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LOCAL CONCENTRATION DISTRIBUTION OF SETTLING SLURRY FLOW IN INCLINED PIPE SECTIONS

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Freight pipelines often contain inclined sections affecting the minimum velocity at which the pipelines should operate without a danger of pipe blockage. Narrow-graded sand-water slurry was investigated on an experimental pipe loop with inclinable pipe sections of inner diameter 100 mm in the Institute of Hydrodynamics in Prague. The investigation was focused on the effect of the pipe inclination, slurry concentration and velocity on the local concentration distribution and deposition limit. The settling slurries tend to stratify in horizontal and inclined pipe sections, typically exhibiting partial or fully stratified flow. Visualization and local concentration measurements revealed the stratified flow pattern of the settling slurry in inclined pipe sections. The solids distribution varied considerably with the pipe inclination, the degree of stratification was sensitive to pipe inclination and depended on slurry concentration and flow velocity. The observed concentration profiles showed different degrees of stratification for the positive and negative slope of the pipe. The ascending flow was less stratified than the corresponding descending flow.

KEY WORDS: settling slurry, concentration distribution, pipe inclination, deposition limit.

1. INTRODUCTION

Settling slurries tend to stratify in horizontal and in inclined pipe sections. The solids distribution expressed as a profile of local volumetric concentration is sensitive to pipe inclination and is different in ascending and descending pipe sections. Pipe inclination induced change in the slurry internal structure, mainly variation in the solids distribution in a pipe cross section, and consequently changes of mutual velocities of conveyed particles and carrier liquid, and of particles and the pipe wall. However, the effect of pipe inclination is insufficiently documented experimentally and/or described by theoretical models.

Freight pipelines often contain inclined sections that affect the operational velocity at which the pipeline systems should operate with optimal energy consumption, and without a danger of pipe blockage and/or extreme pipe wear. Operational velocity, slurry concentration, and pressure drops are the most important parameters for transport pipelines design and operation. A number of theoretical and experimental studies have been carried out on transport of sand or fine particles in horizontal pipes. From mid 1970s physically based models, generally called the layered models, exist (Shook and Roco, 1991; Wilson,

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1976; Wilson et al., 2006). Unfortunately, the effect of pipe inclination on flow of settling slurries has not received an adequate attention up to now.

To obtain experimental data suitable for verification of a newly introduced computational model of partially stratified slurry flow with an interfacial shear layer in inclined pipes (Matousek et al., 2018) the sand-water slurry was investigated in our test loop of internal diameter $D = 100$ mm with inclinable measuring sections.

In the paper we discuss results of experimental investigation of the effect of pipe inclination on the solid particles distribution at slurry velocities close to the deposition limit velocity V_D, which was defined as velocity at which the conveyed particles stop moving and a deposit layer, called the bed, starts to be formed at the pipe invert. The bed slides along the pipe wall at velocities above the deposition limit and forms a stationary deposit below the deposition limit velocity. The bed is an important contributor to the frictional pressure drops in settling slurry flow. Friction losses of settling slurries flow are strongly dependent on the concentration distribution; unfortunately the experimental data containing measured solid distributions, especially in vertical and inclined pipes, are extremely scarce in the literature (Matousek et al., 2018; Vlasak et al, 2017).

2. EXPERIMENTAL EQUIPMENT AND MATERIAL

The experimental investigation of the settling slurry flow was carried out on an experimental pipe loop of inner diameter D = 100 mm with the horizontal [A], inclinable [B], and short vertical [C] pipe sections (see Figure 1) in the Institute of Hydrodynamics in Prague (Vlasak et al., 2017; 2019b). The investigation was focused on the effect of the pipe inclination, overall concentration and average slurry velocity on the local concentration distribution and deposition limit velocity. Measured slurry was prepared in a mixing tank [1] and pumped by a centrifugal slurry pump GIW LCC-M 80-300 [2] with variable speed drive Siemens 1LG4283-2AB60-Z A11 [3].

