Flow regimes over particle beds
Experimental studies of particle transport in horizontal pipes

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ABSTRACT

A flow rig for investigation of liquid-particle transport in pipes has been designed and set up. Analysis of slurry transport in horizontal and inclined pipes and annuli is possible, as well as options for running fluids with various rheological properties. The transport of liquid-particle flow, in particular dune formation, depends largely on flow rate. Rheology has also been reported to be very important for dune formation mechanisms. We have found a distinct correlation between pressure drop and transport velocity that can be used for identification of slurry flow regimes.

INTRODUCTION

There is a wide range of industrial applications of solid-liquid transport in pipes. Among these are coal transport, radioactive waste transport and particle transport in the petroleum industry. For maximum particle transport rate dune formation should be avoided. Dunes appear most frequently in horizontal or near horizontal pipes and annuli. Annulus geometries play an important role in applications like oil well drilling. Once beds of particles are accumulated, they are difficult to remove. They may even lead to pipe blockage.

Beds of particles are formed at sufficiently low flow velocities, typically in the range of 0.2 - 0.5 m/s. The current work is expanding on the works of Ramadan[1] and Ramadan *et al.*[2] who mention dunes and ripples formation in their tests of drilling cuttings transport.

There are surprisingly few papers in the literature dealing with the mechanics of dunes formation and behavior in pipes. Doron and Barnea[3] conducted extensive experimental research in Newtonian fluid to obtain pressure drop and flow pattern for pipe flow of solid-liquid mixtures. Based on the experiments they developed a model of flowing beds as being constituted of three layers; a stationary at the bottom, a moving bed layer above it and a heterogeneous mixture layer at the top.

Turian and Yuan[4] based their pressure drop correlations on a very large experimental data bank and constructed a qualitative flow regime classification based on logarithmic plots of the pressure gradient against mean flow velocity. Even though their approach was semi-theoretical, i.e. correlation of empirical data with the theoretical reasonings, the actual situation was represented. They found it expedient to develop a separate correlation for each of the four flow regimes and used them to outline the various flow regimes.

Takahashi *et al.*[5] studied the stability of solid-liquid mixtures at low velocities in horizontal pipes, both experimentally and theoretically. They observed dunes causing pressure fluctuations associated with their movement. The fluctuations increased with the solid concentration up to 10%.

Peysson[6] emphasize that dispersions of solid/liquid are common in drilling and production in the oil industry. In perspective of the complex mixture mixture behavior, the modelling of the specific properties is not easy. This calls for fundamental knowledge in different areas such as rheology, physico-chemistry, hydrodynamics and thermodynamics.

A detailed analysis of the effect of cuttings bed properties during drilling operations, e.g. bed gel formation, was made by Saasen and Løklingholm[7]. They showed improvement of drilling at low viscosity and low gel forming fluids compared to earlier operations using thicker drilling fluids.

A mechanistic model for underbalanced drilling with aerated drilling fluids was presented by Zhou *et al.*[8]. Their model determines flow pattern and predicts frictional pressure losses in horizontal concentric annulus. Also during their experiments, cuttings dunes were observed at low liquid flow rate.

In the present work we investigate the important characteristics of the solid-liquid mixture by a relationship between friction plus local acceleration pressure drop ΔP and flow rate. Data were analyzed using Matlab (The MathWorks, Inc). A log-log plot of ΔP versus velocity (U) was found useful to identify slurry flow regimes. This way to display data has been well known to loose boundary hydraulics and dates back at least to 1957[9].

EXPERIMENTAL

A simplified view of the experimental setup is shown in figure 1. The flow loop constitutes two sections; one horizontal and one section inclined 5^o from horizontal. The pipe inner diameter is 40 mm. Sections of 1.5 m glass pipes are connected by detachable joints. Liquid (water) is supplied from a tank (item 1 in Fig. 1). The liquid is circulated through the system by a Moineau screw pump (item 3 and motor,item 2). The glass bead particles with a density of 2.52 g/cc in the diameter range 250 to 300 μm, were added initially from the top of the hydrocyclone (item 7). They were fed from the hydrocyclone, flowing through the horizontal section and then to the inclined section. Finally, the particles re-enter the hydrocyclone and are recirculated. The volumetric flow rate is measured using a Coriolis flowmeter (item 5), mounted in vertical position preceding the pump. A pressure column (item 4) is mounted to dampen pressure variations caused by the pump. The venturi mixer (item 6) provides a nearly homogeneous particle slurry. Four pressure recording stations are mounted in the test sections: two on the horizontal section (M1 and M2), and two on the inclined section (M3 and M4). M1, located 2 m from the venturi mixer serves as inlet pressure measurement for the horizontal section. Also it is used during the experimental procedure to determine when the flow has been properly stabilized. All the measuring stations use a vertical water filled thin pipe as a common pressure reference. At zero flow they will therefore all measure the same value. At flowing situation the measured

