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Experimental investigation of fine-grained settling slurry flow behaviour in inclined pipe sections

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Abstract: For the safe and economical design and operation of freight pipelines it is necessary to know slurry flow behaviour in inclined pipe sections, which often form significant part of pipelines transporting solids. Fine-grained settling slurry was investigated on an experimental pipe loop of inner diameter D = 100 mm with the horizontal and inclined pipe sections for pipe slopes ranging from –45° to +45°. The slurry consisted of water and glass beads with a narrow particle size distribution and mean diameter d_{50} = 180 µm. The effect of pipe inclination, mean transport volumetric concentration, and slurry velocity on flow behaviour, pressure drops, deposition limit velocity, and concentration distribution was studied. The study revealed a stratified flow pattern of the studied slurry in inclined pipe sections. Frictional pressure drops in the ascending pipe were higher than that in the descending pipe, the difference decreased with increasing velocity and inclination. For inclination less than about 25° the effect of pipe inclinations on deposition limit velocity and local concentration distribution was not significant. For descending pipe section with inclinations over –25° no bed deposit was observed.

Keywords: Settling slurry; Effect of pipe inclination; Concentration distribution; Pressure drops; Deposition limit; Gamma-ray radiometry.

INTRODUCTION

Hydraulic pipeline transport is commonly used for transport of different bulk materials. Pipeline systems used in industrial applications, e.g. in mining, dredging, land reclamation, building, technological production lines and systems, long-distance product pipelines, or deep-ocean mining systems often contain inclined pipe sections (Thomas and Cowper, 2017; Van Wijket et al., 2016; Vlasak et al., 2012). From an operational point of view transport concentration, operational velocity and pressure drops are the most important parameters for transport pipelines design and operation. Very important - and one of the most difficult parameters to determine of a pipeline system transporting settling slurries - is the deposition limit velocity, V_{dl}, which is defined as the slurry velocity at which conveyed particles stop moving and start to form a deposit at the bottom of a pipe.

Settling slurries tend to stratify in horizontal and inclined parts of the pipeline system. The degree of stratification is sensitive to the flow velocity, slurry concentration, and affects both the pressure drops and the operational velocity at which the system should operate safe and without a danger of pipe blockage. The flow of settling slurry in a pipe may be defined as the flow with an asymmetrical concentration and velocity distribution. The slurry stratification, which affects the pressure drops and deposition limit velocity, depends on the angle of pipe inclination. Unfortunately, the effect of pipe inclination on flow conditions of settling slurries has not received an adequate attention up to now (Matousek et al., 2018).

Many theoretical and experimental studies have been carried out on transport of sand or fine particles in horizontal pipes (Gopaliya and Kaushal, 2016; Shook and Roco, 1991; Vlasak and Chara, 1999, 2009; Wilson et al., 2006). Wilson proposed a two-layer model for settling slurries with a fully stratified flow pattern (Wilson, 1976; Wilson et al., 2006). The layers differ in the local solids concentration and velocity. In each layer there is a difference in the velocities of the particles and the carrier liquid, which results in a transfer of energy from the fluid to the particles and from the particles to the pipe wall (Vlasak et al., 2017). The velocity difference between the solid and liquid phase, called slip velocity, is one of the mechanisms of particle transport in two-phase flow. Due to the slip velocity, there is difference between transport (C_d) and in situ (c_v) concentrations. Friction losses of heterogeneous slurries flow in a pipeline are strongly dependent on the concentration distribution (Matousek, 2002). A granular contact bed forms at the pipe invert, if the slurry velocity is slightly below the deposition limit. The bed slides along the pipe wall at velocities above the deposition limit and forms a stationary deposit below the deposition limit velocity. The contact bed is important contributor to the frictional pressure drops in settling slurry flow. The experimental data containing measured solids distributions are extremely scarce in the literature (Matousek et al., 2018).

EXPERIMENTAL EQUIPMENT AND MATERIAL

The experimental investigation was carried out in a pipe loop of inner diameter D = 100 mm made from smooth stainless steel pipes. The total length of the loop was 93 m, see Fig. 1. The horizontal (A) and inclinable (B) pipe sections are connected by abrasion resistant flexible hoses (12). Slurry flow was measured simultaneously in the ascending and the descending legs of the inclinable U-tube at slopes α varying from –45° to 45°. 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) to a measurement section of the loop.

The inclinable U-tube was used to determine the volumetric transport concentration C_d of the slurry using a method proposed by Clift and Clift (1981). Transparent viewing pipe sections (7) for visual observation of the slurry flow behaviour and deposition limit velocity V_{dl} were situated at the ends of the horizontal pipe section (A) and ascending and descending inclinable section (B).

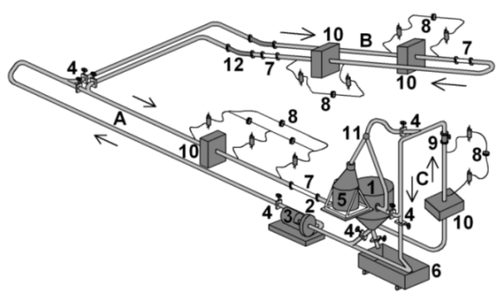

Fig. 1. Experimental test loop D = 100 mm (IH CAS, v. v. i., Prague).

A – horizontal section, B – inclinable section, C – short vertical section; 1 – mixing tank, 2 – centrifugal dredge pump, 3 – electric motor, 4 – slide valves, 5 – pycnometer, 6 – slurry output tank, 7 – transparent viewing pipe section , 8 – differential pressure transducer, 9 – electromagnetic flow meter, 10 – radiometric devices, 11 – flow divider, 12 – flexible hose.

