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Concentration distribution and deposition limit of medium-coarse sand-water slurry in inclined pipe

Pavel Vlasák*, Václav Matoušek, Zdeněk Chára, Jan Krupička, Jiří Konfršt, Mikoláš Kesely

Institute of Hydrodynamics of the Czech Academy of Sciences, v. v. i., Pod Patankou 30/5, 160 00, Prague 6, Czech Republic.
*Corresponding author. Tel.: +420 233109092. E-mail: vlasak@ih.cas.cz

Abstract: Sand-water slurry was investigated on an experimental pipe loop of inner diameter D = 100 mm with the horizontal, inclined, and vertical smooth pipe sections. A narrow particle size distribution silica sand of mean diameter 0.87 mm was used. The experimental investigation focused on the effects of pipe inclination, overall slurry concentration, and mean velocity on concentration distribution and deposition limit velocity. The measured concentration profiles showed different degrees of stratification for the positive and negative pipe inclinations. The degree of stratification depended on the pipe inclination and on overall slurry concentration and velocity. The ascending flow was less stratified than the corresponding descending flow, the difference increasing from horizontal flow up to an inclination angle of about +30°. The deposition limit velocity was sensitive to the pipe inclination, reaching higher values in the ascending than in the horizontal pipe. The maximum deposition limit value was reached for an inclination angle of about +25°, and the limit remained practically constant in value, about 1.25 times higher than that in the horizontal pipe. Conversely, in the descending pipe, the deposition limit decreased significantly with the negative slopes and tended to be zero for an inclination angle of about −30°, where no stationary bed was observed.

Keywords: Sand-water slurry; Pipe inclination; Concentration distribution; Deposition limit; Gamma-ray radiometry.

INTRODUCTION

Hydraulic transport is well-known as a technically feasible and economically attractive method of transporting large volume commodities; it is commonly used in the dredging, building, energy and mining industries, and tailings disposal operations, and in different industrial applications for the transport of bulk materials. Transport pipelines often contain inclined sections, as they have to overcome different terrain irregularities. Despite the fact that published pipeline design guidelines recommend maximum upward inclinations of 25°, it is not always possible for designers to follow these guidelines (Spelay et al., 2016).

Lack of information concerning slurry flow in inclined pipe sections has caused engineers to design them with extreme caution and practice transportation with uncertainty. Extra safety factors have been thrown into the system design to avoid possible problems during operation, start-up, and shutdown. This is reflected by efforts to use gentle slopes in the pipeline designs. This will mean greater construction costs and capital expanses for freight pipeline systems over relatively rugged terrain in mountainous or urbanized and industrial areas (Kao and Hwang, 1979).

For settling slurry, pipe inclination considerably affects behavior, flow structure, and energy consumption. Settling slurries tend to stratify; the degree of stratification is sensitive to the pipe inclination and affects the pressure drops and deposition limit velocity. The deposition limit velocity is the minimum operational velocity at which the pipe should safely operate without danger of blockage. It is defined as the flow velocity at which the conveyed particles fall out of the mixture and stop moving and at which a stationary deposit, called the bed, starts to form at a pipe invert. The deposition limit velocity is affected by the solid concentration, mean flow velocity, and the physical properties of the solids, liquids, and pipe (Parzonka et al., 1981; Sobota and Plewa, 2000; Wilson et al., 2006).

Compared to the horizontal flow, the inclined flow produces an additional force (a component of the submerged weight of grains) that acts either against the direction of the flow (an ascending pipe) or in the same direction (a descending pipe) (Matousek et al., 2018b).

Flow of heterogeneous slurry in inclined pipelines should receive broader attention and stimulate interest in research to obtain design criteria for the transportation of solid particles and accuracy of energy loss correlation equations. Considerable work has been done on test systems composed of horizontal pipes, as well as on vertical pipes for hydraulic hoisting of solids. However, comparatively little work has been conducted on slurry systems involving sloping pipes. The effect of pipe inclination on flow conditions of settling slurries has not received adequate attention up to now (Kao and Hwang, 1979).

Slurry flow behavior, concentration distribution, slip velocity, and pressure drops in ascending and descending pipe sections are distinctly different. Because of the changing solid concentration and the solid and liquid phases' velocity distributions and due to the effect of gravitational force acting on the solid particles, the critical operational conditions in inclined pipes are different from that observed in horizontal pipes.

The pipe inclination induces change in the internal slurry structure, primarily the variation in the solid's distribution in a pipe cross section, and effects the Coulombic (sliding bed) friction and, consequently, the frictional pressure drops, the behavior of the pipeline during unsteady flows (shutdown or start-up), the deposition limit velocities, and the degrees of stratification (Doron et al., 1997; Matousek et al., 2018a; Spelay et al., 2016; Wilson et al., 2006). The internal structure of an ascending slurry flow differs from that of a descending one, the difference being greater for coarse particles than for fine particles because of the greater submerged weight of the bed at the bottom of the pipe (Matousek, 1996).

