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EFFECT OF PIPE INCLINATION ON LOCAL CONCENTRATION AND FLOW BEHAVIOUR OF SETTLING SLURRY

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Abstract: *Settling slurry, consisted from narrow-graded sand of mean particle diameter 0.87 mm and water, was investigated on an experimental pipe loop of inner diameter 100 mm. The investigation was focused on the effect of the pipe inclination, slurry concentration, and velocity on concentration distribution, and deposition limit. The settling slurries tend to stratify; a layered structure is typical for a settling slurry flow. Slurry stratification is sensitive to pipe inclination, and differs for the positive and negative pipe inclination. Deposition limit increases with pipe inclination up to about 25°, and then remain nearly constant.*

Keywords: Sand-Water Slurry, Pipe Inclination, Concentration Distribution, Deposition Limit.

1. Introduction

Freight pipelines often contain inclined sections and the pipe inclination affects the slurry flow behaviour and 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. Pipe inclination induced change in the slurry internal structure, mainly variation in the distribution of solids in a pipe cross section, and changes of mutual velocities of conveyed particles and carrier liquid, and of particles and the pipe wall. Many theoretical and experimental studies have been carried out on transport of sand or fine particles in horizontal pipes. Unfortunately, the effect of pipe inclination on flow conditions of settling slurries has not received an adequate attention up to now and the experimental data containing measured solids distributions are extremely scarce in the literature.

To obtain experimental data suitable for verification of newly introduced computational model of partially stratified slurry flow with an interfacial shear layer in inclined pipes (Matousek et al., 2018) the medium to coarse sand-water slurry was investigated. In the paper we discuss results of experimental investigation of the effect of pipe inclination on the solid particles distribution in pipe cross-section at mean slurry flow velocities close to the deposition limit velocity. The deposition limit velocity V_D 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.

2. Experimental Equipment and Material

The settling slurry flow was investigated on an experimental pipe loop of inner diameter 100 mm with the horizontal and inclinable pipe sections in the Institute of Hydrodynamics in Prague (Vlasak et al., 2017,

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2019). 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. 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 inclinable 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 pipe viewing sections. The pressure drops were measured by Rosemount 1151DP transmitters, slurry velocity was measured by a Krohne OPTIFLUX 5000 magnetic flow meter.

The studied slurry consisted from narrow-graded silica sand SP6012 (mean particle diameter 0.87 mm, density ρ_s = 2 620 kg/m^3) and water, the experiments were carried out for two overall volumetric concentration C_v (11% and 25%). Values of the Archimedes number (13,000 < Ar < 18,000) and the turbulent suspension efficiency parameter (1.15 < TSP <1.45) show that experimental data with this fraction contribute to filling the gap in the experimental database indicated by Spelay et al. (2016).

3. Local Concentration Distribution

A layered structure is typical flow pattern for a settling slurry flow in horizontal and inclined pipe sections, the degree of stratification is sensitive to pipe inclination, decreased with increasing angle of inclination α, and depend on slurry concentration and flow velocity. The visualization and local concentration measurements revealed the stratified flow pattern of the measured slurry in horizontal and inclined pipe sections. The solids distribution considerably varies with the pipe inclination.

Fig. 1 summarizes chord-averaged concentration profiles for velocities close to V_D and volumetric concentration C_v equal 0.11 and 0.25 at different pipe inclination α. 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 increasing inclination angle. In very steep flow ($\alpha \approx \pm 45°$) no bed is present in both ascending and descending pipe sections. For the less inclined pipe sections and slurry velocity close to deposition limit the measured slurry flow was fully stratified at negative slope $\alpha = -35°$ and $-25°$ and becomes less stratified for the pipe inclination from $\alpha = -15°$ to $+35°$. For the steeper slopes the degree of stratification was strongly decreased by the axial component of the gravity force and the flow pattern did not exhibit any bed. Bed layer in the descending pipe reached lower values of local concentration c_v and deposit height h than that in the ascending pipe.