The pressure drops were measured by Rosemount 1151DP differential pressure transducers (8) over 2-meter long measuring sections located in the horizontal and the inclined measuring sections. Slurry velocities were measured by a Krohne OPTIFLUX 5000 magnetic flow meter (9), mounted in the short vertical section (C) at the end of the circuit. 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 by slide valves (4) and a slurry output tank (6). Measurements were taken simultaneously in the ascending and descending sections of the loop from maximum values $V_{max} \approx 3.0$ m/s to values $V_{min} \approx 1$ m/s below the deposition limit velocity V_{dl}.

The loop was equipped with two gamma-ray density meters (10) placed on a special support and controlled by a computer. The support serves for vertical linear positioning of both the source and the detector to measure chord averaged vertical concentration profiles. The radiometric density meters 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 (Krupička and Matoušek, 2014; Vlasak et al., 2014).

The studied slurry consisted of rather fine glass beads B134 with narrow particle size distribution. Particle mean diameter d_{50} = 0.18 mm, d_{18} = 0.16 mm, d_{84} = 0.24 mm, particle density ρ_p = 2460 kg m^{-3}, Ar_{50} = 62.6) and water, the transport volumetric concentration C_d ranged from 12 to 34%. The slurry can be classified as partially stratified.

PRESSURE DROPS

The pressure drops, which depend on slurry concentration, C, and flow velocity, V, on physical properties of carrier liquid and conveyed particles, pipeline physical parameters, and of course on angle of the pipe inclination, α, that seems to be one of the most important flow parameter for transport pipeline design. The effect of pipe inclination on the pressure drops can be determined by using some semi-empirical correlations adapted to inclined pipes (Doron et al., 1997; Shook and Roco, 1991). The well-known Worster and Denny (1955) equation quantifies the effect of pipe inclination, α, on the total pressure drop, dp, over the pipe section, dL, or on hydraulic pressure gradient i = dp/dL, based on so called "the solids effect". The solids effect can be defined as the difference in pressure gradients between slurry and carrier liquid, $\Delta I = i_S - i_L$. For inclination α it is given as

$$-\Delta I\alpha = -(i_{S,\alpha} - i_L) = -\Delta i_0 \cos\alpha + (\rho_S - \rho_L)\, g \sin\alpha, \tag{1}$$

where subscript S and L means slurry and liquid respectively, subscript α means flow in inclined pipe section and subscript 0 means flow in horizontal pipe section, ρ is the density, and g is the gravitational acceleration. The pipe inclination α has positive values in the ascending pipe (α = 0 ÷ +45°) and negative values (α = 0 ÷ –45°) in the descending pipe. The solids effect on the pressure drops in inclined flow consists of two parts – the frictional pressure drop (the first term on right-hand part of Eq. (1)) and the hydrostatic pressure (the second term on right-hand part of Eq. (1)).

Because the pressure gradient due to liquid flow friction i_L is independent of the pipe inclination, and the directly measured manometric pressure gradient $I_{S,\alpha}$ of slurry flow in the inclined pipe section is

$$I_{S,\alpha} = -i_L - (\, i_{S,0} - i_L\,) \cos\alpha + (\rho_S - \rho_L)\, g \sin\alpha, \tag{2}$$

the slurry frictional pressure drop $i_{f,S,\alpha}$ in the inclined pipe is

$$i_{f,S,\alpha} = \; i_{L,0} + (i_{S,0} - i_L) \cos\alpha. \tag{3}$$

Because the solid particles contribute to the frictional pressure drops through the solids effect according to Eq. (3), the frictional pressure drops should be the same at the same inclination angle for a positive or a negative slope. Thus, the slurry flow behaviour in ascending and descending inclined pipe sections should be also the same, including the distribution of solids in a pipe cross section. The Worster and Denny model neglects slip velocity V_{slip}, however, the slip velocity is not negligible in stratified and partially-stratified slurry flows in inclined pipe sections. The slip velocity depends on the difference between the mean in situ concentration, C_v, and the mean transport concentration, C_d. The difference becomes very important especially with increasing diameter of conveyed particles.

This is in contradiction with experimental results, which show that concentration distribution in ascending and descending pipes are different, and concentration profiles are sensitive to the angle of pipe inclination (Matoušek, 1996, 1997). The slurry was less stratified for ascending flow then for descending flow, and the difference increased with increasing size of conveyed particles. It is typical especially for partially-stratified inclined flow and is associated with the difference in velocity of a sliding bed in the ascending flow (slow sliding) and in the descending flow (fast sliding) (Matousek et al., 2018). Wilson and Byberg (1987) argued that Eq. (3) is theoretically valid for flow with a sliding bed, while for partially stratified flow the term cos α should be powered by a factor larger than unity. Gibert (1960) modified the Durand correlation for horizontal heterogeneous slurry flow to inclined flows with the power factor of cos α equal to 1.5 instead of 1.0.

Shook and Roco (1991) adapted the force balance equations of a two-layer model for inclined flow of partially stratified slurry. Doron et al. (1997) introduced a three layers model (a stationary bed, a moving bed, and suspended slurry flow). They assumed the uniform particle distribution in the bed layers and the distribution given by the turbulent diffusion equation in the suspended slurry layer. The model was verified by their own experiments conducted in a pipe of D = 50 mm for pipe inclinations from –7° to +7°.

