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# Modelling approaches for pipe inclination effect on deposition limit velocity of settling slurry flow

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**Abstract.** The deposition velocity is an important operation parameter in hydraulic transport of solid particles in pipelines. It represents flow velocity at which transported particles start to settle out at the bottom of the pipe and are no longer transported. A number of predictive models has been developed to determine this threshold velocity for slurry flows of different solids fractions (fractions of different grain size and density). Most of the models consider flow in a horizontal pipe only, modelling approaches for inclined flows are extremely scarce due partially to a lack of experimental information about the effect of pipe inclination on the slurry flow pattern and behaviour. We survey different approaches to modelling of particle deposition in flowing slurry and discuss mechanisms on which deposition-limit models are based. Furthermore, we analyse possibilities to incorporate the effect of flow inclination into the predictive models and select the most appropriate ones based on their ability to modify the modelled deposition mechanisms to conditions associated with the flow inclination. A usefulness of the selected modelling approaches and their modifications are demonstrated by comparing model predictions with experimental results for inclined slurry flows from our own laboratory and from the literature.

## 1 Introduction

One of the most important and yet one of the most difficult problems associated with the design and operation of a pipeline system transporting settling slurries is a prediction of the deposition limit velocity of the flowing slurry. Coarse settling slurries are transported at very different conditions (pipe size and geometry, solids contents in slurry etc) and exhibit very different properties (slurry density, degree of stratification etc). Moreover, they are often transported in pipelines containing sections that are inclined from the horizontal. Examples include in-plant transfer lines, tailings disposal operations, dredging, deep sea mining, and long-distance pipelining [1].

## 2 Definition and identification of threshold velocity

### 2.1 Issue of definition

In slurry pipeline practice, the term "critical velocity" is often used to determine a threshold below which the flow of slurry should not drop in a pipe in order to avoid operational problems. In the literature, many names and definitions can be found for the so called critical velocity. Some authors refer to it as to velocity at which a stationary bed deposit starts sliding, other authors as to velocity at which the stationary bed or sliding bed disappears. Others consider the critical velocity as the velocity at which the hydraulic gradient is at a minimum on a pipe resistance curve for mixture at certain delivered concentration in a pipe of a certain size.

We consider the deposition limit velocity, $V_{dl}$, as an average flow velocity at which grains first stop moving and start to develop a deposit at the bottom of a pipe. If coarse grains are transported at high delivered concentrations $C_{vd}$ (say $C_{vd} > 0.2$, see e.g. [2]), they tend to form a sliding bed at velocities higher than $V_{dl}$ and hence $V_{dl}$ is a threshold at which the bed stops sliding. In flow of low concentration of coarse grains, no compact sliding bed is formed if the flow decelerates towards $V_{dl}$. Instead the grains tend to form temporal clusters at the bottom of the pipe if the flow velocity gets close to $V_{dl}$, and the clusters interrupt movement before they come to a final stop at $V_{dl}$. If fine grains are transported instead of coarse grains in settling slurry flow, they do not form a sliding bed or any clusters before the deposit develops. In such a flow, a development of the deposit is a much more stable process than in coarse settling slurry flow, where it is often associated with a development of density waves, particularly in closed loops [3].

### 2.2 Issue of experimental identification

A measurement of $V_{dl}$, or its determination by visual observation in a clear pipe, is associated with

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considerable uncertainty caused both by the unstable process of bed forming and by the individual character of each observer's decision making. Hence, a considerable scatter must be expected to occur in experimental results and an expected deviation of predictions from experimental data must be considered generally larger than the deviation for a frictional pressure drop at standard operating velocity in slurry flow. While the deviation up to say 10% is considered good for frictional pressure drop predictions, for $V_{dl}$ the deviation may be considered satisfactory if it does not exceed 20% [4].

## 3 Observations in literature

The deposition limit velocity is sensitive to pipe diameter, to properties of both solids (size, density) and carrying liquid (density, viscosity) and to the concentration of transported solids. Experimental data from large pipes of industrial size are extremely scarce, and a majority of available data are from pipes of diameters up to 100 or 150 mm.