The effect of inclination on frictional pressure drops can be explained using the layered models. Layered models are based on principles formulated originally by Wilson (1976) and are expressed as force balances applied to layers of stratified flow. The layered models exist in different versions for fully or partially stratified flows and some have been adapted to inclined flows (Doron, et al. 1997; Matousek, 1996; Matousek et al., 2018a; Messa et al., 2018; Shook and Roco, 1991; Wilson et al., 2006). Wilson used his early version of the two-layer model for horizontal fully stratified flow to calculate the deposition velocity from the force balance on the bed at the slip point (i.e. at the condition where the bed stops sliding). Later, Wilson and Tse (1984) applied the Durand parameter

$$F = V_D \,/\, [2g\, D\, (\rho_s - \rho_w).\, /\, \rho_w]^{1/2} \qquad (1)$$

to express the effect of pipe inclination α on deposition limit V_D as

$$\Delta F = F_\alpha - F_0, \qquad (2)$$

where F_α and F_0 is Durand parameter for the inclined and horizontal pipe section, respectively. In the Durand parameter, V_D is the deposition limit velocity; g is the gravitational acceleration; ρ_s and ρ_w is the density of solids and carrying liquid, respectively; and D is the pipe diameter. Durand presented an empirical nomogram of dependence of parameter F on slurry concentration C_v and medium grain size d_{50} (Durand and Condolios, 1952).

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., 2018a) the sand-water slurry was investigated in a 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. 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. Matousek and Zrostlik (2018) dealt with the effect of the longitudinal component of the solids' weights in the bed layer and distinguished between contributions of contact solids, suspended solids, and those carrying liquid to the pressure drops in a partially stratified flow. Friction losses of the settling slurries' flows are strongly dependent on the concentration distribution; unfortunately, experimental data containing measured solid distributions, especially in vertical and inclined pipes, are extremely scarce in the literature (Matousek et al., 2019a; Vlasak et al., 2017, 2019a).

EXPERIMENTAL EQUIPMENT AND MATERIAL

The experimental investigation 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 in the Institute of Hydrodynamics of the CAS in Prague (Vlasak et al., 2017, 2019a). The loop was made from smooth, stainless steel pipes; its total length was 93 m, see Fig. 1. 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. Slurry flow was measured simultaneously in the ascending and descending branches of the inclinable U-tube at slopes α, varying from –45° to +45°. Measured slurry was prepared in a mixing tank (1) and pumped by a centrifugal slurry pump GIW LCC-M 80-300 (2) with a variable speed drive Siemens 1LG4283-2AB60-Z A11 (3).

The inclinable U-tube in a vertical position was used to determine the volumetric transport concentration C_d, using a method proposed by Clift and Clift (1981). Local in situ concentration distribution was studied with the application of gamma-ray densitometers controlled by a computer. The slurry flow behavior and deposition limit velocity V_D were investigated in transparent viewing pipe sections (7).

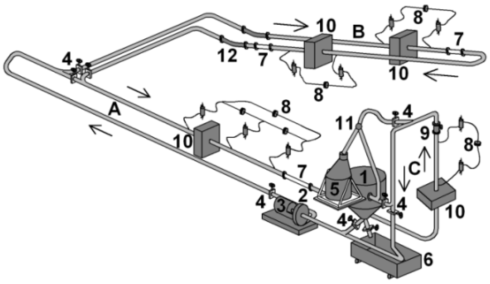

Fig. 1. Experimental test loop D = 100 mm (Institute of Hydrodynamics CAS, Prague).

The pressure drops were measured by Rosemount 1151DP differential pressure transducers (8), and slurry velocities were measured by a Krohne OPTIFLUX 5000 magnetic flow meter (9) mounted in the short vertical section (C). The flow divider (11) and the sampling tank (5) allow for measuring of the flow rate and delivered concentration. For easier operation, the loop is also equipped with slide valves (4) and a slurry output tank (6). Measurements were taken simultaneously in the ascending and descending branches of the loop from maximum values, $V_{max} \approx 3.0$ m/s, to values $V_{min} \approx 1$ m/s.

Based on the law of the gamma radiation absorption, a time-averaged slurry density was determined along a set of horizontal chords, and a density (or concentration) profile along the vertical axis of the pipe was determined. This method was introduced by Michalik (1973) and Przewlocki et al. (1979). The loop was equipped with two gamma-ray density meters (10) placed on a special support and controlled by a computer. The support served as the vertical linear positioning of both the source and the detector to measure the chord-averaged vertical concentration profiles. They consisted 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 analyzer enabled the 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).

The studied slurry consisted of narrow-graded silica sand SP0612 (mean particle diameter d_{50} = 0.87 mm, density ρ_s = 2 620 kg/m^3) and water. Values of the Archimedes number

$$Ar = 4g\rho_w \,.\, (\rho_s - \rho_w).\, d_{50}{}^3 \,/\, (3\mu_w{}^2) \qquad (3)$$

were determined from 13,000 to 18,000, and the turbulent suspension efficiency parameter

$$\mathrm{TSP} = (w \,/\, u_{*w,\,D}).\, \exp\,(d_{50} \,/\, D) \qquad (4)$$

varied between 1.15 and 1.45, thus completing an area of upward slope data covered by Spelay et al. (2016). Here, μ_w is the dynamic viscosity of the carrier liquid, w is particle terminal settling velocity, and $u_{*w,\,D}$ is the friction velocity of the carrier liquid at the deposition limit velocity V_D. The experiments were carried out for three overall volumetric concentrations C_v (11%, 25%, and 35%).

CONCENTRATION DISTRIBUTION

The effect of the mean concentration, slurry velocity, and angle of pipe inclination on the local concentration distribution c_v was studied. The measured chord-averaged concentration profiles for the different overall volumetric concentrations C_v revealed the stratified flow pattern of the measured slurry in horizontal and inclined pipe sections. The solids' distribution varied considerably with the pipe inclination. The shapes of the chord-averaged concentration profiles $c_v = c_v(y)$ indicated the stratified flow with different degrees of stratification for the positive and negative pipe inclinations. The differences between ascending and descending flows are illustrated in Fig. 2 for the constant positive and negative inclination angles α for overall concentrations $C_v = 0.25$ and different flow velocities V close to V_D.