Layered models distinguish between transport and in situ concentrations and use for the hydrostatic pressure drops calculation the appropriate slurry density, based on the in situ concentration. Thus, the mean in situ concentration C_v should be used to calculate the static pressure drops in inclined pipe sections.

The results of directly measured pressure drops are manometric pressure drops, which for the glass beads slurry are illustrated in Fig. 2 for horizontal (α = 0) and positive and negative slopes of the pipe sections (inclination angle α ranging from ±5° to ±45°). Fig. 2 shows the relationships $I_m(V)$, where a manometric pressure drop is expressed as the hydraulic gradient $I_m = -(\mathrm{d}p/\mathrm{d}L) / g\,\rho_w$, where ρ_w is the density of water.

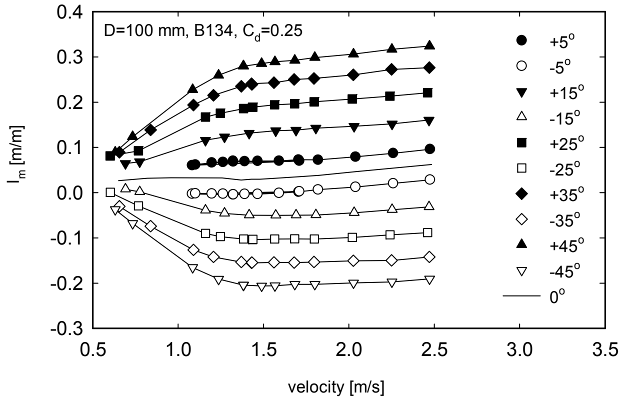

Fig. 2. Effect of the inclination angle α and flow velocity V on manometric pressure drops $I_{m,\alpha}$ (C_d = 0.25).

To recalculate the frictional pressure drops i from the measured manometric pressure drops I_m it is necessary to use the values of in situ concentration C_v , i.e. the values of C_v obtained by integrating concentration profiles over a cross section of the pipe. Because the measured values of C_v are available only at velocities where concentration profiles were measured, we used a linear interpolation of C_v values calculated for each measured velocity. The measured B 134 slurry can be classified as partially stratified; its mean in situ concentration C_v is dependent on flow velocity, especially for velocity close to and below deposition limit, as is illustrated in Fig. 3.

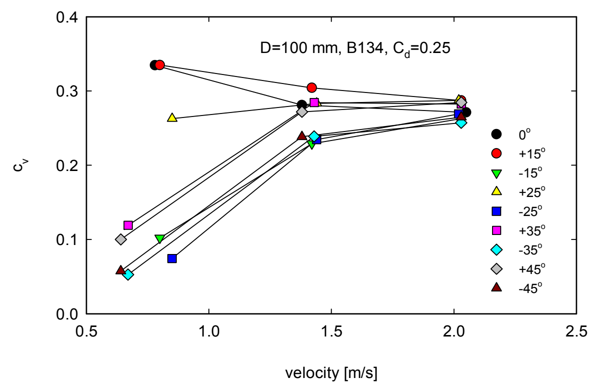

Fig. 3. Effect of the flow velocity V and inclination angle α on the slurry in situ volumetric concentration C_v (C_d = 0.25)

At velocities above deposition limit slurry concentration C_v remains approximately constant, only slightly higher than the transport concentration C_d. At velocities lower than V_{dl}, in situ concentration C_v decreased due to a stronger stratification of the flow throughout the loop, and forming of a sliding or stationary bed, where conveyed particles moved considerable slower than suspended particles and carrier liquid. The value of C_v decreased markedly for slurry velocity lower than the deposition limit.

The effect of pipe inclination α on frictional pressure drops i is illustrated in Fig. 4 for glass beads slurry of transport concentration C_d = 0.25 and pipe inclination from ± 5° to ± 45°. From pressure drops–velocity relationships it follows that frictional pressure drops for ascending and descending flow are not the same and hence do not agree with the assumption by the Worster-Denny formula (Eq. (3)). The data in Fig. 4 illustrates that Eq. (3) overestimates the frictional gradient in the ascending pipe section and vice versa for the descending section. The different effect of positive and negative inclination on frictional pressure drops can be accounted for using the layered models (Shook and Roco, 1991; Spelay et al., 2016; Wilson, 1976; Wilson et al., 2006).

The difference between ascending and descending flow and between horizontal and inclined flow increases from horizontal flow up to about inclination angle α = 25°, then slowly decreases. The difference decreases also with increasing flow velocity V. Maximum difference between horizontal and inclined flow are reached for slurry velocity close to the deposition limit V_{dl}. Frictional pressure drops in the ascending pipe are higher than that in the descending pipe, the difference decreases with increasing velocity and pipe inclination angle.

DEPOSITION LIMIT VELOCITY

The deposition limit velocity V_{dl} can be determined by a semi-empirical correlation or by applying principles of a mechanistic layered model. Durand and Condolios (1952) introduced the dimensionless deposition velocity for horizontal flow, the so called the Durand parameter

$$F_L = V_{dl} / (2g\,D\,(\rho_S/\rho_L - 1))^{1/2}. \tag{4}$$

The parameter F_L can be determined from an empirical nomogram as function of particle mean diameter and slurry concentration.