### 3.1 Effect of grain size

Much more experimental experience than for an effect of the pipe size is available for an effect of the particle size on $V_{dl}$, although data for particles smaller than say 100 micron are not as common. Experimental observations reveal that there is a certain critical size at which $V_{dl}$ is maximal in a given pipe. This size is of about 0.5 mm (medium sand in water), with coarser and finer grains of the same density forming granular deposits at lower flow velocities. In Figure 1, the effect of a variation of $V_{dl}$ (expressed using the dimensionless number $F_L = V_{dl} / \sqrt{2 \cdot g \cdot (S_s - S_f) \cdot D}$, in which g is gravitational acceleration, $S_s$ and $S_f$ relative densities of solids and liquid, D pipe inner diameter) with the grain size (expressed using Archimedes number Ar) is demonstrated on results of a recent experiment.

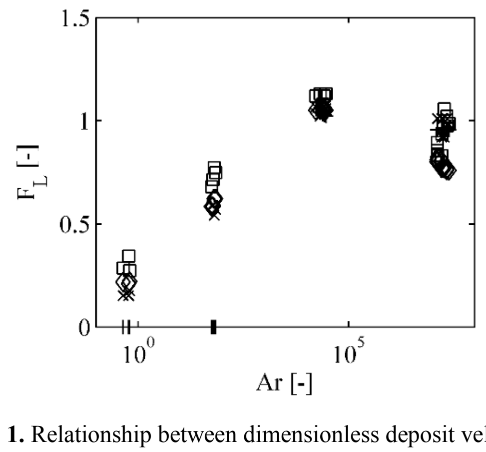



**Fig. 1.** Relationship between dimensionless deposit velocity $F_L$ and Archimedes number Ar for four individual fractions in 203-mm pipe [4]. Legend: square = experiment in GIW Hydraulic Laboratory, diamond = VSCALC-$V_{sm}$ model, x = 1952-Durand model.

A comparison of the experimental results with predictive models also shown in Figure 1 is discussed in Chapter 4 below.

### 3.2 Effect of broad grain size distribution

Industrial settling slurries often consist of particles of very different sizes; the particle size distribution may cover sizes which differ with two orders of magnitude. A broad particle size distribution affects parameters of slurry flow including deposition limit velocity. Recently [4], experimental results were analysed of a comprehensive experimental campaign testing slurry flows composed of solids of different fractions in the GIW Hydraulic Laboratory in 2016.

The experimental results showed that interactions among fractions affected the resulting deposition limit velocity in flows of broadly graded settling slurries. The effect of particle size distribution on the deposition limit velocity was not benign. The deposit velocity was not necessarily lower in a flow of slurry composed of four fractions of different sizes than in slurry flow of the individual fraction with the highest deposit velocity from the four fractions.

### 3.3 Effect of pipe inclination

Compared to the horizontal flow, inclined flow produces an additional force (a component of the submerged weight of grains) which acts either against the direction of flow (an ascending pipe) or in the flow direction (a descending pipe). In the ascending pipe (more often applied in the industry), the upwards inclined flow tends to require higher throughput velocity than the horizontal flow in order to avoid deposition. This is particularly significant for coarse-particle flows.