Slurry flow was measured simultaneously in the ascending and the descending legs of the inclinable U-tube at inclinations α varying from – 45° to + 45°.The U-tube was used to determine the volumetric transport concentration C_d, local in situ concentration distribution was studied with the application of gamma-ray densitometers controlled by a computer. The slurry flow-behaviour and deposition limit velocity V_D were investigated in a transparent viewing pipe sections [7] situated on the end of each leg of the inclinable pipe section [B]. The pressure drops were measured by the differential pressure transducers Rosemount 1151DP transmitters [8], slurry velocity was measured by a Krohne OPTIFLUX 5000 magnetic flow meter [9].

The loop is equipped with two gamma-ray density meters [10] placed on a special supports controlled by the computer. They consist of a γ-ray source (Caesium ^{137}Cs, activity 740 MBq) and of a detector (a scintillating crystal of NaI(Tl)). A multi-channel digital analyser enables an evaluation of the energy spectrum of the detected signal. The measuring time period of 16 seconds was used to sense the local concentration at each position (Krupicka and Matousek, 2014; Vlasak et al., 2014).

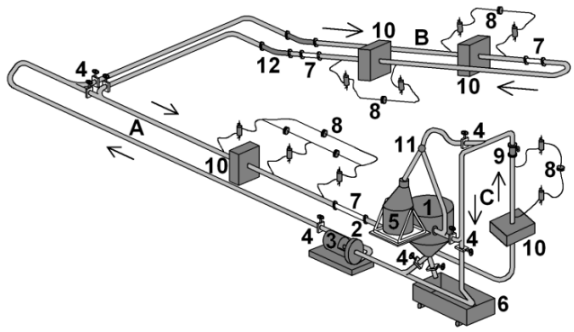

Figure 1. Experimental test loop D = 100 mm (Institute of Hydrodynamics CAS, Prague)

The studied slurry consisted from narrow-graded silica sand SP0612 (mean particle diameter 0.87 mm, density ρ_s = 2 620 kg/m^3) and water. Values of the Archimedes number Ar were determined from 13,000 to 18,000. The experiments were carried out for three overall volumetric transport concentration C_d (11%, 25%, and 35%), thus completing an area of upward slope data covered by Spelay et al. (2016).

3. LOCAL CONCENTRATION

Effect of pipe inclination on concentration distribution was confirmed by measurement of concentration profiles, $c_v(y)$. The solids distribution considerably varies with the pipe inclination. From a comparison of the concentration profiles in ascending and descending pipe sections, the different structure of the flow and the influence of the slope of the pipe on the balance between the resisting of conveyed particles and stress produced by the flow of carrier liquid are obvious (Wilson, 1976; Wilson et al., 2006).

A layered structure is typical flow pattern for a settling slurry flow in horizontal and inclined pipe sections. The visualization and local concentration measurements revealed the stratified flow pattern of the measured sand-water slurry in horizontal and inclined pipe sections. The degree of stratification is sensitive to pipe inclination and depended on mean slurry concentration C_v and slurry velocity V.

The effect of the pipe inclination on the shape of concentration profiles is illustrated in Figure 2 for slurry volumetric concentration C_v = 0.25 and slurry velocities V slightly above deposition limit V_D. The shapes of the concentration profiles indicate the partially stratified flow with different degrees of stratification for the positive and negative slope of the pipe; the degree of stratification varied with the inclination angle, decreasing with increasing angle of inclination. For the less inclined pipe sections and slurry velocity close to deposition limit the measured slurry flow was fully stratified at negative slopes $\alpha = -35°$ and $-25°$, and became less stratified for the pipe inclination from $\alpha = -15°$ to +45°. For the steeper negative slopes slurry stratification was strongly decreased by the axial component of the gravity force and the flow pattern did not exhibit any bed. For pipe inclination $\alpha \approx \pm 45°$ no bed was observed in both ascending and descending pipe sections, see Figure 2. The local concentration c_v in the upper part of the pipe increases, more pronounced in the ascending than in the descending pipe section.