Since 1960, numerous correlations for deposition limit velocity have been developed, mostly based on dimensional analysis. Wilson (1976) determined for fully stratified slurry flow the deposition limit velocity from the force balance at slip point (i.e. the moment when the granular bed starts to slide) and introduced the well-known demi-McDonald nomogram (Wilson, 1979). To express the effect of pipe inclination α on deposition limit velocity V_{dl}, Wilson and Tse (1984) employed the difference between the Durand parameter F_L in an inclined and a horizontal pipe and introduced the change of Durand parameter

$$\Delta F_L = F_{L,\alpha} - F_{L,0}, \tag{5}$$

where $F_{L,\alpha}$ and $F_{L,0}$ is value valid for the inclined and horizontal pipe section, respectively. Wilson and Tse developed a computer program and after evaluation of their own experiments with narrow size distribution sand and gravel (from 1 to 6 mm in diameter) in a pipe of D = 76 mm they provided a nomogram relating ΔF_L with α. Their results were in agreement with measurements conducted by Hasimoto et al. (1980). De Hoog et al. (2017) also verified the Wilson-Tse nomogram for coarse material (gravel of d_{50} = 4.6, 6.3 and 12 mm) in a 100-mm pipe, and they found the maximum V_{dl} at the pipe inclination of about α = 30°.

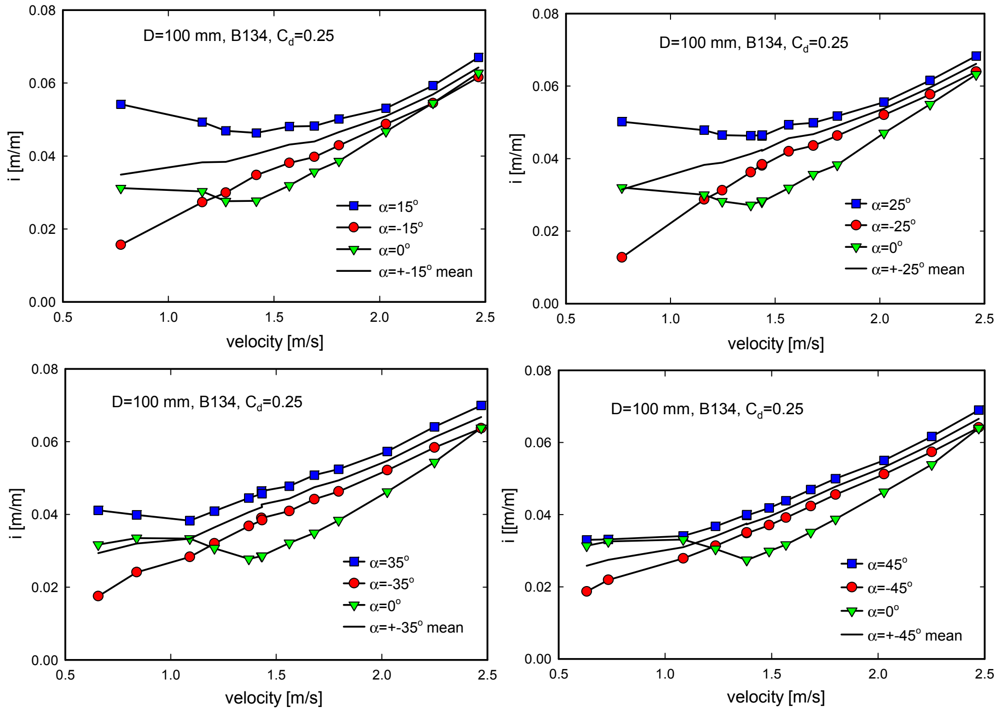

Fig. 4. Effect of the inclination angle α and flow velocity V on frictional pressure drops i.

Spelay et al. (2016) proposed two criteria for the effect of pipe inclination on the deposition limit velocity. The first is the Archimedes number

$$Ar = 4\, g\, \rho_L\, (\rho_p - \rho_L)\, d^3 / (3\mu_L^2), \tag{6}$$

where μ_L is the dynamic viscosity of the carrier liquid. The second is the turbulent suspension efficiency parameter

$$\mathrm{TSP} = (w \,/\, u_{*L,\, dl}) \exp\,(d/D), \tag{7}$$

where w is particle terminal settling velocity, $u_{*L,\, dl}$ is the friction velocity of the carrier liquid at the deposition velocity. They suggested that the effect of inclination is negligible for $Ar < 500$ and TSP < 0.5, and recognized a trivial effect of the pipe inclination on deposition limit velocity for fine to medium sand and a significant effect for coarse sand and gravel.

The most often used method of an experimental determination of V_{dl} is a visual observation of a deposit formation in a transparent pipe section. In order to increase the accuracy of V_{dl} and reduce uncertainty, we combine visual observation and changes of the $i(V)$ diagram with application of radiometric measurement, i.e. to trace the velocity value at which a stationary bed first forms at the bottom of the pipe by measurement of local concentration in a layer close to the pipe invert. The deviation in determined values of V_{dl} may be considered satisfactory if it does not exceed say 20%.

In addition to chord-averaged concentration profiles, measured at three slurry velocities (i.e. above, below, and roughly at deposition limit V_{dl}), for each measured velocity V, a value of concentration, $c_{v,10}$, in the layer at a height of 10 mm above the pipe invert was measured to identify the origin of deposit at the bottom of the pipe.