The local concentration in the ascending pipe section was always higher than that in the descending pipe section due to the effect of the axial component of the gravity force. It is also valid for vertical upward and downward flow, where the difference between the concentration values corresponds to the particle slip velocity. For the vertical pipe, a nearly constant concentration distribution was observed (see Fig. 3).

In very steep flows ($\alpha \approx \pm45°$, see Fig. 2, bottom right panel), no bed was present in both the ascending and descending pipe sections. For the less inclined pipe sections and slurry velocities close to the deposition limit, the measured slurry flow was fully stratified at negative slopes $\alpha = -35°$ and $-25°$ and became less stratified for the pipe inclination ranging from $\alpha = -15°$ to $+35°$ (Vlasak et al., 2019b).

For a low pipe inclination $\alpha = \pm15°$ and a velocity close to the deposition limit $V \approx V_D$, a bed layer was observed in both the ascending and descending pipe sections. The local concentration c_v and the deposit height h in a bed layer of the descending flow reached lower values than those in the ascending pipe ($c_v \approx 0.50$ instead 0.60, see top left panel). The local concentration c_V in a bed layer slightly decreased with increasing pipe inclination. In the direction to the pipe top, the local concentration in the central portion of the pipe gradually decreased. For velocity $V > V_D$, a sliding bed was observed in both the 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 the inclination angle α was not significant, as it is similarly valid for pressure drops (Spelay et al., 2016; Vlasak et al., 2014, 2016, 2017).

The effect of the pipe inclination was verified for two other concentrations, $C_v = 0.11$ a 0.35 (see Fig. 4 and Fig. 5) for slurry velocity V below and above the deposition limit V_D, respectively. A similar effect of the pipe inclination was found as for the slurry concentration $C_v = 0.25$. The measured profiles document an increase of slurry stratification with a decreasing slurry concentration C_v and pipe slope α.

The shape of the concentration profiles was highly dependent on the slurry velocity; for gentle pipe slope ($\alpha = \pm15°$) and the slurry velocity $V > V_D$, a bed layer with a local concentration around $c_v \approx 0.55$ was observed for higher values of overall concentrations $C_v = 0.35$ and only $c_v \approx 0.40$–0.50 for lower concentrations $C_v = 0.11$. The local concentration in the bed layer decreased for both ascending and descending branches for velocity values $V < V_D$. For the ascending branch, the slurry stratification was smaller than that for the descending branch, and this trend decreases with the increasing slurry concentration. For higher pipe slopes ($\alpha > \pm35°$), the bed layer originated in the descending branch only.

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

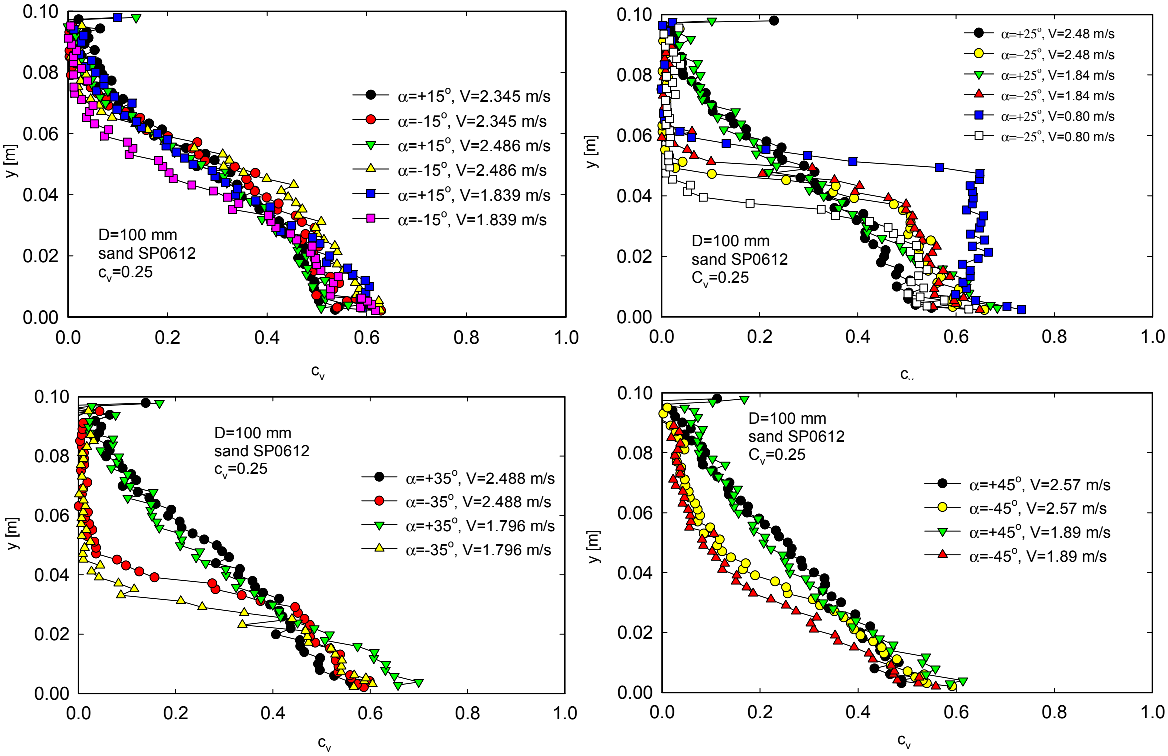

Fig. 2. Effect of the pipe inclination α and slurry velocity V on local concentration profiles, $C_v = 0.25$.