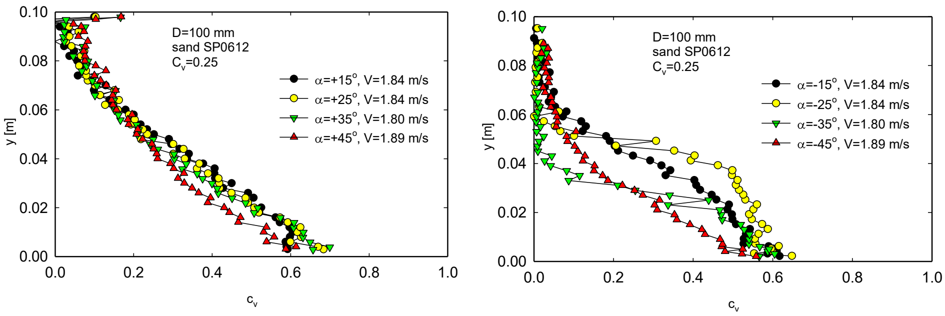

Figure 2. Effect of the pipe inclination α on local concentration profiles, $C_v = 0.25$

Similar trend was observed for different slurry concentration, $C_d = 0.11$ and 0.35 (see Figure 3). For slurry concentration $C_v = 0.11$ and the descending pipe section at flow velocities under the deposition limit V_D the difference between the shape of the concentration profiles was relatively small, stratification increased with increasing negative inclination. For descending pipe the solid particles concentrated in the layer near the pipe bottom and moved more quickly due to joint effect of the carrier liquid flow and an axial component of the gravitational force. For the slope $\alpha \geq -35°$, the concentration profiles were probably already influenced by the sedimentation of sand particles in the horizontal and ascending pipe sections and due to the reduction of the transport concentration no stationary bed was observed.

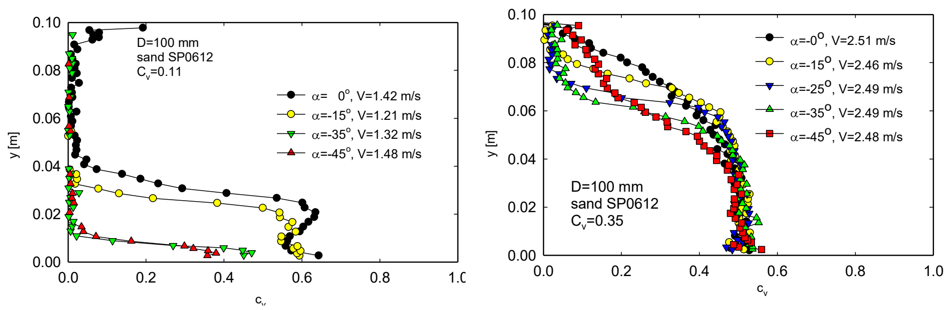

Figure 3. Effect of the pipe inclination α on local concentration profiles, Cv = 0.11 and Cv = 0.35

For slurry concentration $C_v = 0.35$ and velocity $V \approx 2.5$ m/s, i.e. above the deposition limit V_D, the concentration profiles in the ascending pipe were similar to $C_v = 0.25$, only relatively more flat and less stratified than the corresponding descending flow. For descending pipe, the stratification increased with increasing negative inclination up to value about $\alpha \approx -35°$, for pipe inclination $\alpha = -45°$ the degree of stratification became less.

Difference between ascending and descending flows is illustrated in Figure 4 for different flow velocities V and constant positive and negative couple of inclination angle α. For low inclination angle $\alpha = \pm 15°$ and velocity $V < V_D$ a bed deposit was observed in both ascending and descending pipe sections. Local concentration c_v in a bed layer in the descending pipe reached lower values than those in the ascending pipe ($c_v \approx 0.50$ instead 0.60). For velocity $V > V_D$ a sliding bed was observed in both, ascending and descending pipe sections. No deposit was observed for inclination angles $\alpha > +25°$ in the ascending pipe. It was confirmed that the effect of pipe inclination on concentration distribution for low values of inclination angle α was not significant, similarly as for pressure drops (Vlasak et al., 2014; 2016; 2017; Spelay et al., 2016).

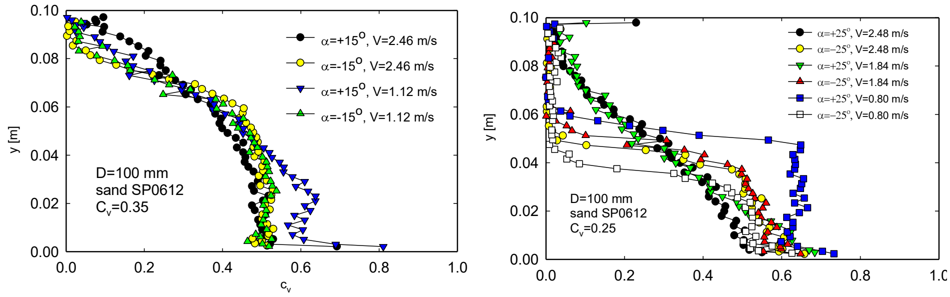

Figure 4. Effect of mean slurry velocity V on local concentration profiles for given inclination α