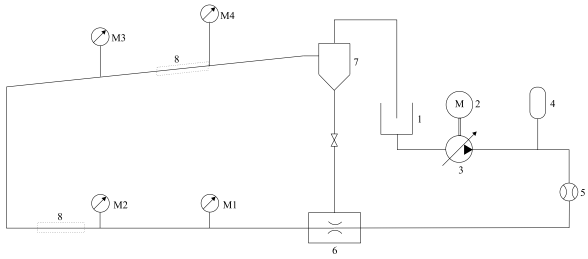

Figure 1: Schematic representation of the flow loop system.

pressure will be a sum of frictional pressure drop and Bernoulli (local acceleration) contributions. The distance between M1 and M3 (as well as M3 and M4) is 1.5 m. To enable optical recording of the particle transport events, a rectangular optical box (item 8) filled with water is mounted in both section. This minimizes the optical impact of pipe curvature. The flowmeter and the differential pressure transmitters are connected to a data acquisition system, using LabView (National Instruments) as programming environment.

All experimental test series started at highest velocity, reducing the velocity stepwise (in 0.04 l/s steps) for each new test. This was done in order to minimize the effect of uneven dune formation in the test sections.

DUNES GENERATION

When beds of particles in slurry flows are exposed to shear by the carrier fluid they are deformed, and dunes or ripples are commonly generated at low velocities. Dunes exert a significant influence on the flow process, such as frictional pressure drop, erosion and deposition[10]. A dune can be visualized as being composed of a toe, trough, stoss, crest and brink (see illustration in Fig. 2). Particles deposit at the bottom of the pipe, normally according to size. Regarding particle motion one may distinguish between traction and saltation. During traction, particles are moving by rolling or climbing/sliding (Fig. 3) along the bed, while during saltation, particles are moving by hopping along the bed (Fig. 4).

During erosion, particles are moved from the back of the dune, deposited at the crest, and avalanche down on the lee side. As the flow area is expanding downstream on the crest, the velocity decreases correspondingly, and the pressure, according to Bernoulli equation rebuilds.

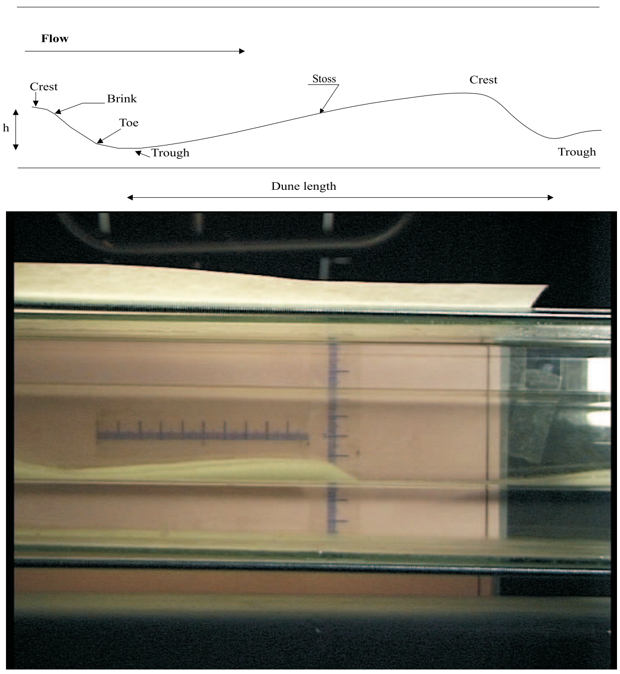

Figure 2: Morphology of a dune. Flowrate 0.38 l/s.