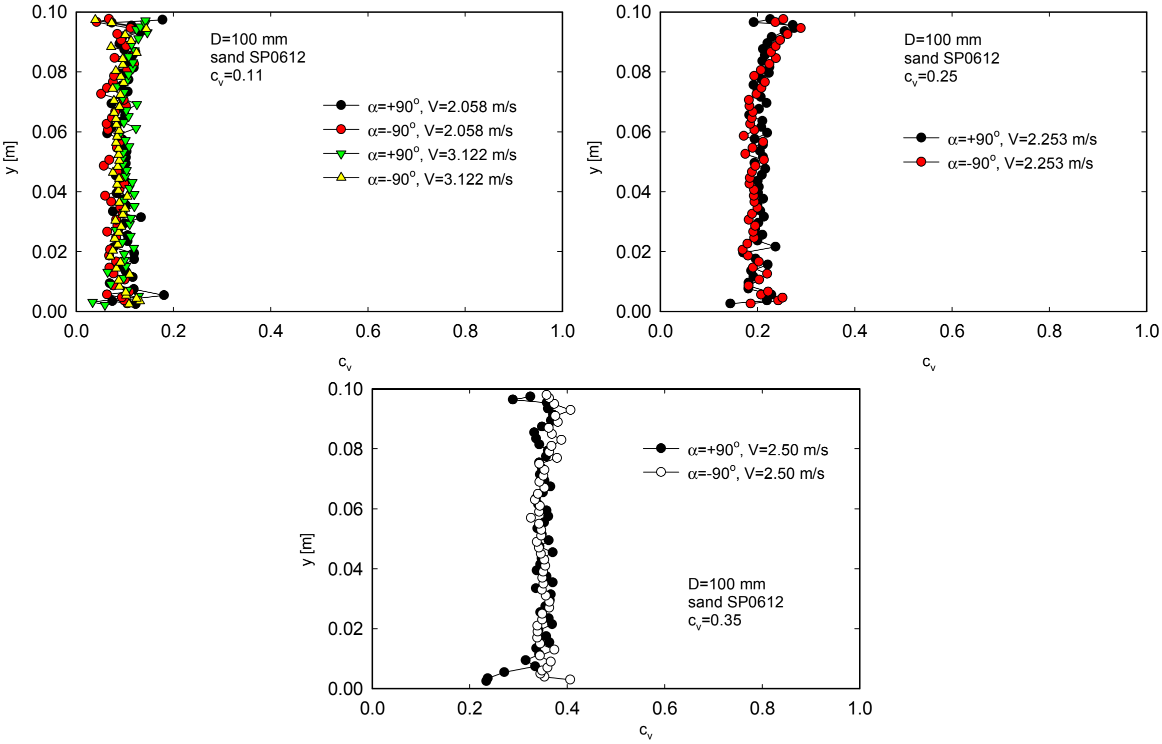

Fig. 3. Local concentration profiles in vertical pipe section.

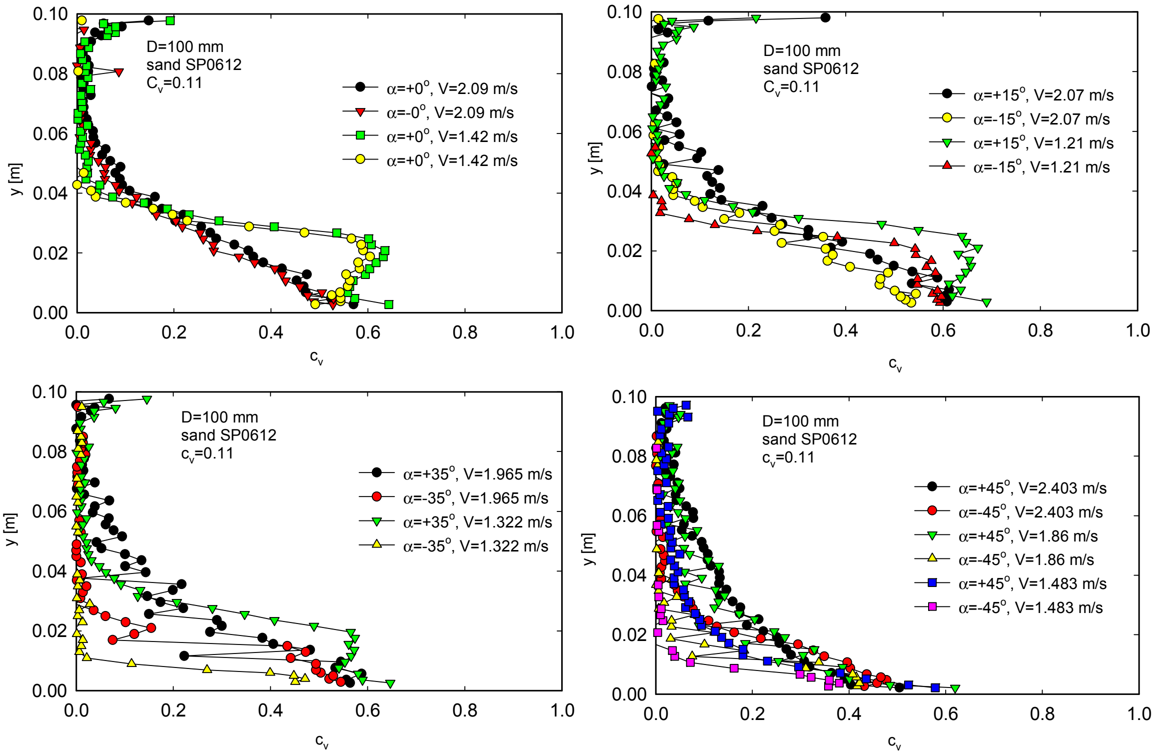

Fig. 4. Effect of mean slurry velocity V on local concentration profiles for given inclination α and $C_v = 0.11$.