From Fig. 5 it is obvious, that when the flow velocity V gradually decreased, $c_{v,10}$ remained nearly constant until the deposition limit is approached. For the flow velocity V close to the deposition limit, the local concentration $c_{v,10}$ gradually increased and relatively quickly reached a value typical for the

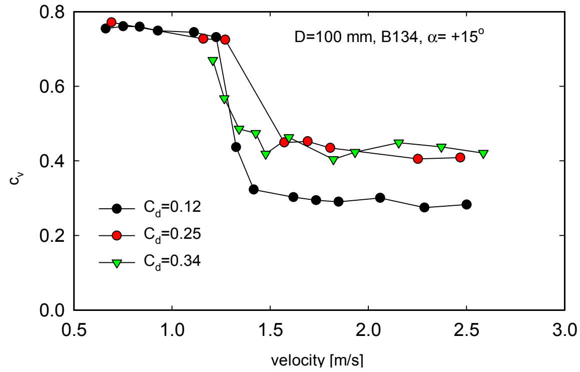

Fig. 5. Effect of the flow velocity V and slurry transport volumetric concentration C_d on chord averaged local concentration c_v in height y = 10 mm above pipe bottom.

stationary bed, since a bed layer is formed at a velocity lower than V_{dl}. Increasing of $c_{v,10}$ starts at V between 1.50 and 1.60 m/s and the stationary bed is formed at a slurry velocity below 1.25 m/s. The deposition limit should be between these two velocity values. By comparing the measured concentration profiles and the local concentration $c_{v,10}$, we estimated that the deposition on the pipe bed occurred at a local concentration value of $c_{v,10} \approx 0.50$. Thus the deposition velocity V_{dl} is reached, depending on the mean concentration, at about 1.40 m/s for a mean transport concentration C_d = 0.12 and 0.34 and pipe inclination of α = 15°.

Table 1 shows the deposition limits obtained both by visualization method and by determining from the I/V diagrams. Obviously, the values are not very different from each other. The difference between values ranges from 5% to 15% for ascending flow. Significant differences are for descending flow, where, for so fine material as B134, it had often been difficult to identify the bed layer visually. From the experimental data we can see that the V_{dl} in the inclined pipes is slightly lower than in the horizontal pipe. Deposition limit V_{dl} in the ascending pipe section (determined by visual observation) reaches minimum values for an inclination angle α between 15° and 25°, then for higher pipe inclination it again slightly increased. On the contrary, in the descending pipe, the deposition limit values from the visual observation decreased significantly.

Table 1. Deposition limit, B134, $C_d = 0.25$.

α [°]	0	± 5	± 15	± 25	± 35	± 45
from *I* / *V* diagram						
V_{dl} [m/s]; $\alpha > 0$	1.50	1.35	1.38	1.43	1.43	1.50
V_{dl} [m/s]; $\alpha < 0$	1.50	1.34	1.38	1.43	1.43	1.50
from visualisation						
V_{dl} [m/s]; $\alpha > 0$	1.45	1.47	1.25	1.25	1.43	1.50
V_{dl} [m/s]; $\alpha < 0$	1.45		1.25	0.95	0.80	0.65

LOCAL CONCENTRATION DISTRIBUTION

Effect of pipe inclination on concentration distribution of partially stratified settling slurry flow behaviour was confirmed by measurement of chord-averaged local concentration profiles, $c_v(y)$.

Both the slurry flow behaviour in the pipe, and, in particular, the concentration distribution which significantly influences the degree of stratification and sliding bed friction, are important for the determination of the pressure losses and the deposition limit velocity. From the mutual comparison of the concentration distribution 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).

In Fig. 6 the effect of the angle of inclination on the shape of experimental chord-averaged concentration profiles, $c_v(y)$, is illustrated for three different slurry velocities V and pipe inclination from horizontal to +45° or –45° at constant transport concentration C_d = 0.25. The concentration profiles confirmed the stratified flow pattern in inclined pipe sections (Krupicka and Matousek, 2014; Vlasak et al., 2016, 2017). The concentration profiles showed different degrees of stratification for the positive and negative slope of the flow. 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.