Downstream at the lee side, there is a flow reversal zone leading to a velocity and pressure fluctuation. At some distance downstream the trough, a flow reattachment (stagnation point) occurs and the main flow again governs the available flow area.

RESULTS AND DISCUSSIONS

The dune flow analysis in this work is carried out for both Newtonian and

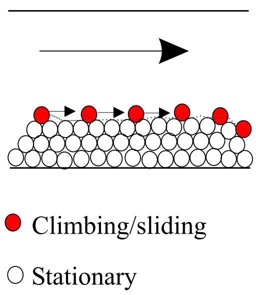

Figure 3: Particle sliding.

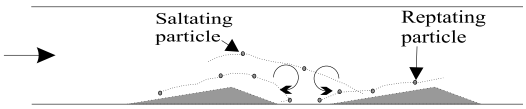

Figure 4: Saltating and reptating particles.

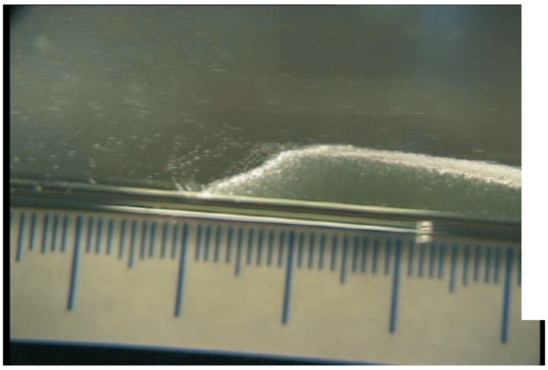

Figure 5: Flow reversal zone downstream the crest. The flow (Q=0.34 l/s) direction is from right to left on the inclined section. 200 ppm of PAC solution is used.

non-Newtonian water based liquid. The amount of particles (glass beads) is 2% by volume (dry, in volume relative to hydrocylone and the test loop section). We analyzed primarily the relationship between differential pressure ΔP (due to friction and local acceleration) and flow rate. Water (i.e. Newtonian flow) was used first. The results obtained from this test is plotted as a basis and reference for the non-Newtonian fluid.

The following plot (Fig. 6) serves as the base case for identification of the different flow regimes. In this plot the pressure drop spans between 0.44 to 3.5 mbar while the velocities lie between 0.14 to 0.72 m/s. It is clearly seen that as U is increasing ΔP is also increasing up to a maximum at U=0.24 m/s. In this region the pressure drop variations do not increase before approaching this velocity value. This is the so-called "*lower flow regime*". In this regime the particles are transported in sliding or climbing motion. The bedforms were usually flat beds, while some times also very small amplitude dunes were seen, probably ripples due to its sharp lee angle.

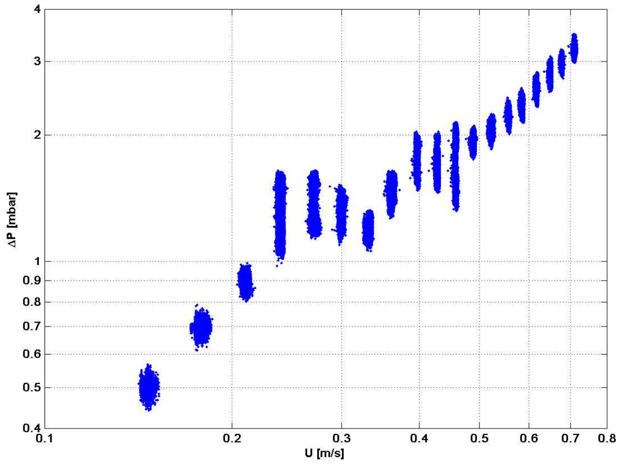

Figure 6: Log-log plot of ΔP versus U for water in the horizontal section.

In the region between U = 0.24 m/s and U = 0.46 m/s the pressure drop is fluctuating and there is a local minimum ΔP of 0.33 mbar corresponding to U = 0.33 m/s. Dune formation is developing in time and make the flow unstable. The mechanism may resemble Kelvin-Helmholtz instability, in combination with a shearing particle motion. In this region the so-called "*transition flow regime*" is depicted. The bedforms are mainly dunes and the ΔP is varying with time. The modes of particle transport are saltation and reptation. The pressure drop variations are due to flow area variation and thus mainly a Bernoulli effect. This was also observed by Zhou *et al.*[8].