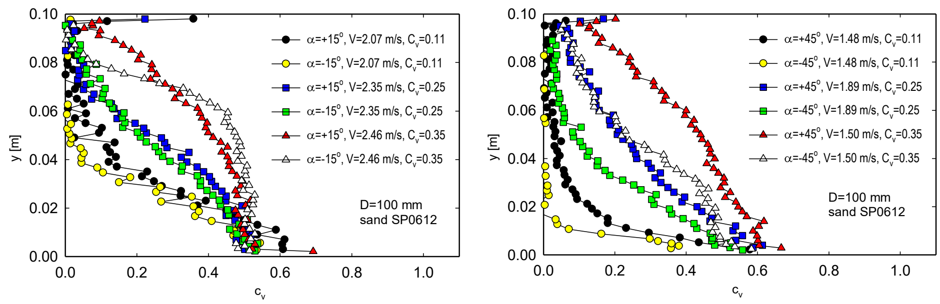

Figure 5. Effect of the mean slurry volumetric concentration C_v on local concentration profiles

The influence of the mean slurry volumetric concentration C_v on the chord-averaged concentration profiles is illustrated in Figure 5 for different pipe inclination α and slurry flow velocity V below and above deposition limit V_D. The graphs document decrease of the degree of stratification with increasing slurry concentration C_v and pipe slope α.

The shape of the concentration profiles is highly dependent on the slurry velocity; for gentle pipe slope ($\alpha = \pm 15°$) and the slurry velocity V higher than the deposition limit V_D we could observe a bed layer with local concentration around $c_v \approx 0.55$ for mean slurry concentrations $C_v = 0.35$, and $c_v \approx 0.40$-0.50 for lower mean concentrations. For velocities below deposition limit V_D the local concentration in the bed layer decreases for both branches. For higher pipe slopes ($\alpha > \pm 35°$), the bed layer originated in the descending branch. For the ascending branch stratification of the suspension is smaller than for descending branch, and it decreases with increasing slurry concentration.

4. DEPOSITION LIMIT

The conducted experiments confirmed that the solids distribution in stratified slurry flow considerably varies with the pipe inclination. Determination of deposition limit velocity V_D in stratified slurry flow is rather difficult and complicated, because the flow is usually unstable near the deposition limit. The most often used method of deposition limit velocity determination is a visual observation of a deposit formation in a transparent pipe section. To determine the slurry velocity at which stationary deposit starts to be formed we applied camera system. Unfortunately, when for slurry velocity V approached region close to the value of deposition limit velocity V_D the slurry flow became very unstable, especially for higher concentration. Even concentration waves were observed. The velocity range for which a stationary bed was developed was relatively broad, since the deposit repeatedly interrupted and start sliding - we call this behaviour a „caterpillar behaviour“ of the sliding bed.

To reduce uncertainty of V_D determination we combined visual observation with measurement of local concentration, c_{v10}, in the layer at a height of y = 10 mm above the pipe invert to identify the velocity value at which a bed forms at the invert of the pipe (i.e. gamma-ray measurement). A typical result of a c_{v10} test run is shown in Figure 6. The measurement started at the flow velocity V higher than the deposition limit, and then V was gradually decreased during the test run. The local concentration c_{v10} gradually increased until the flow velocity decreased to value close to the deposition limit. Near the deposition limit, local concentration c_{v10} suddenly increased and reached a value typical for the sliding or stationary bed (approximately 0.55 - 0.60) when a stable deposit was formed at velocities below V_D (Matousek et al., 2019; Vlasak et al., 2019a). The results of radiometric method agree rather well with visual observations if the flow is steady and stable, difference was less than 10%. The variation of local concentration c_{v10} illustrated concentration waves in flow regime with slurry velocity above the deposition limit.