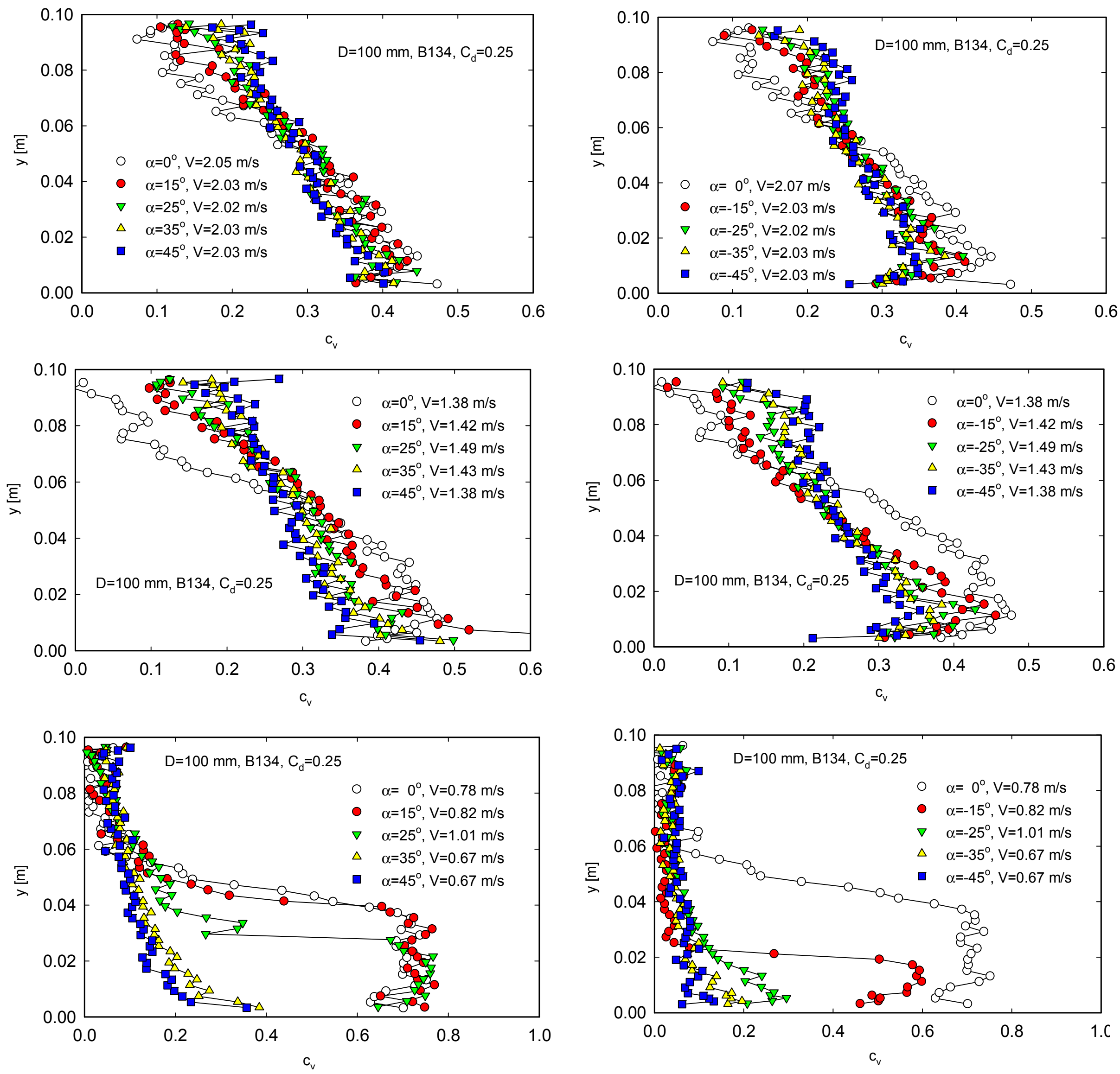

Fig. 6. Effect of the pipe inclination α on chord-averaged local concentration profiles (C_d = 0.25).

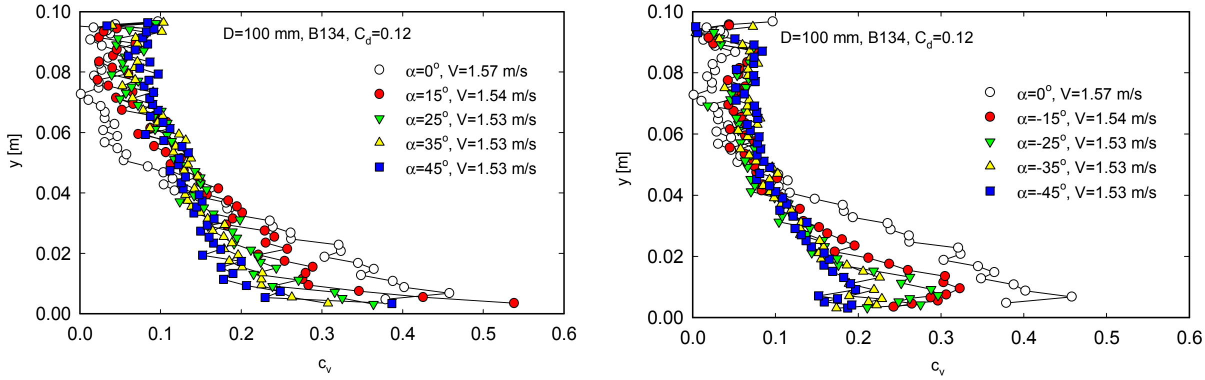

Fig. 7. Effect of the pipe inclination α on chord-averaged local concentration profiles ($C_d = 0.12$).

The thickness of the sliding bed tended to decrease with the increasing inclination angle, for slurry velocity $V \approx 2$ m/s no sliding bed was observed in ascending flows.

Local concentration reached a maximum near the pipe invert, however, for flow velocities above the deposition limit, i.e. $V \approx 2.0$ m/s, the slope of the concentration profile increased with increasing inclination angle α, see Fig. 6 (upper panels). Similar flow pattern was observed for velocities $V \approx 1.45$ m/s, i.e. close to the deposition limit (middle panels). For $V < V_{dl}$ sliding or stationary beds were observed in ascending pipe for inclination angle $\alpha < 30°$, for higher inclination angles ($\alpha > 30°$) the sliding bed disappeared (lower panel left). For descending flow the thickness of sliding bed was significantly less and the bed disappeared for pipe slope $\alpha > 15°$.

The slope effect on the concentration profiles was significant for low pipe inclination angles (i.e. for $\alpha < 25°$), however, the flow remained almost fully stratified. For the steeper slopes the degree of stratification was strongly affected (decreased) by the axial component of the gravity force the flow pattern did not exhibit any bed at inclination angle $\alpha > 30°$.

Similar behaviour was observed for lower transport concentration $C_d = 0.12$ (see Fig. 7). Slurry concentration in the bed layer significantly decreased with increasing inclination angle α, both for ascending and descending pipe sections. Local in situ concentration at the top of the pipe was higher in the ascending pipe section than that in the descending section. With increasing inclination angle the solid particles, due to the increasing effect of the axial component of the gravitational force, reached probably higher velocities and thus lower values of local in situ concentration.