This fluctuating transition regime could be divided into two subregimes, namely:

1. The pressure drop ΔP is slightly decreasing with increasing U. In this region with mixture velocities between 0.24 and 0.33 m/s, the ΔP variations were caused by the flow area variations between the dunes. The recirculation wake behind the crest was extending nearly to the preceding dune. However, a nearly bed free region as-

sociated with a stagnation point separating the dunes was observed. In this region spurious individual particles were thrown stochastically forward and backward. The following plot (figure 7) of ΔP versus time shows the fluid pressure variation as a dune is passing. Apparent from the plot is the ΔP variation, from a minimum indicating a dune crest and to a maximum indicating the reattachment (or stagnation) point somewhere downstream the dune toe. The ΔP in this plot decreases along the dune stoss reaching to a minimum again at the next dune crest. The sliding/moving bed

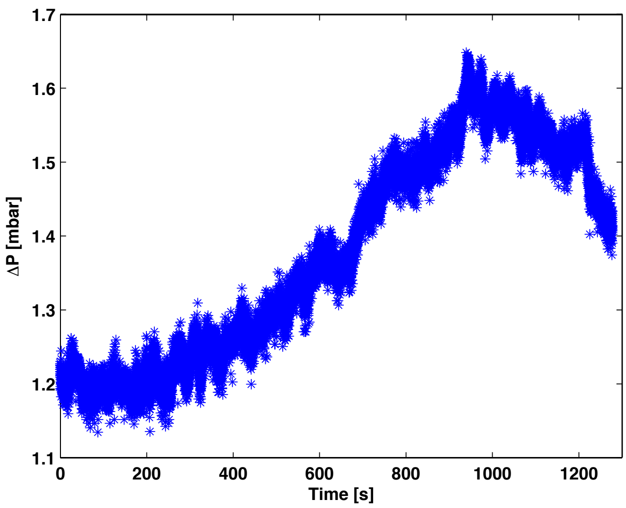

Figure 7: Fluid pressure on the crest, at the lee and on the stoss. U≈0.27 m/s.

and the particles trajectory associated with saltation from the lee side to the crest of the preceding dune was very clear.

2. In the other sub regime, for flow velocities between 0.33 and 0.46 m/s the pressure variations increase slightly with respect to flow velocity. An interesting feature here was the succession of medium dunes and small dunes. "Megadunes" , i.e. smaller dunes superimposed on other larger dunes or vice versa, were also seen. These large dunes overtook the small dunes so that they vanished and transformed into a uniform bed.

Another interesting result seen from Fig. 6 is the local minimum pressure drop at mixture velocity U = 0.33 m/s. Above this critical velocity, as also reported by Doron and Barnea[3], Raudkivi[9] and Takahashi *et al.*[5], we find the incipient conditions of flow with particles in suspension.

The last region depicted in Fig. 6 is the so-called "*upper flow regime*". This regime thus starts from U = 0.46 m/s. The type of the observed bedform was antidunes. A thin stationary bed layer was observed and the particles were saltating on top of it. An illustration of this type of bedform is presented in Fig. 8.

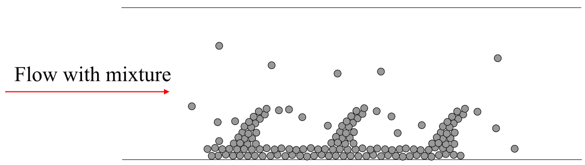

Figure 8: Illustration of flow in upper regime

Two different Polyanionic cellulose (PAC) concentrations were used: 200 and 400 ppm dissolved in water. A mixer was used to prepare the solution before filling into to the flow loop. A satisfactory polymer distribution was achieved after one day's pumping time.

The fluid polymer mixtures are described by:

$$\tau = \tau_0 + K \cdot \dot{\gamma}^n, \qquad (1)$$

where,

τ is shear stress [Pa],
τ_0 is the yield stress [Pa],
K is the consistency factor [Pa·s^n],
$\dot{\gamma}$ is the shear rate [s^{-1}], and
n is the power-law index

and $\tau_0 = 0$ for the PAC solutions.

The rheology is presented in table 1. The measurements were taken using a Physica UDS 200 rheometer with concentric cylinder configuration Z3.1 DIN. The two samples were taken at 20^{o}C downwards with ten different shear rates. It should be noted that the viscosities were measured at ten seconds intervals between the shear rates on different separate samples than that from the tank.

