Characteristic of the velocity profiles over fixed dunes in pipe

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ABSTRACT

Liquid-particle flow in pipes involves bed dune formation. Turbulent flow over fixed dunes is investigated for flow with both water and water with polyanionic cellulose fluids. While real beds change with time we study fixed bed to keep constant boundary conditions. Particle Image Velocimetry (PIV) in combination with Ultrasonic Velocity Profiling (UVP) technique was used. Complementary results from the experiments to characterize the time averaged and instantaneous flow properties with a high spatial resolution are obtained. Furthermore, the instantaneous flow field is investigated with emphasis on the occurrence of coherent vortical structures.

INTRODUCTION

Transport of solid-liquid mixtures in closed channels and pipes is encountered in various engineering activities. Applications range from coal and waste transports to transport of cuttings during oil well drilling. Previous studies[1,2] have shown that for certain flow conditions, liquid-particle flow in pipe involves development of dune bedforms. The bedforms modify the conveying fluid flow and pressure drop. These studies revealed a local minimum of the pressure drop in the transition regime between heterogeneous and bedload transport. These dunes appear most frequently in horizontal or near horizontal pipes and annular geometries. In pipe flow allowing bedload transport of particles, the system of particle transport significantly influences pipe conveyance, rates of particles transport and system head losses[3].

The dunes are associated with large scale turbulence which is generated over the dune[4,5]. This large scale turbulence is reported to occur with flow separation in the lee side. Furthermore, this structure has been associated with and influence particle transport. A shear layer is developed from the dune crest and extends to the flow reattachement point. This shear layer is sandwiched between a recirculation zone and the main stream. Instability of this shear layer induces these large scale coherent structures. These in turn carry significant momentum and particles. For maximum particle transport rate flow with dune formation should be avoided because once beds of particles are accumulated, they are difficult to remove. They may even lead to pipe blockage.

The objective of the current study was to examine the characteristics of the velocity profiles over dune and examine the generated turbulence in the dune lee side.

FLUID DYNAMICS AT THE DUNE LEE

As mentioned, the fluid motion at the lee side of the dune is dominated by flow separation. This in turn creates a zone of slowly recirculating fluid which is delimited by the shear layer with high velocity gradient. The size of this shear layer varies from the type of fluid. The characteristics of pipe flow over dune lee side are illustrated in Fig. 1. The coordinate system is presented in the figure showing the stream-

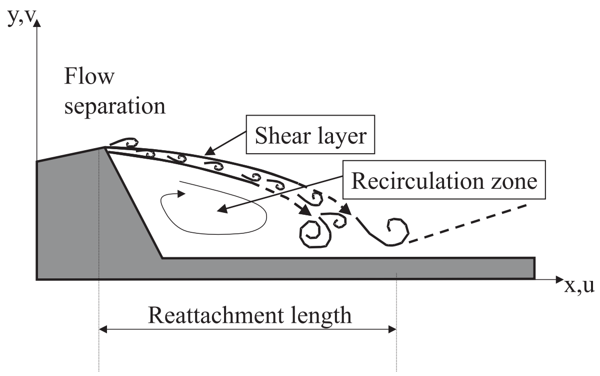

Figure 1: Schematic description of the flow at the dune lee side. The coordinate system used is also shown.