The same flow behavior of the slurry was also observed for the highest measured transport concentration $C_d = 0.34$, see Fig. 8. Stratification of the slurry decreases with the increasing angle of inclination, the local concentration c_v in the upper part of the pipe increases, more pronounced in the ascending pipe section.

Difference between ascending and descending flows is illustrated in Fig. 9 for constant positive and negative couple of inclination angle α and different flow velocities V. For low inclination angle $\alpha = \pm 15°$ and velocity $V < V_{dl}$ a bed deposit was observed in both ascending and descending pipe legs. Bed layer in the descending pipe reached substantially lower values of local concentration c_v and deposit height y than that in the ascending pipe ($c_v \approx 0.60$ instead 0.75, and $y/D \approx 0.2$ instead 0.4). For velocity $V \approx V_{dl}$ a very thin deposit was observed in the ascending pipe only. For inclination angles $\alpha > \pm 35°$ no deposit was observed. 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 (Spelay et al., 2016; Vlasak et al., 2014, 2016, 2017). The local concentration in the ascending pipe section was always higher than that in the descending pipe section.

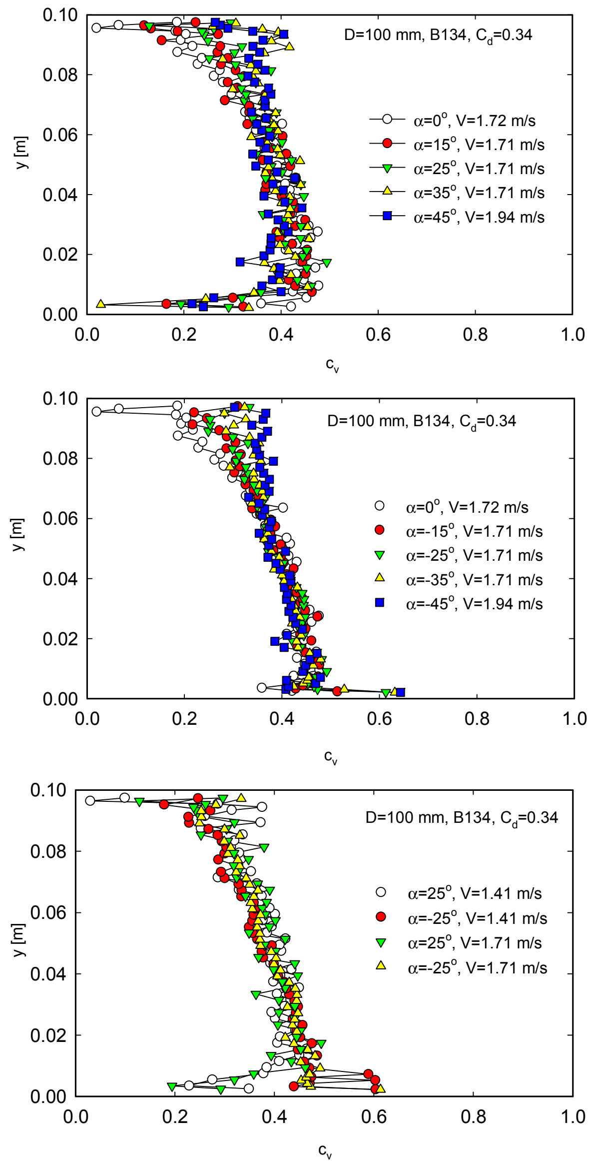

Fig. 8. Effect of the pipe inclination α on chord-averaged local concentration profiles ($C_d = 0.34$).

Deposition limit V_{dl} in the ascending pipe was slightly lower than that in the horizontal pipe ($V_{dl} \approx 1.5$ m/s); it decreased with increasing pipe inclination and slurry velocity. In the descending pipe no deposition limit was observed for angles $\alpha < -25°$.

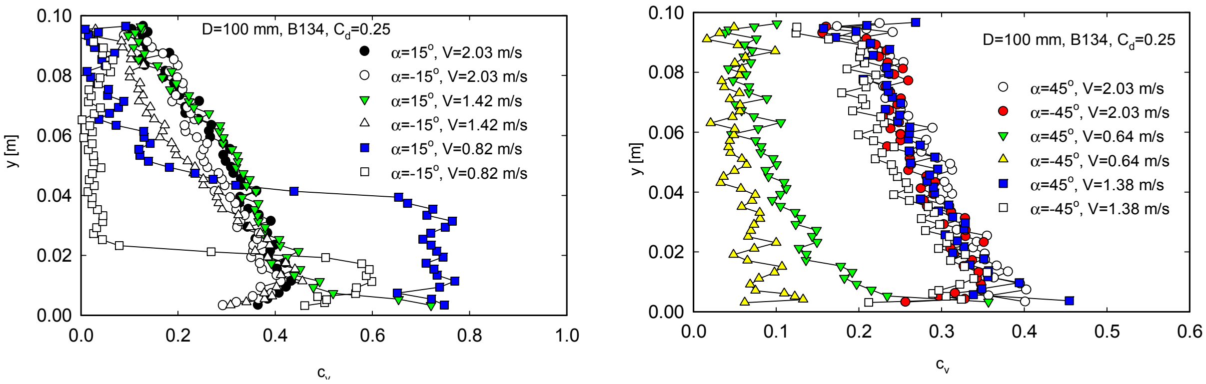

Fig. 9. Effect of mean slurry velocity V on chord-averaged local concentration profiles ($C_d = 0.25$).

