity, and thus increased the particle slip velocity and in-situ concentration in the ascending pipe section. For the descending pipe sections the opposite is valid and the in situ concentration is less than transport concentration.

Similarly to inclined pipe sections the concentration distribution was observed different in the ascending and descending pipe section. In the ascending pipe section the maximum concentration was located in an annulus from about $h = 0.15 D$ to $h = 0.30 D$, with increasing flow velocity the difference of local concentration in the central portion and region with a maximum concentration decreased. For the descending pipe section the local concentration reached its maximum in the central portion of the pipe and in the direction to the pipe wall the local concentration smoothly decreased.

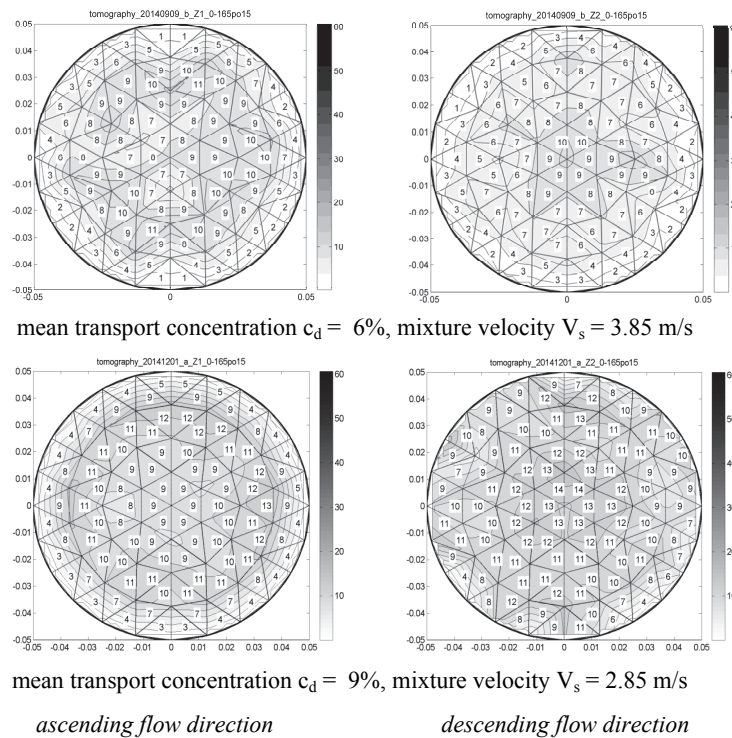


Fig.8 Maps of local volumetric concentration c_v distribution in vertical pipe section.

5. CONCLUSION

The effect of slurry velocity and mean concentration on a narrow particle size distribution basalt pebbles (mean diameter $d_{50} = 11.5$ mm) – water mixtures’ flow

behaviour in the turbulent regime was studied in horizontal, inclined, and vertical 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 principally in an area close 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.

In the horizontal and inclined pipe sections the chord averaged concentration profiles for coarse-grained mixtures can be divided in three parts: the zero concentration region in the upper portion of the pipe, a nearly linear concentration distribution in the central portion of the pipe, and a region near the pipe invert, where concentration reached a maximum.

The effect of pipe inclination on local concentration distribution is not significant for lower values of inclination angle α (up to about 30°), especially in the upper and central portion of the pipe. The zero concentration region increases for descending flow direction with decreasing mixture velocity and mean transport concentration. Local concentration at the pipe bottom slightly decreased with increasing velocity; this effect increased with increasing inclination angle.

The zero concentration region for descending flow is bigger than that for the ascending flow direction. In descending pipe sections the local concentration near lateral walls of the pipe was slightly less than that in the ascending pipe sections.

The concentration maps confirmed that the in situ concentration reached higher values in the ascending section than in the descending section. In the vertical ascending pipe section the maximum concentration was located in an annulus from about $h = 0.15 D$ to $h = 0.30 D$, contrary to the descending pipe section, where the local concentration reached its maximum in the central portion of the pipe.

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