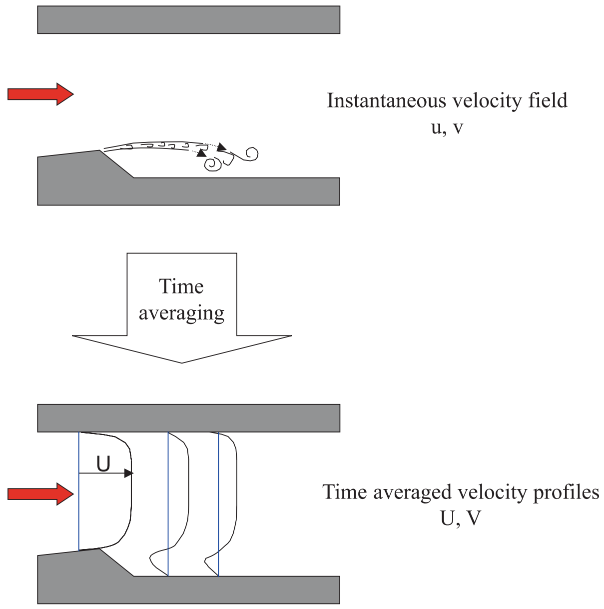

Figure 2: Schematic description of the data analysis sequence at the dune lee side.

wise axial x-direction with it's corresponding axial velocity, u, and y-direction with it's vertical velocity, v.

Turbulent structures play an important role in particle transport. Identification of coherent vortical structures is not only useful in understanding the turbulent motion, but also necessary in development of turbulence models for dune transport in pipe.

The instantaneous velocity vector is decomposed into its components as:

$$u = U + u^{'}, v = V + v^{'} \qquad (1)$$

where U, V are the time averages of u and v respectively, and the fluctuating part of the velocity components are represented by $u^{'}$ and $v^{'}$.

The time averaged properties are the statistical average of the instantaneous properties during a period of time. The sequence of our data analysis steps which will be used in this study is schematized in Fig. 2.

EXPERIMENTAL PROCEDURE

Details of the flow loop using natural occurring dunes in pipe can be found in Rabenjafimanantsoa et al.[6]. In this flow loop two artificial dunes are mounted inside the same pipe. The experimental setup presenting trains of dunes in pipe is shown schematically in Figure 3. A single glass pipe segment 1 meter long and 4cm inner diameter is placed inside a water filled optical cell 90x20x30 cm. Two gear pumps were connected in series to circulate the system. Only one pump is shown in the figure for simplicity. The flow rate was controlled using a magnetic flowmeter from Heinrichs Messgeräte, type Europik - 567. The two dunes were made from

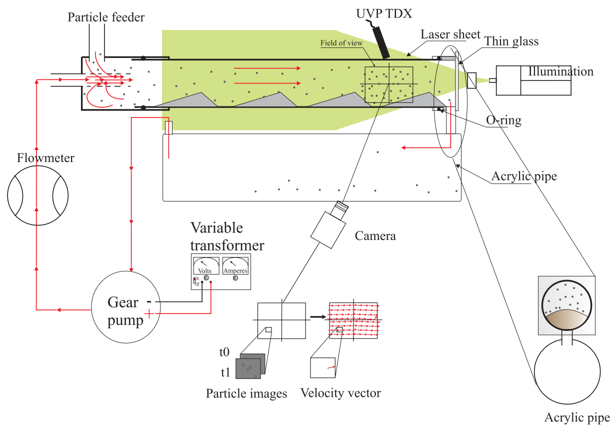

Figure 3: Schematic representation of the flow loop system.

acrylic block each having a length of 11 cm, a height of 1.5 cm and a slip face angle of 45^o. They were positioned at the outlet end of the pipe and the dune spacing was set to 2 cm. We choose to use artificial dunes configuration in order to study the simultaneous use of the UVP and the PIV, and to obtain reproducibility in time-averaged flow measurements and turbulence. In addition, the fluid velocity is one of the most important parameters in studying the fluid dynamics above particles bed. In order to fully understand the physics of the fluid process measurements on flow velocities are essential.

Our PIV system from Dantecdynamics supplies a 1mm thick lasersheet (Solo ND:YAG laser set to 106 mJ, New Wave Research) acting as a fast repetition flash into the flow. It is synchronized with a computer controlled high speed camera (HiSense, 1024x1280 pixels) to record multiple instant pictures. The laser sheet acts like a flash for the camera which records series of image pairs. The processing unit (Flowmap 1500) performs picture analysis to determine particle speed based on a two-dimensional cross correlation technique. The whole unit is controlled from PC using the program Flowmanager 4.1.