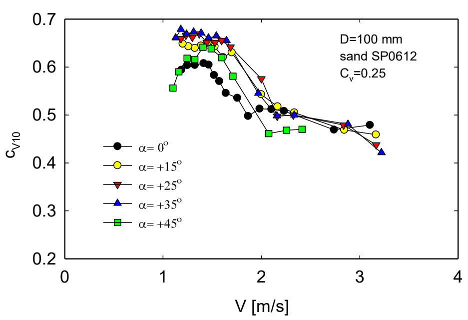

Figure 6. Effect of the flow velocity V on local in situ concentration c_{v10}

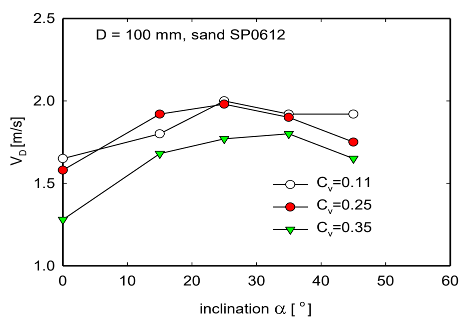

Figure 7. Effect of the pipe inclination α and concentration C_v on deposition limit V_D

From the experimental data (see Table 1 and Figure 7) it is obvious that the deposition limit velocity V_D in the ascending pipe was higher than in the horizontal pipe. Deposition limit V_D in the ascending pipe section increased in range of inclination angle α = 0° and

+25°, then remained practically constant on value about 1.25 times higher than that in the horizontal pipe. This is fully consistent with Wilson and Tse (1984) results, which indicate that deposition limit V_D can increase up to 50% for coarse materials (sand and gravel with mean diameter d_{50} from 1.1 to 5.8 mm). De Hoog et al. (2017) verified a usefulness of the Wilson-Tse nomogram for three gravel fractions (d_{50} from 4.6 to 12 mm) and found the maximum V_D at the pipe inclination of about 30°. On the contrary, in the descending pipe, the deposition limit values decreased significantly with the increasing negative slope and tended to zero for inclination angles exceeding say value $\alpha \approx - 30°$, where no stationary bed was observed. For such flow pattern, particles in sliding bed were driven downward predominantly by the submerged weight.

Table 1

Deposition limit velocity V_D, SP0612, $C_d = 0.25$

Deposition limit velocity VD [m/s]						
inclination α [°]	measurement	0	15	25	35	45
concentration Cv = 0.11	gamma-ray	1.65	1,80	2.00	1.92	1.92
concentration Cv = 0.25	gamma-ray	1.58	1.92	1.98	1.90	1.75
concentration Cv = 0.25	visual	1.56	1.79	1.82	1.84	1.81
concentration Cv = 0.35	visual	1.28	1.68	1.77	1.80	1.65

5. CONCLUSIONS

The effect of pipe inclination α, overall slurry concentration C_v and mean velocity V on flow behaviour, concentration distribution c_v *(y)* and deposition limit velocity V_D of narrow-graded medium to coarse sand SP0612 (mean diameter $d_{50} = 0.87$ mm) and water slurry was studied in an experimental pipe loop of inner diameter D = 100 mm. The measurement of local concentration and visualization revealed the stratified flow pattern of the slurry in inclined pipe sections.

The chord-averaged concentration profiles showed different degrees of stratification for the positive and negative pipe inclination. Concentration profiles tended to become less stratified in an ascending pipe with increasing inclination angle. In a descending pipe the flow tended to be more stratified if inclination changes from horizontal to value about – 35°, then stratification slowly decreased.

The mean in situ concentration for descending flow was always lower than that for the ascending flow. For inclination angle α lower than about ± 25° the effect of pipe inclination on local concentration distribution was not significant. The concentration profiles showed different degrees of stratification for the positive and negative slope of the pipe. For slurry velocity near and above the deposition limit the ascending flow was less stratified than the corresponding descending flow, the degree of stratification decreased with increasing angle of inclination.

Deposition limit velocity was sensitive to the pipe inclination α. The maximum deposition limit value was reached for an inclination angle α about + 25°, and then the deposition limit remains practically constant. Deposition limit V_D reached slightly higher values in the ascending pipe sections than in the horizontal pipe. For descending pipe sections the deposition limit V_D gradually diminishes and tends to zero for inclination angles exceeding values about $\alpha = - 30°$.

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