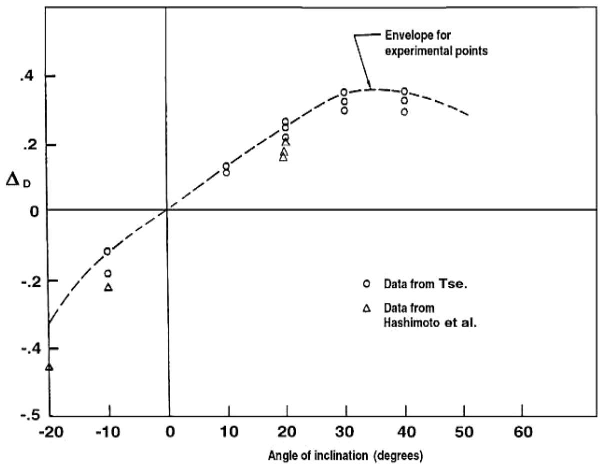



**Fig. 2.** Effect of angle of inclination on Durand deposition parameter [5].

Wilson and Tse [5] conducted experiments with very coarse grains (1 to 6 mm) in a 76-mm pipe that could be inclined up to 40 deg from the horizontal. The effect of pipe inclination on $V_{dl}$ was expressed as the change in the dimensionless Durand parameter ($\Delta_D = F_{L,\theta} - F_{L,0}$, where $F_{L,\theta}$ is for $V_{dl}$ in a pipe inclined to angle θ and $F_{L,0}$ for $V_{dl}$ in a horizontal pipe) with the pipe inclination angle θ (Fig. 2).

Matoušek [6] demonstrated that the deposition limit velocity is associated with a degree of flow stratification. His experimental work with a 150 mm diameter pipe and inclinations angles between -35 degrees and +35 degrees showed a strong influence of pipe inclination on slurry flow stratification. The observed concentration profiles were less stratified for rising inclinations and more stratified for descending inclinations in flows with coarse sands and gravel while they remained very similar in flows with fine to medium sands. This effect of different flow velocity relative to the sliding bed developed in the ascending flow (slow sliding) and in the descending flow (fast sliding) is a result of the mechanics of partially-stratified inclined flow.

Spelay et al. [1] proposed a criterion (turbulent suspension efficiency parameter) to evaluate the extent and impact pipe inclination will have on the deposition limit velocity.

De Hoog et al. [7] verified a usefulness of the Wilson-Tse diagram (Fig. 2) for very coarse grains by experiments with gravel fractions (4.6, 6.3 and 12 mm) in a 100-mm pipe inclined up to 52 degree. They found the maximum $V_{dl}$ at of about 30 degrees.

## 4 Approaches for predictive modelling

### 4.1 Semi-empirical approach

An estimation of deposition limit velocity has been subject of numerous studies over last 60 years with pioneer works dating to early 1950s. The two most often used semi-empirical models are the Durand model [8,9] and the Wilson-GIW model (described as the VSCALC model in [10]).

The Durand model uses an empirical nomograph which relates the dimensionless $V_{dl}$ ($F_L$) with the particle size and solids concentration ($C_v$ up to 0.15). There are two versions of the nomograph in the literature [11].

The VSCALC model combines the Wilson formulae for medium and coarse fractions with the Thomas formula for fractions finer than say 100 microns. The model gives a maximum value of deposit velocity for given sizes of particle and pipe ($V_{sm}$) and a value modified for different delivered concentrations ($V_s$).

A modification was proposed for a deposit velocity predictive model in order to take effects of a disproportionate contribution of individual fractions to the deposition limit velocity in flow of broadly graded slurry into account [4].

In the VSCALC model, the effect of pipe inclination on $V_{dl}$ is calculated using the Wilson-Tse method.

### 4.2 Mechanistic approach: two-layer model

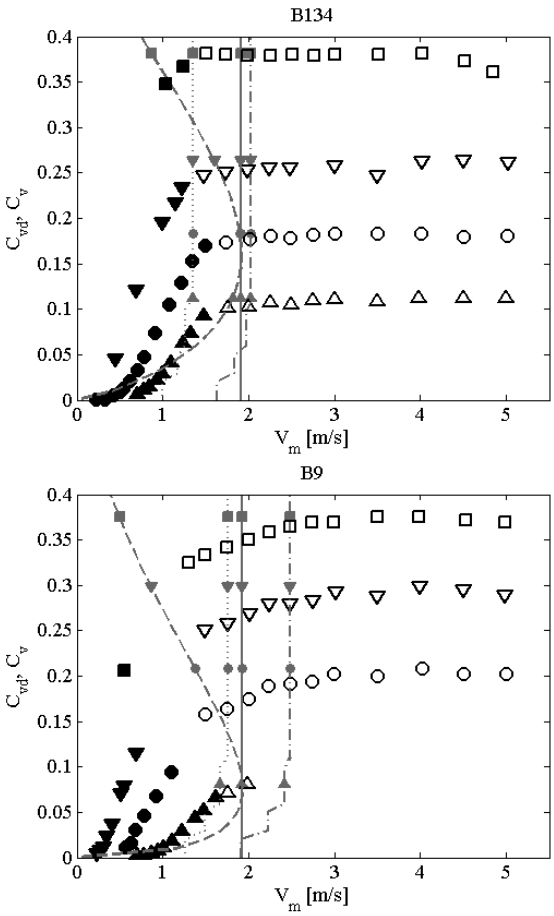
The horizontal-flow Wilson-GIW correlation is calibrated by predictions of an early version of a two-layer model for fully stratified flow. A more refined and complete two-layer model for partially stratified flow can predict the effect provided that proper transport- and friction formulae are used for the top of the bed in the model.