inclination. For the descending pipe, the solid particles concentrated in the layer near the pipe bottom and moved more quickly due to the joint effects 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 (Vlasak et al., 2019c).

In Figs. 6–8, the chord-averaged concentration profiles, $c_v(y)$, are illustrated for different pipe inclinations α and slurry velocities V close to deposition limit V_D. The concentration profiles showed different degrees of stratification for the positive and negative pipe inclination (Krupicka and Matousek, 2014; Vlasak et al., 2016, 2017, 2018a). The degree of stratification varied with the pipe inclination, decreasing with increasing pipe inclination and slurry velocity for both the ascending and descending pipe sections. For the less inclined flow and

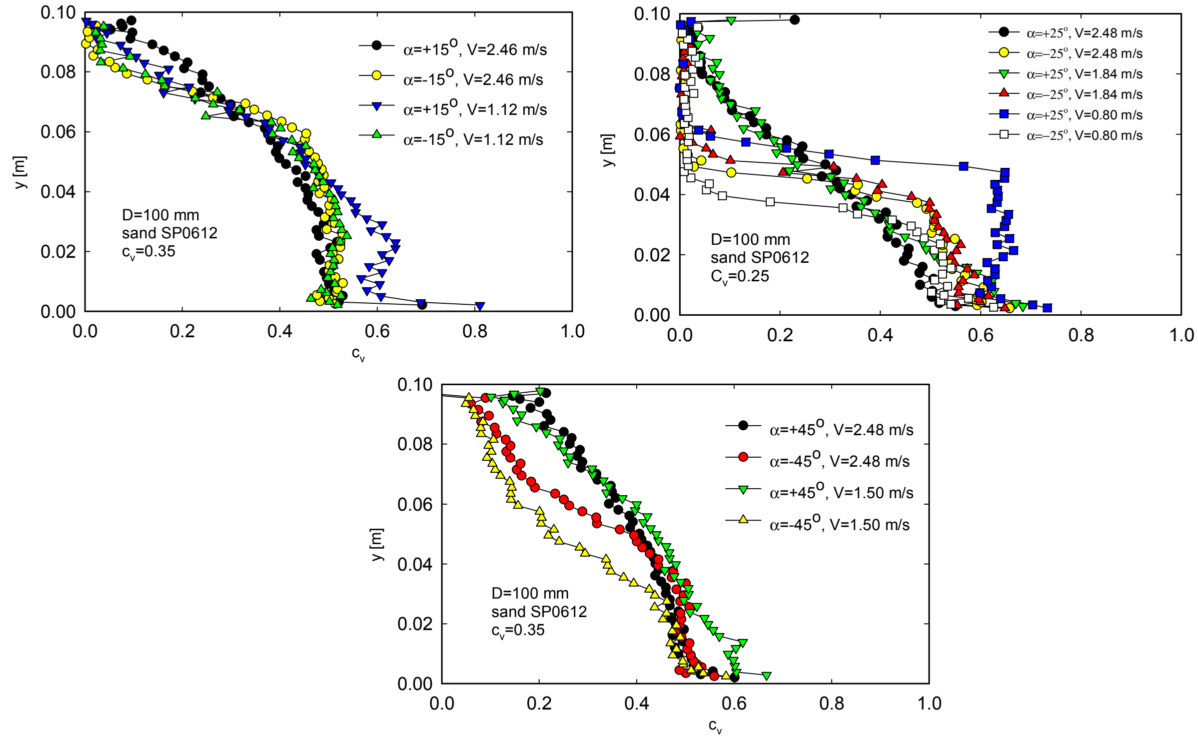

Fig. 5. Effect of mean slurry velocity V on local concentration profiles for given inclination α and $C_v = 0.35$.

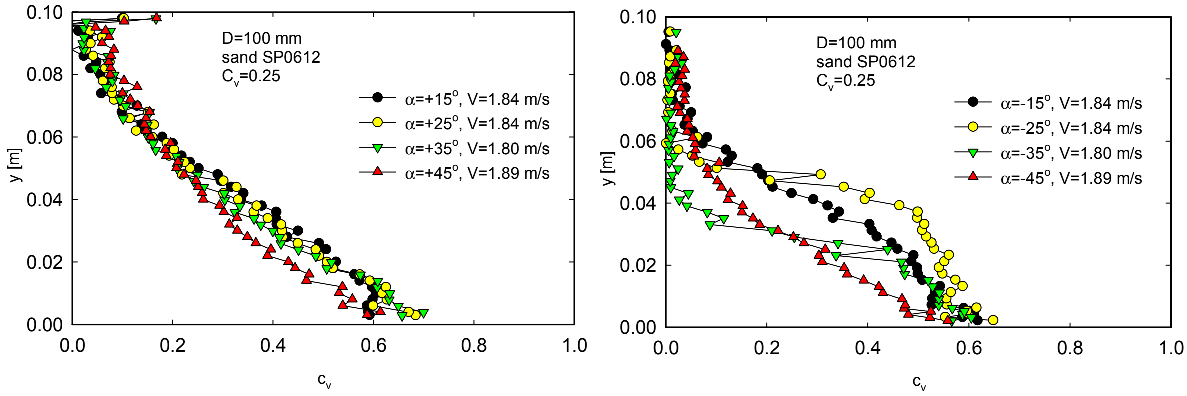

Fig. 6. Effect of the pipe inclination α on local concentration profiles for given V, $C_v = 0.25$.