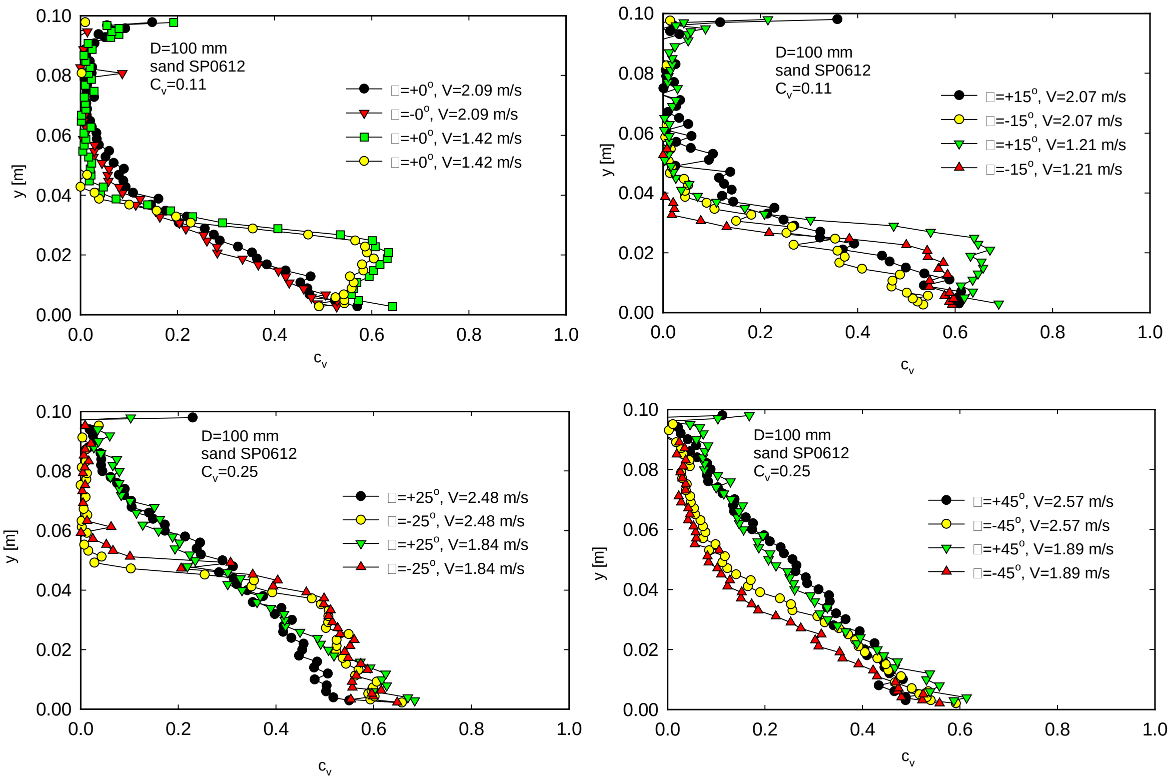

Fig 1: Effect of the pipe inclination α and slurry velocity V on local concentration profiles.

For slurry velocity V above the deposition limit V_D, the ascending flow was less stratified than the corresponding descending flow. This fact is in contradiction with the assumption of the Worster-Denny (1955) formula, which from this reason overestimates the frictional pressure gradient in an ascending pipe section.

4. **Deposition limit velocity**

The conducted experiments confirmed that the solids distribution in stratified slurry flow considerably varies with the pipe inclination. Experimental identification of deposition limit velocity V_D in stratified and partially stratified slurry is rather uphill work, because a usually unstable flow pattern near the deposition limit. The most often used method of an experimental determination of V_D is a visual observation of a deposit formation in a transparent pipe section. We applied cameras aimed on the pipe invert to determine the slurry velocity at which stationary deposit starts to be formed. Unfortunately, especially for higher concentration, when slurry velocity V approached region close to the value of V_D the slurry flow became very unsteady, even concentration waves were observed. The velocity range between velocity values for which the first particles stopped and a real stationary bed (steady state deposit) was developed was rather broad, sometimes even about 1 m/s. Into this velocity range the bed interrupted and start sliding regularly for a period of time. We call this behaviour "caterpillar behaviour" of the sliding bed. The value of deposition limit V_D was determined to a ratio roughly equal to 1 to 5 of periods of sliding bed to stationary bed.

In order to increase the accuracy of V_D and reduce uncertainty, we combine visual observation and changes of the pressure gradient versus velocity diagram with application of radiometric measurement of local concentration close to pipe invert, i.e. to trace the velocity value at which a stationary bed forms at the invert of the pipe by measurement of local in situ concentration, c_{v10}, in the layer at a height of y = 10 mm above the pipe invert to identify the deposit at the pipe invert.