## 5 Experimental modelling for testing predictive models

In order to evaluate predictive modelling approaches, we produce experimental results by testing flow behaviour of heterogeneous mixtures using solids fractions of very different grain sizes over the wide range of volumetric solids concentrations in a 100-mm pipe loop with and inclinable section at Institute of Hydrodynamics (IH) of Czech Academy of Sciences. The test loop is described in details elsewhere [12].

### 5.1 Horizontal flow

Tests in a horizontal pipe were carried out for four narrow-graded fractions of glass beads (B134 of $d_{50}$ = 0.18 mm, B9 of $d_{50}$ = 0.44 mm, B8 of $d_{50}$ = 0.53 mm, TK0810 of $d_{50}$ = 0.9 mm).



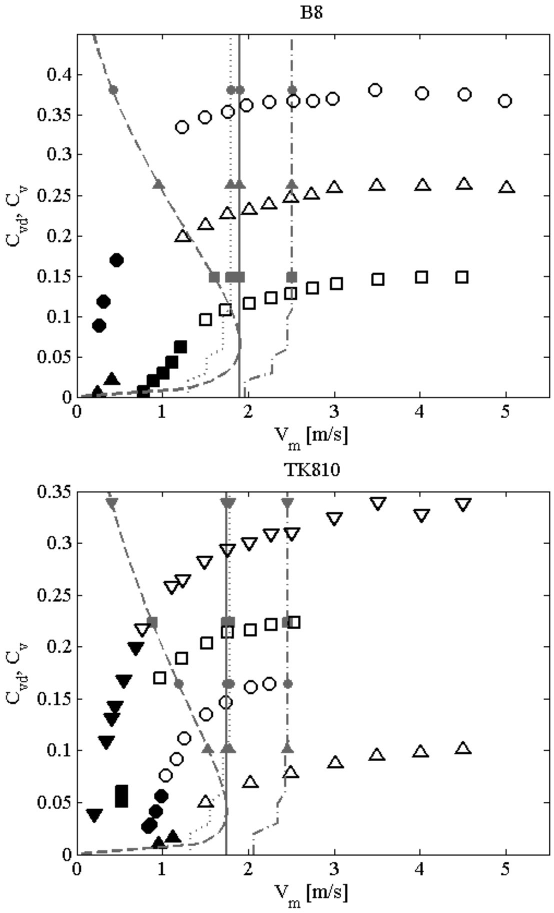



**Fig. 3.** Deposition limit velocity depicted in plot of delivered concentration of solids ($C_{vd}$) against average velocity of slurry flow ($V_m$) in flow of slurries of different solids contents. Plots are for four different tested solids. [13] Legend: black marker = $V_m$ below deposition limit velocity, blank marker = $V_m$ above deposition limit velocity, lines = predictions using different models, best prediction by VSCALC-Vsm (dash line).

Flows of different fractions exhibited rather different behaviour near the deposition limit velocity, where the stationary deposit had started to be formed. While slurry flow of the fine fraction (B134) was quite stable and exhibited a smooth transition between deposit-free flow and flow with stationary deposit, the coarser fractions exhibited transition associated with instabilities and formation of density waves. Under such unstable conditions, measurement of $V_{dl}$ was impossible; hence missing markers around the depoisition limit in the plots for B9, B8 and TK0810 in Figure 3. The experimental results from the horizontal pipe and their comparison with predictive models are described in [13].