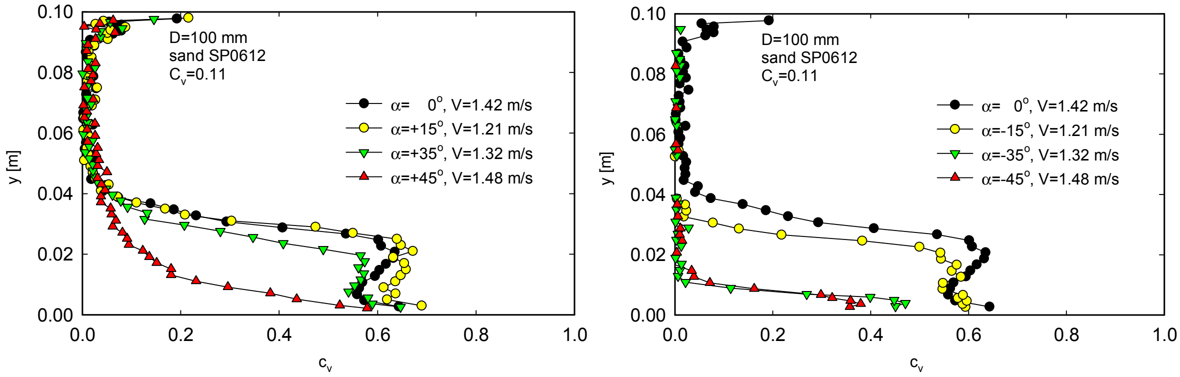

Fig. 7. Effect of the pipe inclination α on local concentration profiles for given V, $C_v = 0.11$.

slurry velocity close to the deposition limit, the slurry was fully stratified at negative slopes $\alpha = -35°$ and $-25°$ and became less stratified for the pipe inclination ranging from $\alpha = -15°$ to $+45°$. For slurry velocity $V > V_D$, the thickness of the bed layer decreased with increasing slurry velocity V.

For the steeper negative slopes, the flow did not exhibit any bed, and slurry stratification was strongly decreased due to the increasing axial component of the gravity force acting on the sand particles. For pipe inclination $\alpha \approx \pm 45°$, no bed was observed in both the ascending and descending pipe sections. The local concentration c_v in the upper part of the pipe increased, this effect is more pronounced in the ascending than in the descending flow.

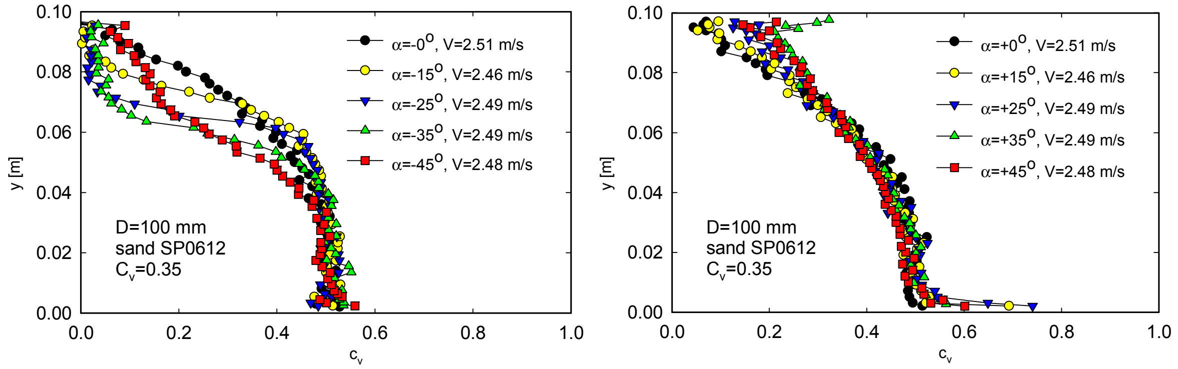

Fig. 8. Effect of the pipe inclination *α* on local concentration profiles, $C_v = 0.35$.