Table 1: Viscosity data

	PAC200	PAC400
n	0.4357	0.4275
K	0.2491	0.5561

Table 2 and Fig 9 summarize the tests after using PAC.

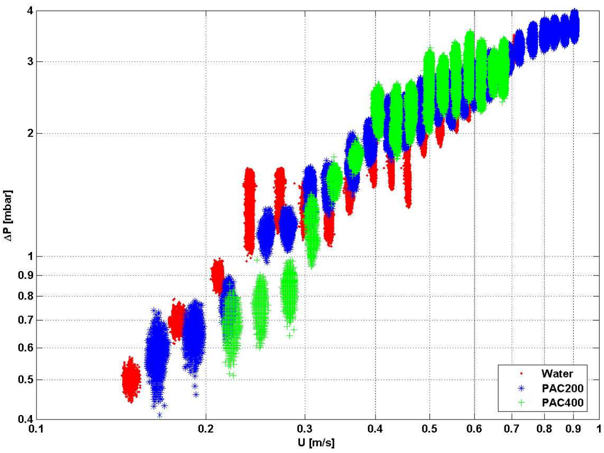

Figure 9: Log-log plot of ΔP versus U for water, PAC200 and PAC400 in the horizontal section.

In Table 2 the flow velocities with the different flow regimes is presented for different fluid systems. In Fig. 9 log(ΔP) is plotted against log(U) showing flowing of water, PAC200 and PAC400 solutions.

Table 2: Flow velocities in m/s

Flow regimes	Water	PAC200	PAC400
Lower	0-0.24	0-≈0.27	0-0.31
Transition	0.24-0.46	0.27-0-48	0-31-0.53
Upper	>0.46	>0.48	>0.53

Separation problems were encountered after adding PAC to the loop. The glass particles went more easily into suspension, causing the hydrocyclone separation efficiency to be reduced. It was no longer possible to fully separate particles, and they were transported to the tank and recirculated through the pump. It was decided to trap the particles by putting a 25 l plastic barrel at the exit of the pipe entering the tank. The surplus fluid would then float over into the tank, leaving the particles behind in the barrel. This was seen to be quite efficient. After accomplishing the run for the 200 ppm PAC, 17.4% of particles were collected and put back into the flow loop before changing to 400 ppm PAC.

In Fig. 9 the flow velocity range is 0.14 to 0.91 m/s corresponding to 0.38 and 3.98 mbar average pressure drop, respectively. The pressure drop is lower for both PAC200 and PAC400 flows in the lower regime with respect to water flow. However, the reason is most likely the gradually reduced amount of particles associated with the inefficiency of the hydrocyclone in conjunction with the polymer flow. There is, however, a small overlap of the data in the transition regime. In the upper regime there is a relatively good overlap of the different fluids. The reason might be that the experimental test series for each fluid type always started at high flow rates . Thus there is always sufficient amount of particles when flowing in the upper regime. It could also be seen from the figure that both PAC200 and PAC400 exhibit higher ΔP's in this regime.

The reason for starting the test series at highest flow rates was also in order to avoid from air coming into the pipe at the pressure damping T-junction (4) after the pump. Higher flow rate causes is set up by higher pump pressure thus maintaining a sufficiently high liquid column at (4).

During the 400 ppm PAC tests, 30% of particles were collected from the barrel and returned back before proceeding to the next test series. From a slurry transportation point of view this is of course a positive effect; since increasing the viscosity of the flowing medium would facilitate the lift of particles into the conveying liquid. It was not attempted to increase the amount of PAC further, due to the problems met with the hydrocyclone even with low flow rates. At the end of this test 780 ml of glass particles had accumulated.

It was observed that PAC may cause the dunes to become more consolidated, although they become less compact than with water as carrier fluid. With water only, the dunes are in fact more compact but still easier to transport. In the polymer case the the dunes become more consolidated because of the large increase of viscosity associated with low internal shear. At the same time the external fluid shear rate increases over the dunes resulting in decreased flow viscosity.