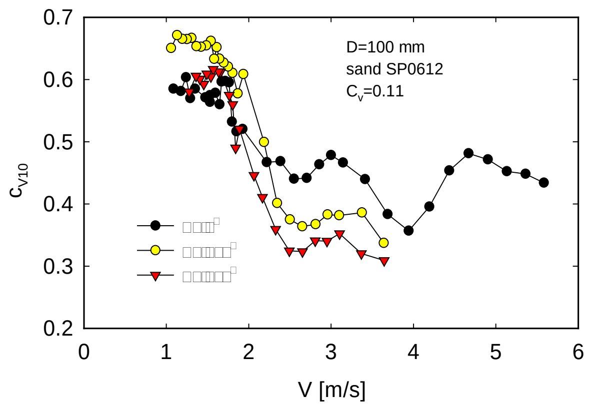

Fig. 2: Effect of the flow velocity V on local in situ concentration c_{v10}.

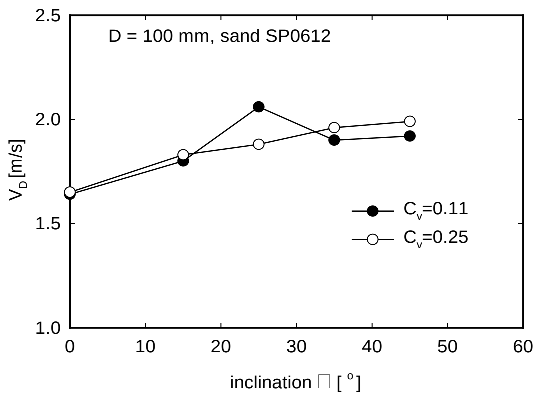

Fig. 3: Effect of the pipe inclination α and concentration C_v on deposition limit V_D.

A typical result of a c_{v10} test run is shown in Fig. 2. The measurement started at the flow velocity $V > V_D$, then V was gradually decreased during the test run. The local concentration c_{v10} increased weakly until the flow velocity close to the deposition limit was approached. Near the deposition limit, local concentration c_{v10} suddenly increased and reached a value typical for the 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., 2019). The results of radiometric method agree rather well with visual observations if the flow is steady and stable near the deposition limit velocity. The variation of local concentration c_{v10} illustrated concentration waves in flow regime with slurry velocity above the deposition limit.

From the experimental data (see Fig. 3) we can see that the deposition limit velocity V_D is sensitive to the pipe inclination; in the inclined pipes it was higher than in the horizontal pipe. Deposition limit V_D in the ascending pipe section increases with an inclination angle α between 0° and 25°, then for higher pipe inclination remains practically the same and for the measured SP6012 sand slurry reached value up to 1.25 times higher than 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 velocity decreased significantly with the increasing negative slope and tended to zero for inclination angles exceeding say $\alpha = -30°$. For inclination angle over $\alpha \approx -30°$ no stationary bed was observed. For such steep negatively sloped flows particles are driven downward predominantly by the submerged weight.

5. Conclusions

The presented investigation of narrow-graded medium to coarse sand (particle mean diameter 0.87 mm) and water slurry, conducted in an experimental pipe loop of inner diameter D = 100 mm, was focussed on the effect of pipe inclination α, overall slurry concentration C_v and mean velocity V on slurry flow behaviour, concentration distribution $c_v(y)$ and deposition limit velocity V_D.

The visualization and local concentration measurements revealed the stratified flow pattern of the studied slurry in horizontal and inclined pipe sections. The solids distribution in the tested slurry flow was very sensitive to the pipe inclination. The measured chord-averaged concentration profiles showed different degrees of stratification for the positive and negative pipe inclination.

For slurry velocity above the deposition limit the ascending flow was less stratified than the corresponding descending flow, the degree of stratification decreased with increasing slurry velocity and angle of inclination.

Difference between ascending and descending flow increased from horizontal flow up to about inclination angle α = 30°. The mean in situ concentration for descending flow was always lower than that for the ascending flow. The local concentration in the bed layer decreased with increasing mean slurry velocity and decreasing pipe inclination angle.

Deposition limit velocity V_D was sensitive to the pipe inclination, V_D reached higher values in the inclined pipes than in the horizontal pipe, the maximum deposition limit value was reached for an inclination angle α about + 25°, then the deposition limit remains practically constant. For negative pipe inclination the deposition limit gradually diminishes and tends to zero for inclination angles exceeding say – 30°.

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