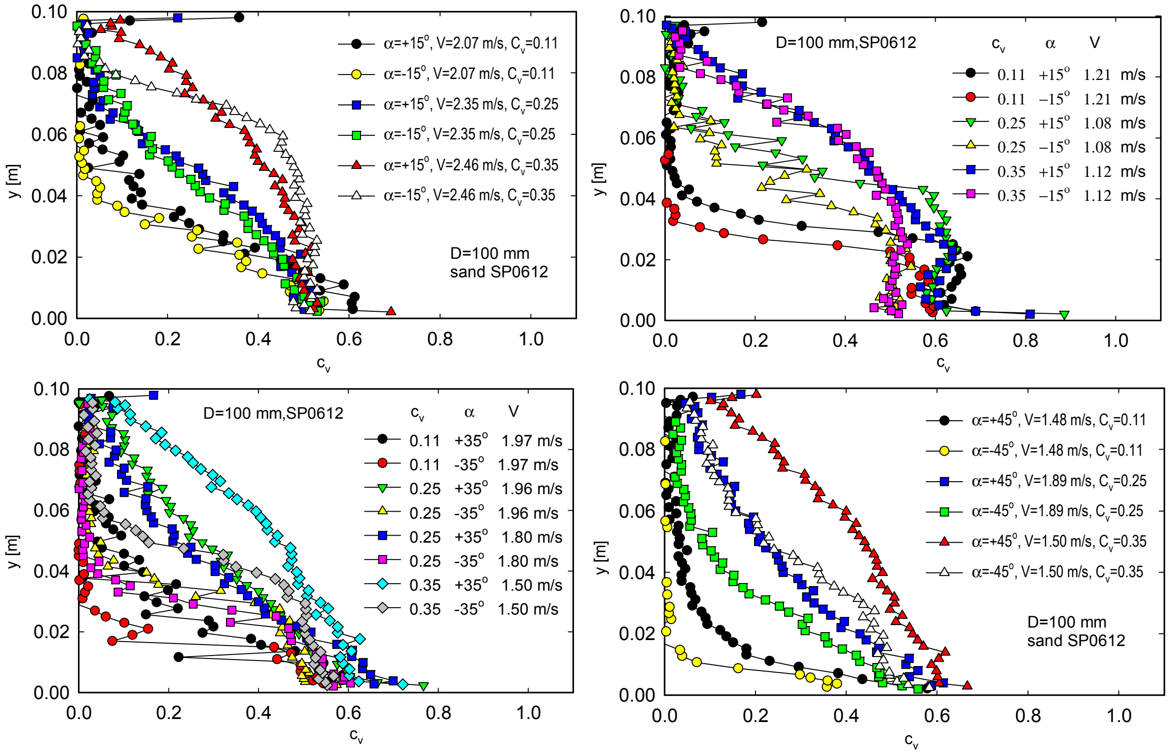

Fig. 9. Effect of the mean slurry volumetric concentration C_v on local concentration profiles.

Near and above the deposition limit, the ascending flow was less stratified than the corresponding descending flow. For velocities below the deposition limit, the stationary bed was observed in the ascending pipe for an inclination angle $\alpha < 30°$. For descending flow, the thickness of the bed layer was significantly less, and the bed disappeared for pipe slope $\alpha < -15°$ (Vlasak et al., 2018a). Analogous behavior was observed for lower and higher transport concentrations, $C_v = 0.11$ and 0.35 (see Figs. 7 and 8).

The effect of the mean slurry concentration C_v on the chord-averaged concentration profiles is illustrated in Fig. 9 for different pipe inclinations *α* and slurry flow velocities *V* above and below deposition limit V_D. The velocity profiles document a decrease of the degree of stratification with increasing slurry concentration C_v and pipe slope *α*.

The shape of the concentration profiles was highly dependent on the slurry velocity; for a gentle pipe slope ($\alpha = \pm 15°$) and the slurry velocity $V > V_D$, a bed layer was observed 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 the deposition limit V_D, the local concentration in the bed layer decreases for both branches. For higher pipe slopes ($\alpha > \pm 35°$), a bed layer originated in the descending branch. For the ascending branch, slurry stratification was smaller than for the descending branch, and it decreased with increasing slurry concentration (Vlasak et al., 2019c).

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 (Vlasak et al., 2019b).

In comparison, this sand slurry with fine-material slurry (glass ballot B134, d_{50} = 0.180 mm – Vlasak et al., 2018b, 2019a) stratification was more pronounced. For velocities close to V_D, stratification was significant for the low values of pipe inclination ($\alpha < 25°$). For higher inclination and ascending flow, the shape of the concentration profile was less stratified with an increasing pipe slope, while for descending flow the conveyed solids were concentrated in the lower part of the pipe even for high pipe inclinations ($\alpha = -35°$). At low concentration values, stratification was more pronounced for both upward and downward flows.

DEPOSITION LIMIT VELOCITY

The conducted experiments confirmed that the solids distribution in stratified slurry flow considerably varies with the pipe inclination, flow velocity, and slurry concentration. Determination of the deposition limit velocity V_D in stratified and partially stratified slurry flow is rather difficult and complicated work because of a usually unstable flow pattern near the deposition limit. The most often used method of an experimental determination of the deposition limit velocity V_D is a visual observation of a deposit formation in a section of viewing pipe. With increasing content of fine particles, the visual observation becomes difficult and not very accurate, and it was necessary to use another method, for example, radiometric measurement (Gillies et al., 2000). To determine the slurry velocity at which stationary deposit starts to be formed, we applied a camera system aimed on the pipe invert. Unfortunately, when the slurry velocity V approached a region close to the value of the deposition limit velocity V_D, the slurry flow became significantly unstable, especially for higher concentrations, and concentration waves were even observed. The velocity range for which a stationary bed was developed, such as velocity values for which the first particles stopped moving and velocity values when a real stationary bed (steady state deposit) were developed, was rather broad, sometimes even about 1 m/s. Into this velocity range, the bed deposit was repeatedly interrupted and started sliding - we call this behavior a “caterpillar behavior” 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.

To increase the accuracy of V_D determination and reduce uncertainty, we combined visual observations and changes of the pressure gradient versus the velocity diagram with radiometric measurements 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 pipe. A typical result of a c_{v10} test run is shown in Fig. 10 for slurry volumetric concentrations C_v = 0.11 and 0.25.

