Dunes dynamics and turbulence structures over particle beds Experimental studies and numerical simulations.

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ABSTRACT

Transport of particles/cuttings in circular pipes involves formation of dunes in the transition flow regime. The interface between the bed and fluid (both Newtonian and non Newtonian) flowing on top experiences accelerative/shearing forces leading to instability of bed. The dune and bed roughness controls the particle transport, generate turbulence and create flow resistance. The instantaneous velocity profiles over the dunes sheared by water and viscous fluid was measured by means of Ultrasound Velocity Profile (UVP) Monitoring instrument. Numerical simulation was conducted to predict the velocity profiles behavior.

INTRODUCTION

Deposition and erosion of particles by the flowing medium are phenomena occurring in many industrial processes, such as transport of cuttings from an oil well to the surface. Different bedforms are reported to form during transport of solid-liquid mixtures or drilling cuttings in wells. Dunes occur commonly at low and moderate flow velocities and are responsible for the bedload transport and flow friction. Dune buildup may eventually lead to blockage of pipes or wells. The current work is expanding the works of Ramadan[1] and Ramadan *et al.*[2] who mentioned that dunes and ripples were forming during their tests. A detail study of dune dynamics clearly was needed to be carried out.

Fluid flow over dunes is divided in five different zones: the accelerating flow over the dune crest, a flow separation zone on the crests lee-side with its characteristic recirculation pattern, a deceleration region overlying the separation zone and extended downstream, an outer near surface region and a region where the flow reattaches[5,9].

Much laboratory research focus on the study of fixed artificial dunes. However, natural dunes are often three-dimensional, and may exhibit temporal variation in dune wavelength and steepness.

In our work, the instantaneous velocity profile over the dunes were measured by the means of an UVP Monitor[3]. The technique is non intrusive and based on measuring the instantaneous velocity profile over the particles bed. Dunes dynamics as well as flow over dunes are obtained in Newtonian and non-Newtonian fluids.

The UVP instrument can also be used in characterizing the rheological behavior of solid-liquid mixture. Shekarriz and Sheen[6] demonstrated the new approach for measurement of the velocity profile in a heterogeneous slurry pipe flow in viscous Newtonian and non-Newtonian fluid.

A novel in-line and non-invasive rheological instrument and technique was evaluated and tested by combining UVP and pressure difference method[7,8]. The rheological behavior of the suspensions flowing in a pipe was obtained.

Further literature on the UVP method may be found on the Met-Flow SA web page[10].

EXPERIMENTAL FLOW LOOP

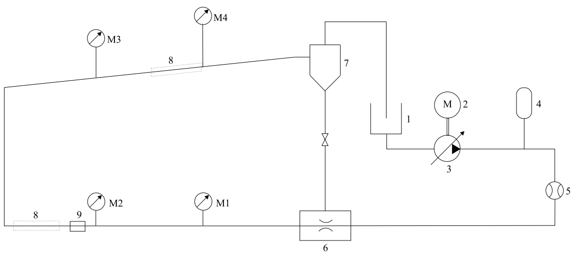

Figure 1: Schematic representation of the flow loop system.

The flow loop constitutes a horizontal and 5^o inclined (from horizontal) section. The pipe inner diameter is 40 mm. Sections of 1.5 m glass pipes are connected by detachable joints. A brief description of the flow loop is presented in an other paper by Rabenjafimanantsoa *et al.*[4]. In figure 1 a schematic description of the flow loop system is presented.

UVP PRINCIPLE AND ARRANGEMENT

The UVP-XW instrument consists of transducers, a multiplexer box, and a PC unit. In addition a digital oscilloscope (LeCroy,1 GHz Model LC 534) was used. The oscilloscope is very important for optimum ultrasonic beam setup. For this work we used 4 MHz transducers (7 mm in diameter). For further description, please refer to the UVP Monitor user guide[3].

The UVP instrument measures Doppler shift of a pulsed ultrasonic beam scattered from particles in the flowing medium. Time of flight of the pulse after emission gives the distance to the scattering particles. The cross sectional velocity profile is obtained from the Doppler shift from distinct particles. This Doppler shift is given by:

$$\frac{v}{c} = \frac{f_d}{2f_o} \tag{1}$$

where,

- v is the velocity in the direction of the ultrasonic beam [m/s],
- c is the speed of sound in water [m/s],
- f_d is the Doppler shift [Hz], and
- f_o is the transmitting frequency [Hz].

The time between transmitted and received signal is given by:

$$t = \frac{2x}{c} \tag{2}$$

where,

- t is the time between transmitted and received signal [s],and
- x is the distance of scattering particle from the transducer [m].