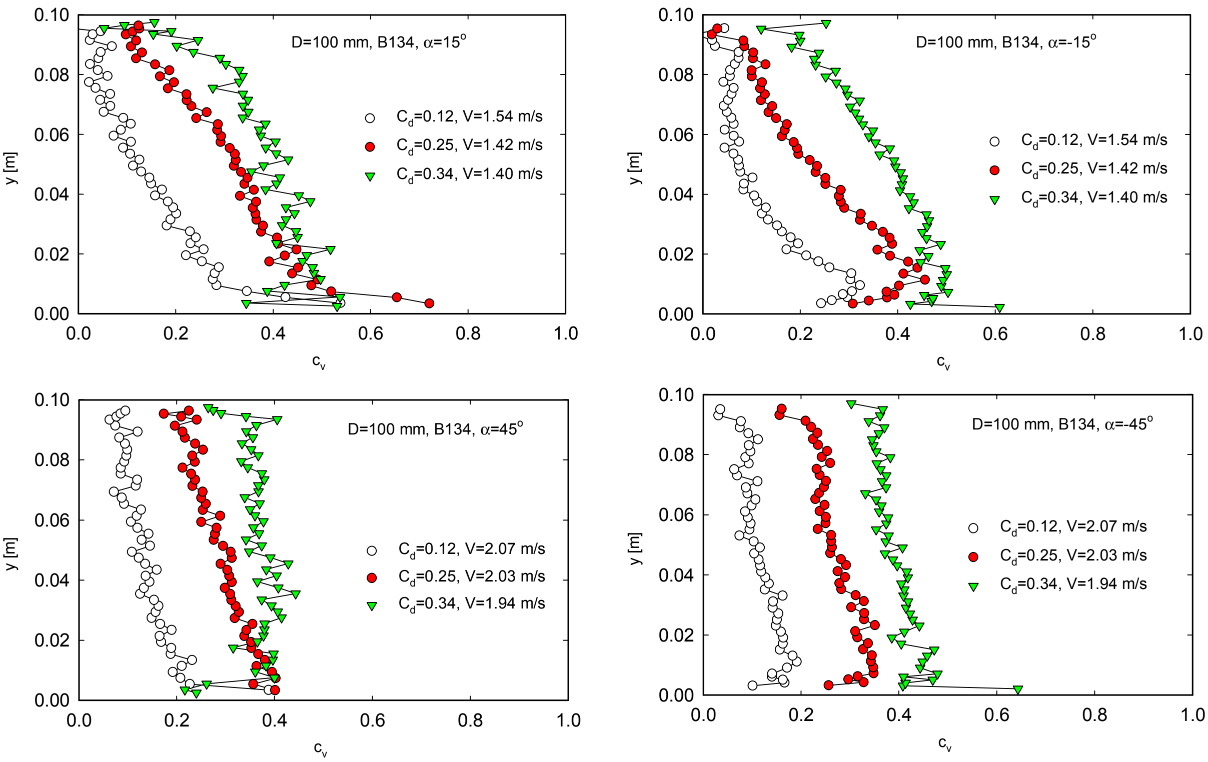

Fig. 10. Effect of transport concentration C_d on chord-averaged local concentration profiles for constant slurry velocity V and pipe inclination α.

The influence of the mean transport concentration C_d on the chord-averaged concentration profiles is illustrated in Fig. 10 for two values of the slurry flow velocity ($V \approx 1.5$ and 2.0 m/s). The graphs document decrease of the degree of stratification with increasing pipe slope and increasing transport concentration C_d. Whereas, for the angle of inclination $\alpha = \pm 15°$, the stratification is visible even for higher slurry velocities (see upper panels), for the angle of inclination $\alpha = \pm 45°$, the stratification was considerably smaller, and for $V = 1.94$ m/s and $C_d = 0.34$ it practically disappeared in the ascending pipe (see lower panel left).

CONCLUSIONS

The effect of pipe inclination, transport concentration, and mean velocity on flow behaviour of fine-grained settling slurry was studied in an experimental pipe loop of inner diameter D = 100 mm with inclinable pipe sections. The pressure drops, deposition limit velocity, and concentration distribution were studied for slurry of narrow particle size distribution glass beads (B134, mean diameter d_{50} = 180 μm) and water.

The visualization and local concentration measurements revealed the stratified flow pattern of the settling slurry in inclined pipe sections.

Frictional pressure drops in the ascending pipe were higher than that in the descending pipe; this fact is in contradiction with the assumption of the Worster-Denny formula. The difference decreased with increasing velocity and pipe inclination. Based on the conducted experiments it has been found that for fine-grained settling slurry the effect of the hydrostatic component of the pressure drops becomes more significant than the effect of the frictional pressure drops with increasing pipe inclinations.

Difference between ascending and descending flow and between horizontal and inclined flow increased from horizontal flow up to about inclination angle $\alpha = 25°$, then slowly decreased.

The mean in situ concentration for descending flow was always lower than that for the ascending flow. For low 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. The slope effect on the concentration profiles was significant for low pipe inclination angle (i.e. for $\alpha < 25°$).

With increasing mean slurry velocity the local concentration in the bed layer decreased; this effect increased with increasing inclination angle.

Deposition limit in the inclined pipes was slightly lower than in the horizontal pipe, the minima reached the values of V_{dl} for an inclination angle α about 25°, then in the ascending pipe the deposition limit again slightly increased. For negative pipe inclination ($\alpha < -15°$) no bed deposit was observed.

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