Our UVP system from Metflow[7] allows instantaneous flow profiles to be recorded. It is clamped on to the pipe wall and can be placed from virtually any position outside the pipe, as shown in Figure 3. The instrument measures velocity profiles split into 128 intervals along the beam path. We record 1000 profiles with time separation Δt=229 ms. The starting channel was set to 5 mm and the distance between channels 0.74 mm. We used the 4 MHz probe for all these tests with the sound velocity of water being 1480 m/s.

The UVP system is triggered to start simultaneously with the PIV system, thus enabling timing synchronization and comparison of the one dimensional flow profiles with calculated velocity along the UVP line in the PIV pictures.

As mentioned, the method for measuring velocity profile measurements above the artificial dune is shown in Fig. 2. The transducer is placed on top of the pipe at an angle of 12^o from vertical. For the PIV, one recording consists of two image frames, say frame 1 and frame 2. The time between recording of frame 1 and frame 2 was set to 250 μs while the time between recording between image pairs was set to 500 ms. The number of records was always set to 10. This gives a number of ten image pairs which was considered to resolve the turbulent fluctuations in the flow. The analysis of the experimental results is aimed at describing the detailed features of the flow using both Newtonian and non-Newtonian fluids.

The dune flow analysis in this work is carried out using water based liquids. Water was used for a basis and reference for the polymer solutions.

Two different concentrations of polyanionic cellulose, PAC regular obtained from MI-Swaco, were used: 200 and 400 ppm PAC dissolved in water. The Silverson mixer model L4RT-A at 1500 rpm was used to prepare the solution before pouring to the flow loop. The rheological measurements were taken using a Physica UDS 200 rheometer with cone plate configuration MK 24 (75 mm, 1^o). The two samples were measured at 26.6^oC with increasing shear rates. The viscosity measurements were taken after the tests have been run. The viscosity of the fluids used is presented in Fig. 4.

RESULTS AND DISCUSSIONS

The artificial dune located closest to the pipe outlet was chosen for this study. The reason was to avoid sight blockage and light sheet reduction if the upstream dune was considered. No additional seeding particles were needed since the dust particles within the flow were sufficient to be used as tracer particles. In all figures both the

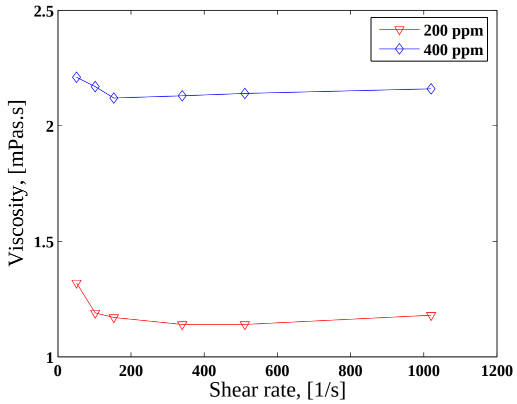

Figure 4: Viscosity versus shear rate at 26.6^{o}C of the 200 and 400 ppm concentrations of PAC dissolved in water.

dune and pipe boundaries are drawn manually for clarity of the presentation. In addition, the flow direction is from left to right. Result from the flow of water is presented in Fig. 5. A shear layer is generated

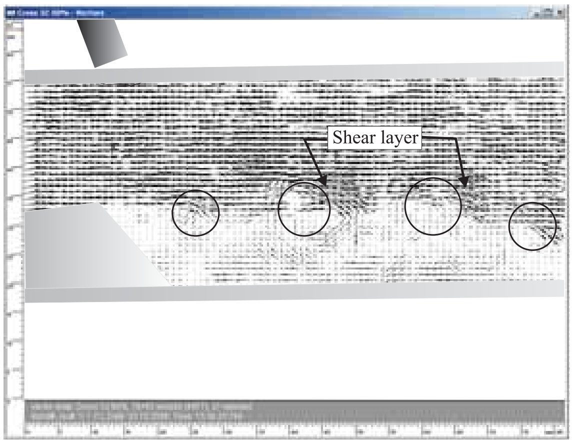

Figure 5: PIV instantaneous velocity profile using water. Four vortices (circled) are moving along the shear layer from left to right. $\overline{U}_x = 0.18m/s$.