The measurement started at the flow velocity V higher enough than the deposition limit V_D, and then slurry velocity V was gradually decreased during the test run. The local concentration c_{v10} in this chord was then measured as a function of the slurry velocity. As the slurry velocity decreased, the value of $c_{v10,}$ at first slowly and then rapidly, increased until the flow velocity V decreased to a value close to the deposition limit V_D. Near the deposition limit, the local concentration c_{v10} suddenly increased and reached a value typical for the sliding or stationary bed (approximately $c_{v10} \approx 0.55–0.60$), when a stable deposit was formed at velocities below V_D (Matousek et al., 2019a; Vlasak et al., 2019a). The results of the radiometric method agree rather well with the visual observations; if the flow is steady and stable, the difference was less than 10%. The variation of the local concentration c_{v10} illustrated concentration waves in the flow regime with a slurry velocity above the deposition limit.

From the experimental data (see Table 1 and Fig. 11) it was obvious that the deposition limit velocity V_D was sensitive to the pipe inclination; in the ascending pipe, V_D was higher than in the horizontal pipe. The deposition limit V_D in the ascending pipe section increased with an inclination angle α in range of the inclination angle α = 0° and +25°; for higher pipe inclinations, it remained practically constant on value about 1.25 times higher than that in the horizontal pipe.

This is fully consistent with Wilson and Tse’s (1984) results, which indicated that the deposition limit V_D can increase up to 50% for coarse materials (sand and gravel with **a** 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 a value $\alpha \approx -30°$, where no stationary bed was observed. For such negatively steep sloped flows, a sliding bed was observed, where particles were driven downward predominantly by the downward component of the gravity force.

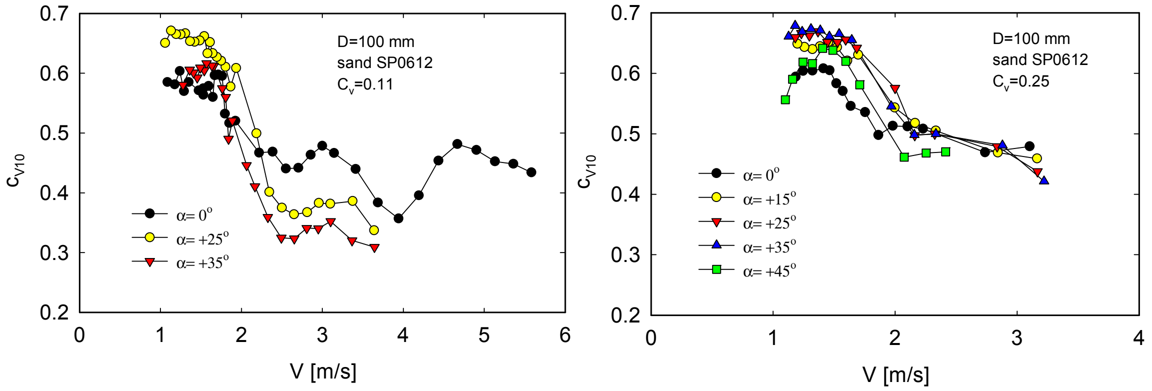

Fig. 10. Effect of the flow velocity V on local in situ concentration c_{v10}.

Table 1. Deposition limit velocity V_D, SP0612.

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

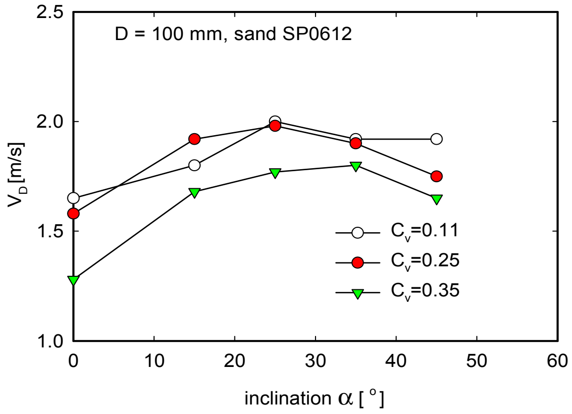

Fig. 11. Effect of the pipe inclination α and volumetric concentration C_v on deposition limit velocity V_D.

CONCLUSIONS

The effect of pipe inclination, slurry concentration, and mean velocity on flow behavior of medium-coarse sand-water slurry was studied in an experimental pipe loop of inner diameter D = 100 mm with inclinable pipe sections. The experimental investigation was focused on the effect of pipe inclination, overall slurry concentration, and mean velocity on flow behavior, concentration distribution, and deposition limit velocity.

It was revealed that a layered structure is a typical flow pattern for a settling slurry flow 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 inclinations.

For slurry velocity above the deposition limit, the ascending flow was less stratified than the corresponding descending flow. The degree of stratification was sensitive to pipe inclination and depended on the mean slurry concentration and the slurry velocity. This fact is in contradiction with the assumption of the Worster-Denny (1955) formula, which overestimates the frictional pressure gradient in an ascending pipe section.

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

The deposition limit velocity was sensitive to the pipe inclination; it reached higher values in the ascending pipes than in the horizontal pipe. The maximum deposition limit value was reached for an inclination angle of about +25°, while for the higher pipe inclination the deposition limit remained practically constant on value at about 1.25 times higher than that in the horizontal pipe.

On the contrary, in the descending pipe, where particles were driven by the downward component of the force of gravity, the deposition limit decreased significantly with the increasing negative slope and tended to be zero for inclination angles about −30°, where no stationary bed was observed.

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