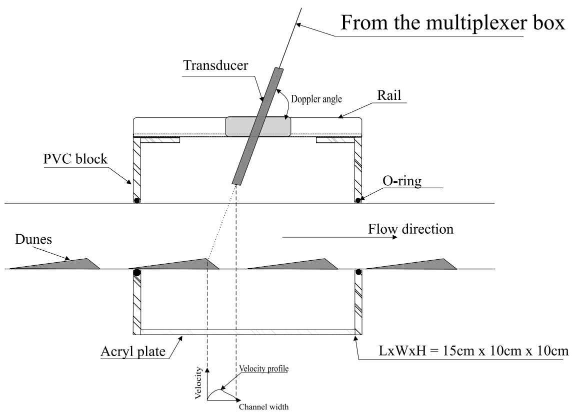

Figure 2: Arrangement of the UVP in the particle flow loop system.

The velocity profile data file from the UVP are stored on hard disk. Pulse repetition frequency and channel information are also stored. A total of 128 (position) channels represent the beam range. Each measurement series consists of 1000 profiles, thus giving an array of 128x1000 data points. Another program ("MFXW", shipped with the UVP) can be launched for quick review of stored velocity profiles. Figure 2 shows the details of the arrangement of the UVP to the particle flow loop. This is referred to as unit 9 in Fig. 1. The capabilities of the UVP with the mentioned arrangement to measure the dunes are shown. The transducer is mounted at an angle of 12^o from vertical (see Fig. 2 for explanation) for optimum elimination reflections from the pipe walls. Negative velocities indicate flow towards the transducer, and vice versa.

EXPERIMENTAL RESULTS

The particles used to generate dunes were spherical glass beads of 250-300μm in diameter. The data were processed off-line using Matlab (The MathWorks, Inc). Seeding particles were used to increase the UVP signal. Neutrally buoyant particles (density 1.05 kg/l, 63-80μm, concentration 0.7 g/l) from Griltex, EMS-Chemie AG Switzerland were used.

The main flow erodes particles from the stoss of the dune. The particles deposit at the crest and avalanche down on the lee side. The pressure along the dunes varies largely in accordance with the Bernoulli equation. The lowest pressure is over the crest, while downstream on the crest where the flow area expands the fluid moves slowly and the pressure is restored[4]. At the crests lee side, flow reversal occurs leading to considerable fluctuation. Downstream the reattachment point particle may be re-injected into the main flow.

With single phase flow using Polyanionic cellulose (PAC) polymer the flow profile shown in Fig. 3 was obtained. Only seeding particles were present, the flow and particles moving away from the transducer. The abscissa represents the profiles number (or time evolution) while the ordinate represents distance from transducer face. The colorbar represents the velocities in millimeters per second. These conventions applies also to all subsequent profile plots.

In Fig. 4 is shown a typical profile with

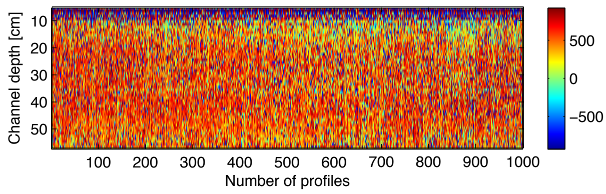

Figure 3: Instantaneous velocity profiles in an empty pipe. The flowing medium (from right to left) is viscosified and U = 0.27 m/s.

particles and dune transport. One may observe from profile numbers 400 to 900 the passage of a dune. The green field (zero velocity has green color) represents the dune. One may also see the toe of the preceding dune from profiles 1 to 100. Above the dunes the instantaneous velocity profiles are displayed. The flow reversal is also revealed.

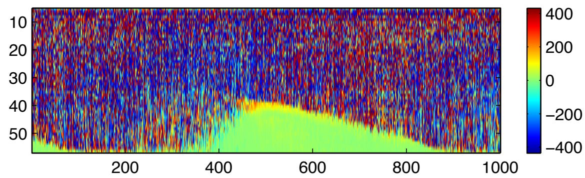

Figure 4: Instantaneous velocity profiles over one dune. The flowing medium (from right to left) is water and U = 0.27 m/s.

The next figure 5 shows the flow profile at further increased liquid viscosity. The flow rate is almost doubled. The higher speed is clearly seen in red color at the stoss of the dune. Again, the flow reversal is

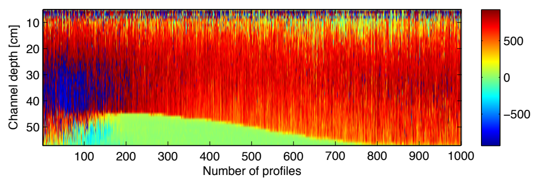

Figure 5: Instantaneous velocity profiles over one dune. The flowing medium (from right to left) is viscosified and U = 0.46 m/s.

revealed downstream the dune crest. This is situated approximately between profiles number 50 and 180. Above this there is also a negative flow region.