as a product of the flow separation. This shear layer is populated with vortical structures which are circled in Fig. 5 which also create shear layers. These are instantaneous positions of vortices generated from Kelvin-Helmholtz instabilities[4,5]. We can at least see 4 instantaneous vortical structures, represented by the circles, aligned in the streamwise direction.

In order to illustrate the simultaneous application of PIV and UVP, the streamwise velocity profiles from PIV were extracted and compared with the UVP profiles along the ultrasonic beam. The UVP profiles to be plotted should be from profile 1 to 22 in order to represent the PIV recording of ten image pairs. Figure 6 shows a comparison of the PIV with the UVP profiles. Both PIV and UVP profiles

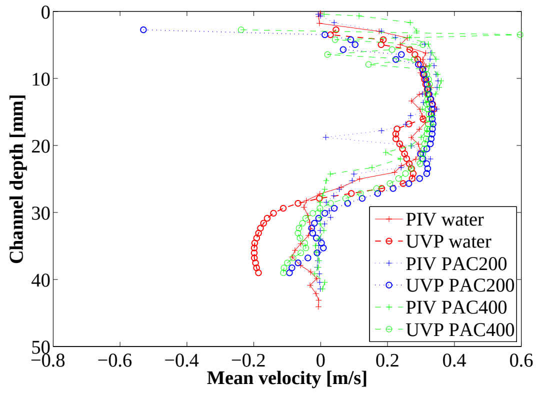

Figure 6: Comparison of PIV and UVP on the streamwise velocity profiles along the ultrasonic beam for both Newtonian and non-Newtonian fluids. $\overline{U}_x = 0.18m/s$.

overlap well, especially in the upper part of the flow. However, the PIV seems to have a problem of measuring the flow close to the bed. This is probably due to light reflection from the artificial acrylic dune. In such case, the result from UVP would be more consistent than that from the PIV. This demonstrates one of the complementary applications of both instruments. An inflection point is found at approximately channel depth 27 mm. This inflection point in velocity profile indicates a relationship between the upper flow and the generated shear layer beneath it. Figure 7 shows a UVP comparison plot of the mean velocity profiles together with the standard deviations for both PAC200 and PAC400. It can be seen that the deviation bands

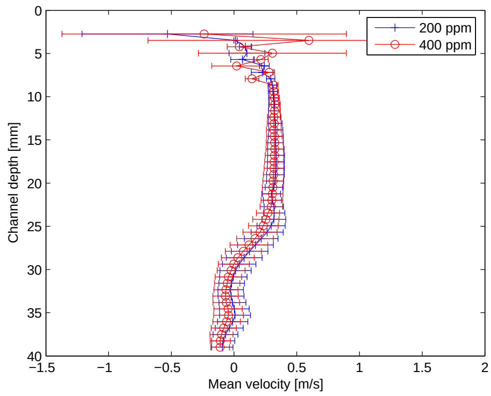

Figure 7: Comparison of the mean UVP velocity profiles including the error bands along the ultrasonic beam for 200 and 400 ppm PAC.

are much larger from the shear layer and within the recirculation zone, if the signals below channel depth of approximately 8 mm is neglected. This might indicate that the ultrasonic signals are more distorted in this region.

Measurements of the flow with different concentration of PAC were acquired. For each concentration the liquid mass flow was held constant. Figure 8 shows result obtained from PIV of the flow with the solution of 400 ppm PAC in water.