### 5.2 Inclined flow

Our new inclined-pipe experiments include measurements of local concentration at the bottom of the pipe in flow at each installed slurry velocity (above and below $V_{dl}$). Also, profiles of local concentration are measured across a pipe cross section at (or very near to) the deposition limit velocity. The local concentration is measured by radiometric instruments with which our test loop is equipped and which are described e.g. in [12].

Our goals are twofold. First, we want to make the experimental identification of $V_{dl}$ less subjective by including the new measuring technique: an establishment of the deposit is sensed through the measurement of local concentration at the bottom of the pipe (at the vertical position 10 mm above the pipe wall). This enables to compare $V_{dl}$ obtained by the traditional (and subjective) visual observations with $V_{dl}$ by the radiometric technique. Second, we aim to evaluate a relation between the distribution of solids across the flow and the establishment of the deposit at the bottom of the flow. We hypothesize that mechanisms responsible for grain support in the flow, and hence for the solids distribution (thus for the shape of a concentration profile), affect the way the deposit is established.

#### *5.2.1 Experimental identification of deposition limit velocity*

The new tests in an inclined pipe were carried out for one narrow-graded fraction of glass beads (B134 of $d_{50}$ = 0.18 mm) and one narrow-graded fraction of sand (P0612 of $d_{50}$ = 0.87 mm). Experimental data for medium-to-coarse sands as P0612 are not available in the literature database.

The use of a measurement of local concentration at the bottom of the pipe, $c_b$, for a determination of the deposition limit velocity is demonstrated in Figure 4. During a test run the flow velocity $V_m$ is gradually decreased and $c_b$ remains approximately constant until the deposition limit is reached. At the deposition limit, $c_b$ jumps to a higher value typical for deposit formed at the bottom of the pipe. In Figure 4, $c_b$ starts to increase at $V_m$ about 2.4 m/s and the deposit starts to be formed (i.e. the deposition limit velocity is reached) at approximately 2.2 m/s.

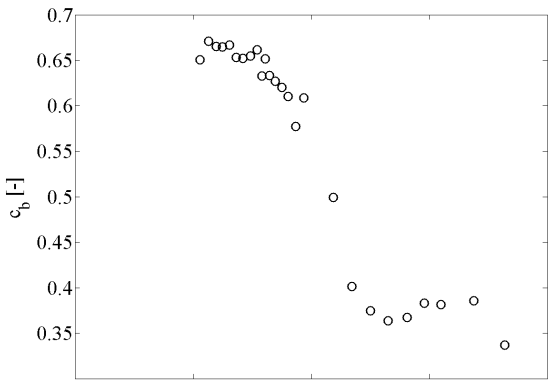



**Fig. 4.** Development of local concentration at bottom of pipe with velocity of P0612-slurry flow ($C_{vd}$ = 0.11) in pipe inclined to +25 degree.

Values of $V_{dl}$ determined using the radiometric method are compared with results of the traditional visual observation in Figure 5. In general, the agreement is good. The visually observed values tend to be slightly lower than the values identified as the velocity at which $c_b$ starts to increase. Typically, a visually observed value corresponds with velocity at which $c_b$ reaches approximately 0.6, which is a value typical for granular deposit (it is bigger than $c_b$ for the sliding bed).

The identified values of $V_{dl}$ are less sensitive to a variation of the pipe inclination angle than the VSCALC model (including the Wilson-Tse method) predicts for the P0612-slurry (medium to coarse sand slurry) at $C_{vd}$ = 0.11 in the 100-mm pipe inclined between 0 degree (horizontal pipe) and +45 degree (ascending pipe) (Figure 5). The Wilson-Tse method was constructed [5] and verified [1,7] for considerably coarser slurries (gravel slurries). We hypothesize that the over-prediction by the method for the medium to coarse sand is caused by the fact that the sand flow is less stratified than the gravel flow. The degree of stratification (expressed by a shape of a concentration profile) varies significantly with a grain size and also with a slope to which flow is inclined. This is demonstrated on our measured profiles below.