As the flow passes over the dune crest, the particles partly follow the flow reversal profile. This is shown as dark blue (negative) indicating flow towards. A thin laser was used to study the flow pattern along a horizontal line transversal to the flow, slightly above the crest. A flow reversal from the pipe wall towards the crest center was clearly seen.

The flow detachment and separation zone is clearly seen in both figures as shown in Fig. 5 and 6. It is situated between profiles number 700 and 800 in Fig. 6. In Fig. 5 the same zone is depicted between approximately profile number 50 and 150. This flow reversal was also clearly visualized by the video still picture in Fig. 7. The picture was from the inclined section.

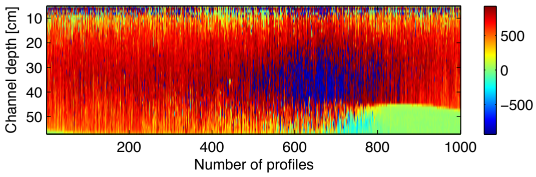

Figure 6: Flow reversal. The flow (U=0.27 m/s) direction is from right to left on the inclined section.

The flow reattachment point is close to the left edge of the picture and the flow continues developing towards the next dune to the left (not seen in the picture).

NUMERICAL SIMULATION

The numerical simulation focus on the rheological models in computational fluid dynamic (CFD) programs. In this study we used the program Fluent, which is a 3D general-purpose fluid simulation program with capabilities to use different viscous models.

In the numerical study we used a geometry with fixed artificial dunes. The geometry of the dunes in Fig. 8 was based on video recordings. The flow rate of water was Q = 0.36 l/s, which is equivalent to 0.29 m/s inlet velocity.

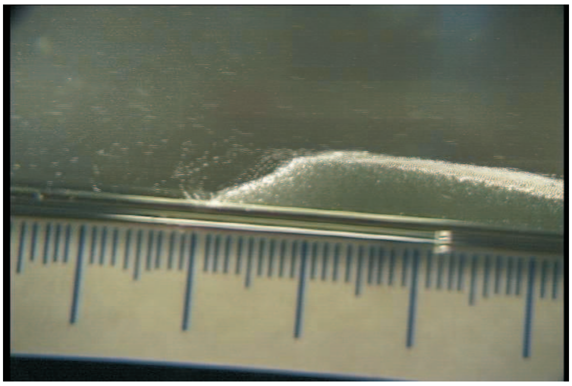

Figure 7: Flow reversal. The flow (U=0.27 m/s) direction is from right to left on the inclined section. 200 ppm of PAC dissolved in water was used.

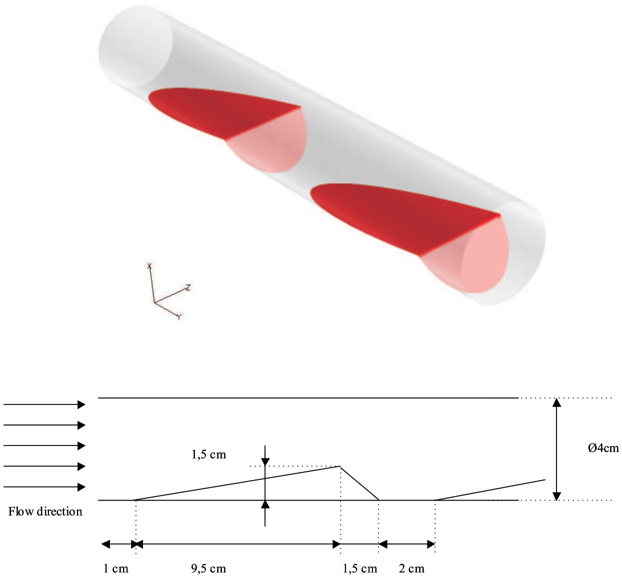

Figure 8: The geometry of the dune.

Simulation with water

The first simulation was done using only water as the flowing medium. Fig. 9 shows the result of the simulation.

Herschel-Bulkley model

Fluent has different ready-to-use viscosity models. However, in this study we used the capabilities in Used Defined Function

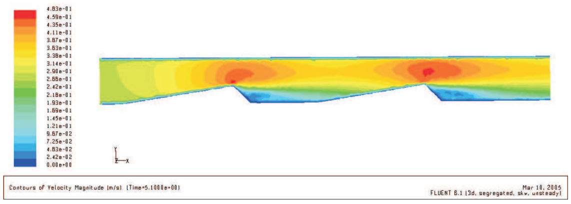

Figure 9: Velocity contours water. The flow is from left to right.