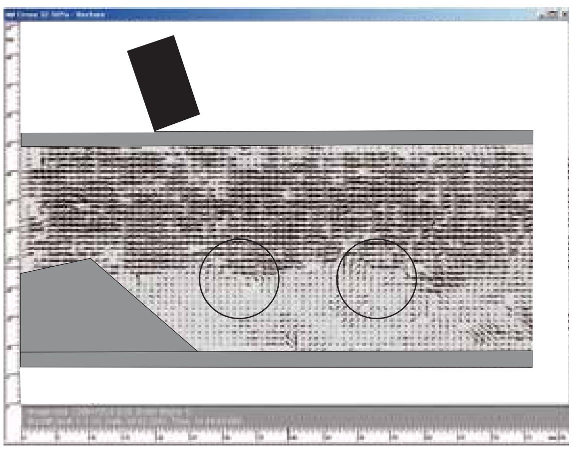

Figure 8: PIV instantaneous velocity profile using 400 ppm PAC. $\overline{U}_x = 0.18 m/s$.

It can be seen by visual inspection of Fig. 8 that only two vortical structures which are circled in the figure appear. The same flow rate, i.e 0.18 m/s, as in Newtonian fluid was applied. The fluid viscosity is likely to dampen the vortical structures which are self-organized. The comparison with the case with the water shows that the viscosity of the fluid has a stabilizing effect at the dune lee side. We also observe from both figures that the vortical structures which are transported by the main flow.

The time averaged streamwise velocity profile of the same fluid system (400 ppm PAC) is shown in Fig. 9. In this figure it is observed that the distribution of velocities show flat profiles. The flow undergoes acceleration, deceleration and separation. The reattachement point situated further downstream is not observed. By decomposing the velocity contour by its streamwise and radial component we present the pattern of the flow in Figs. 10 and 11, respectively.

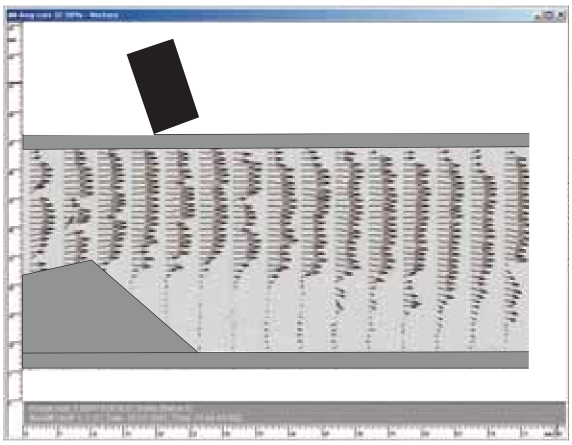

Figure 9: PIV time averaged velocity at the lee side using 400 ppm PAC. $\overline{U}_x = 0.18 m/s$.

Flow deceleration is associated with the flow separation at the lee side of the artificial dune. This can be seen in Fig. 10 and represented by the greenish color. This region is the generated shear layer which

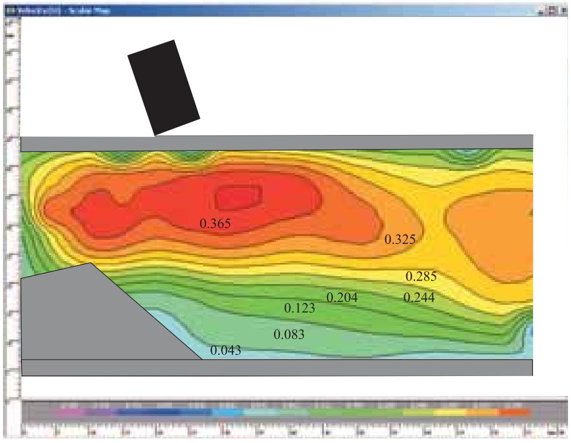

Figure 10: PIV time averaged streamwise horizontal velocity contour using 200 ppm PAC at the lee side. The flow is from left to right. The colorbar spans from -0.199 (left) to 0.365 (right) m/s.