In the presence of the PAC solutions higher pump rate was needed to break up dunes that were formed and consolidated after pump stop for a day or so. In addition, high pump rate was also needed to shear them from the pipe wall. The PAC - water mixture undergoes gel formation, and causes particles to be glued together. Saasen and Løklingholm[7] mentioned that gel formation was controlled by the combination of water, solid particles and polymers. Their observation therefore supports the observations done in our tests. The dunes also became more distinct and with larger dune-to-dune distance.

It was also observed with PAC, and not with water, that some particles were sliding along the pipe wall approximately at the height of the dune crests. The slurry system seems to split into a more or less straight flow channel above the dunes and detached lower regions of recirculation between the dunes. In a layer between these regions the pattern of sliding particles along the wall was observed.

Another contribution to the wall slide phenomenon comes from a lateral migration at the level of the crest tops. As mentioned previously a recirculation zone is found there. We observed the recirculation not only in the vertical plane. A recirculation was also sideways from the flow core, both towards the pipe center and towards the pipe wall.

The bed consolidation seemed to increase when PAC concentration was increased. A similar trend was observed for the lowest flow rate needed mobilize the particles. When using 200 ppm of PAC, this threshold was $Q = 0.28$ l/s ($U = 0.22$ m/s). Increasing the amount of PAC to 400 ppm, the threshold was $Q = 0.36$ l/s ($U = 0.29$ m/s), 22 % higher than with 200 ppm. For water, this critical flow rate was observed at as low as 0.18 l/s ($U{=}0.14$ m/s). It was difficult to conduct reliable tests at lower flow rates than 0.22 l/s because of air entrainment from the 3-ways oscillation damping junction (item 4). Apparently also higher energy is needed to mobilize the beds with the PAC concentration increasing. At these critical flow rates, the ΔP difference was also at a local minimum.

CONCLUSIONS

This work demonstrates that dunes definitely occur as an important regime in particle slurry transport. The flow loop provides reliable and valuable data for frictional plus local acceleration pressure drop ΔP in both horizontal and deviated pipes. The relation between ΔP and flow velocity U is an important tool for identification of flow regimes, and may be used independently of optical and visual observation.

Results from three series of experiments were shown, using water and two different concentrations of PAC. The different flow regimes were identified by using a log-log correlation of ΔP and flow velocity U. Although only three types of fluid one fixed particle size, and one average particle concentration have been used in our experiments, these observations can be expected to be representative.

The data obtained using PAC solutions demonstrated the limited particle separation efficiency of the hydrocyclone for shear thinning liquids. Another separator design clearly needs to be developed for fluids with stronger shear thinning properties and also for Newtonian fluids with higher viscosity.

For slurry transport optimization, this means that an optimum amount of PAC is when the fluid beds do not form gel and at the same time the liquid is capable of lifting the particles into the flow.

ACKNOWLEDGEMENTS

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Errata in: "Flow regimes over particle beds Experimental studies of particle transport in horizontal pipes"

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The time scale in figure 7 is mistyped in the published version[1]. The correct figure is:

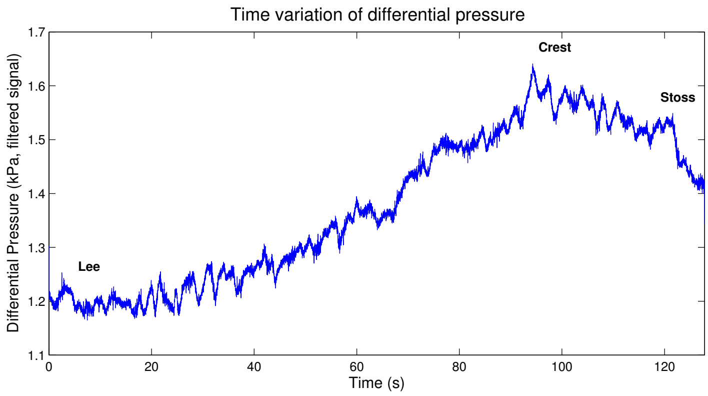

Figure 7: Fluid pressure on the crest, at the lee and on the stoss. U≈ 0.27 m/s.

[1]Rabenjafimanantsoa, A. H., Time, R. and Saasen, A. (2005), "Flow regimes over particles beds - Experimental Studies of Particle Transport in Horizontal Pipes", Annual Transactions of the Nordic Rheology Society, vol. 13, pp. 99 - 106.