(UDF's) in Fluent[11]. First we used the Herschel Bulkley model:

$$\eta = \frac{\tau_0 + k \cdot [\dot{\gamma}^n - [\frac{\tau_0}{\eta_0}]^n]}{\dot{\gamma}} \quad (3)$$

when $\dot{\gamma} > \frac{\tau_0}{\eta_0}$, and

$$\eta = \eta_0 \quad (4)$$

when $\dot{\gamma} < \frac{\tau_0}{\eta_0}$, where,

- η is viscosity,
- η_0 $= 1.64 \cdot 10^{-3}$ is the yielding viscosity [N·s/m^2],
- τ_0 $= 0$ is the yield stress [N/m^2],
- k $= 1$ is the consistency factor,
- $\dot{\gamma}$ is the shear rate, and
- n $= 0.8$ is the power-law index.

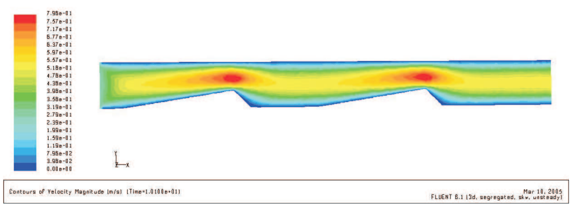

Figure 10: Velocity contours of the Herschel-Bulkley model with n = 0.8. The flow is from left to right.

Experimental viscosity

Using the viscosity from experimental measurements[4] on the fluid where 200 ppm PAC was dissolved in water, the following result was obtained (see Fig. 11).

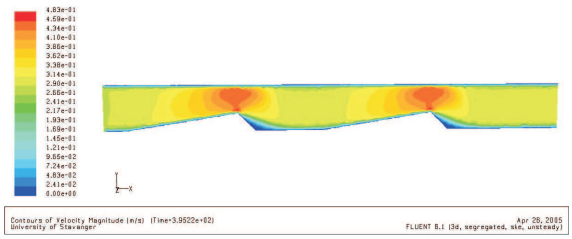

Figure 11: Velocity contours from experimental viscosity. The flow is from left to right.

Strain rate

As we see from figures 12, 13 and 14 the straining point is changed when the viscous models are implemented. The straining point is moved upstream on the dune crest. This is contradictory to what is experienced in real life. The explanation for this is that these numerical simulations are of fixed artificial dunes with no porosity. When a viscous fluid flows over a dune it will seep into the pores and bind the dune particles more together. This is an effect not accounted for in numerical simulations.

Figures 12, 13 and 14 show the simulation results from water, Herschel-Bulkley model and experimental viscosity, respectively.

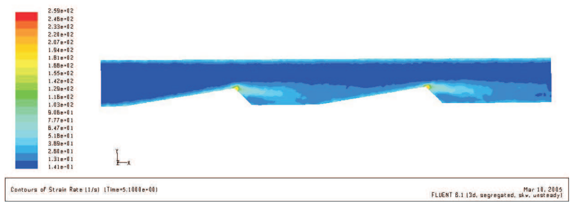

Figure 12: Strain rate from water. The flow is from left to right.

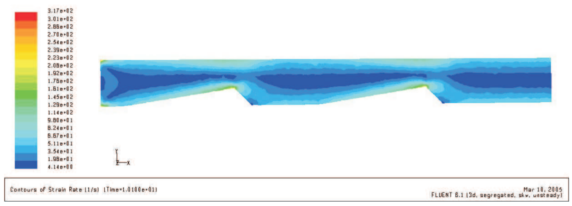

Figure 13: Strain rate of the Herschel-Bulkley model. The flow is from left to right.

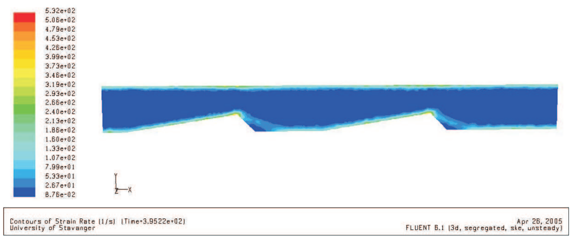

Figure 14: Strain rate from experimental viscosity with n = 0.8. The flow is from left to right.

CONCLUSIONS

The ultrasonic technique using the Met-Flow UVP Monitor is successfully applied in a study of particle transport in pipes. Results from series of experiments were shown. The UVP technique has demonstrated a large potential for in-situ measurements of particle bed dynamics, liquid-particle flow profile and turbulence intensity. Experiments were carried out for both water and non-newtonian (water-based) fluids. The experimental results agree well with CFD simulations.

ACKNOWLEDGEMENTS

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