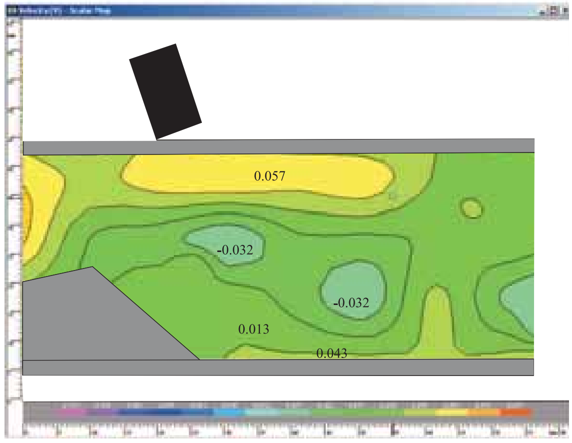

Figure 11: PIV time averaged vertical/radial velocity contour using 200 ppm PAC. The colorbar spans from -0.121 (left) to 0.087 (right) m/s.

is sandwiched between the upper flow and the recirculating flow beneath it. The recirculating region has reverse or low velocities less than approximately 0.043 m/s. The maximum streamwise velocity over the dune crest is approximately 0.365 m/s represented by the darker area. The vertical or radial component velocity presented in Fig. 11 show positive values in the lower part of the lee side flow separation zone. This is represented by the light yellow color meaning that the fluid is moving away from the bottom of the pipe. However, the flow is directed toward the recirculation zone, i.e. the two blueish regions with negative vertical velocities of approximately -0.032 m/s. The broad pattern of the flow at the lee side corresponds thus to expanding and separated flow pattern. This pattern has been shown in many past studies to dominate the turbulence production. This has been demonstrated by the capability of the PIV in providing the entire flow field information and quantitative visualization of the turbulent structures.

The generated turbulence in the shear layer and recirculation zone is considered to be modified due to the increase in viscosity by addition of PAC in the flowing liquid. In this region, our results show that the higher the polymer concentration is, the lower is the intensity of the turbulence. This can be seen in Fig. 12. By flowing

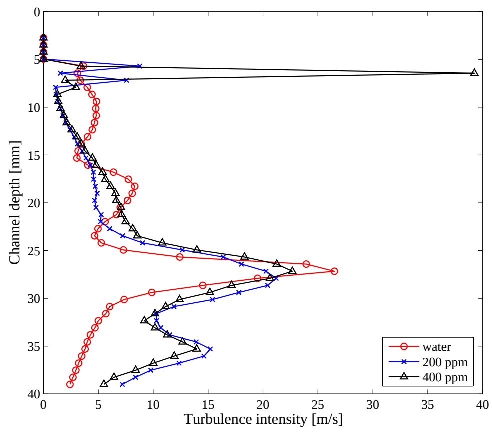

Figure 12: Comparison of the UVP turbulent intensity profiles between water, PAC200 and PAC400. $\overline{U}_x = 0.18 m/s$

with the same axial velocity, the UVP profiles of the different flowing medium show the same trends. The intensity of the turbulence above the crest shows a slightly increase in PAC400 compared to PAC200. Water flow is affected by some increase and decrease. At the shear layer the maximum intensity of turbulence is observed in all liquid. Within the recirculation zone PAC200 appears to be higher than both water and PAC400. The reason might be that there are more particles in this region when using PAC400. There are probably higher particle loading using PAC400 than PAC200. Particles within the viscosified fluid probably may travel longer time in the retarded flow and affect the turbulence.

CONCLUSIONS

This work demonstrates that adding polymers to water stabilized the shear layer downstream the dune crest.

Vortical structures are observed to be generated at the separation zone along the shear layer. They develop from the dune crest to the reattachment point further downstream. This shear layer structure was transported along the main flow until it reached the reattachment point.

Increasing PAC concentrations to water led to attenuation of turbulence intensity within the recirculation zone.

Comparison of UVP with PIV instruments showed good agreement.

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