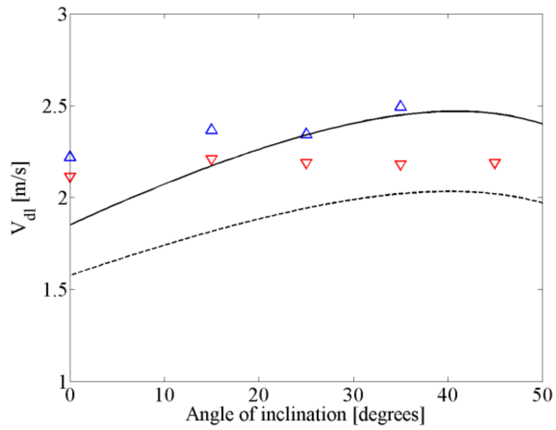



**Fig. 5.** Deposition limit velocity of P0612-slurry flow ($C_{vd}$ = 0.11) in pipe at different inclination angles. Legend: red marker = experiment - visual observation, blue marker = experiment – $c_b$-method, full line = prediction VSCALC-Vsm, dash line = prediction VSCALC-Vs.

### *5.2.2 Distribution of solids concentration at deposition limit velocity*

Solids distributions were measured simultaneously in the ascending leg and in the descending leg of the inclinable invert U-tube, which is a part of our test loop. The measurements were carried out for the fractions of very different grain size and very similar grain density (finer B134 and coarser P0612). This enables to demonstrate the effect of both the grain size and the pipe inclination angle on the shape of the concentration profile.

In Figures 6-9, concentration profiles are plotted for the two fractions at the same delivered concentration ($C_{vd}$ = 0.11) and flow velocity slightly above the deposition limit velocity. It is typical for the finer fraction (Figs. 6-7) that the concentration gradient is mild across the flow suggesting that the degree of stratification is very weak and $c_b$ does not reach a high value even if the flow velocity is only slightly above $V_{dl}$. Moreover, the effect of pipe inclination on the shape of concentration profiles is weak too as the flow exhibit very similar shapes in the ascending pipe (Fig. 6) and descending pipe (Fig. 7).

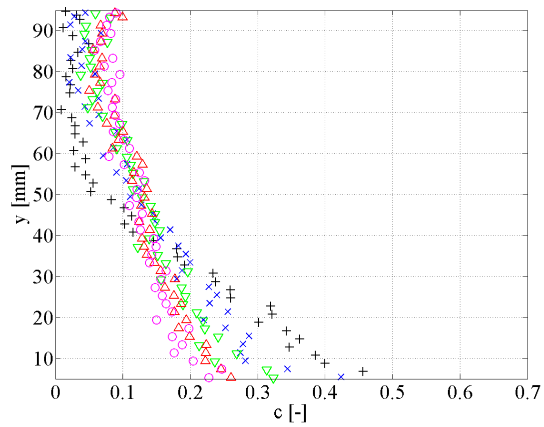



**Fig. 6.** Distribution of granular concentration at velocity near deposition limit for flow of B134-slurry ($C_{vd}$ = 0.11) at different pipe inclinations (ascending pipe). Legend: black = 0 deg, blue = +15 deg, green = +25 deg, red = +35 deg, magenta = +45 deg.

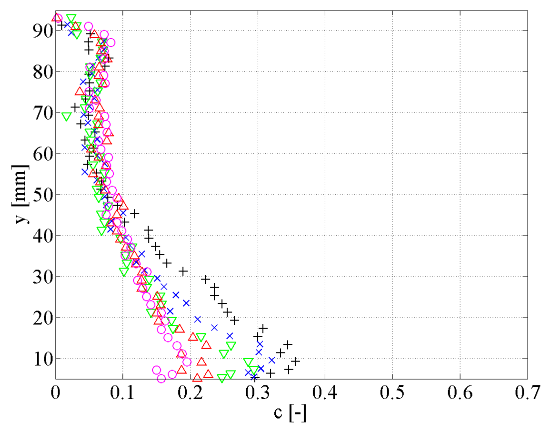



**Fig. 7.** Distribution of granular concentration at velocity near deposition limit for flow of B134-slurry ($C_{vd}$ = 0.11) at different pipe inclinations (descending pipe). Legend: black = 0 deg, blue = -15 deg, green = -25 deg, red = -35 deg, magenta = -45 deg.

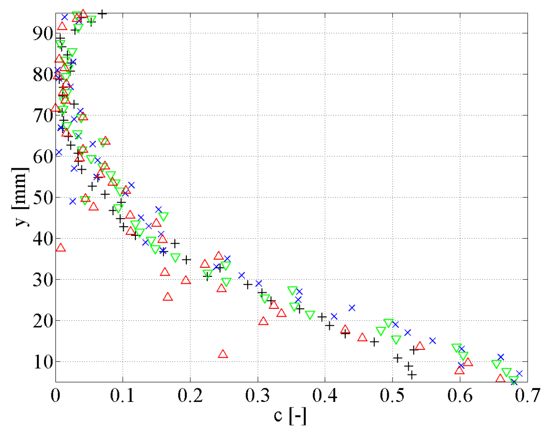



**Fig. 8.** Distribution of granular concentration at velocity near deposition limit for flow of P0612-slurry ($C_{vd}$ = 0.11) at different pipe inclinations (ascending pipe). Legend: black = 0 deg, blue = +15 deg, green = +25 deg, red = +35 deg.

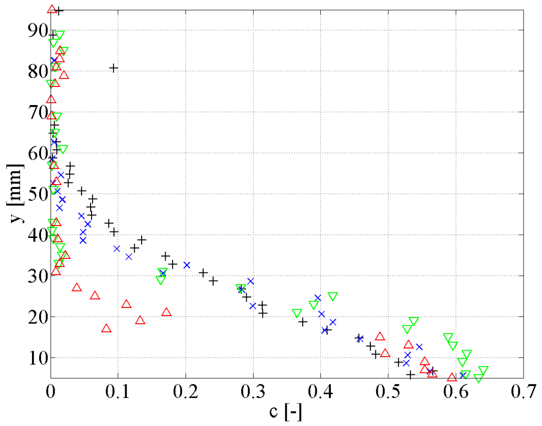



**Fig. 9.** Distribution of granular concentration at velocity near deposition limit for flow of P0612-slurry ($C_{vd}$ = 0.11) at different pipe inclinations (descending pipe). Legend: black = 0 deg, blue = -15 deg, green = -25 deg, red = -35 deg.

A situation is very different flow carrying the medium-to-coarse sand (Fig. 8-9). The flow is partially stratified with a steep concentration gradient and with high values of the local $c_b$ at the velocity slightly above the deposition limit. Furthermore, the effect of pipe inclination is strong as the flow tends to be less stratified in the ascending pipe (Fig. 8) that in the descending pipe (Fig. 9) at the same slope. This is in an agreement with our earlier observation at velocities higher above the deposition limit in other pipe loop [6]. Mechanisms leading to this effect are described in [6] as well, their incorporation to an appropriate model for the effect of pipe inclination on the deposition limit velocity in partially stratified settling slurry flows in work currently in progress.

## 6 Conclusions

Existing modelling approaches for pipe inclination effect on the deposition limit velocity seem to be inappropriate for settling slurry flow which are partially stratified.

Experimental results for a medium-to-coarse sand are new to the literature database. They indicate that the effect of the angle of flow inclination on the deposition limit velocity is weaker than predicted by the Wilson-Tse method calibrated and validated for coarser (gravel) fractions but not negligible as expected for finer fractions (fine to medium sands). A new modelling approach must be found for the medium to coarse sand slurries.

A new experimental technique of an identification of the deposition limit velocity by sensing a change in the local concentration at the bottom of the pipe using a collimated gamma-ray gives reliable results provided that the solids concentration in a pipe is high enough to constitute a deposit. The results agree well with the visual observations.

Solids distribution in a pipe cross section tends to vary with the angle of pipe inclination. Modelling of the process of deposit formation using mechanisms responsible for solids distribution in settling slurry flow in work currently in progress.

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