Simultaneous UVP and PIV measurements related to bed dunes dynamics and turbulence structures in circular pipes

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An Ultrasound Velocity Profile (UVP) monitoring instrument is used for measurement of shear, turbulence and friction for particles transport and bed dunes dynamics in circular pipes. In order to complement and verify the measurements from the UVP a Particle Imaging Velocimetry (PIV) was used. Simultaneous 2D velocity vector maps above the dunes was obtained by PIV to detect the spatial flow structures while the instantaneous 1D velocity profiles as well as the turbulence structures over the dunes sheared by water flow was measured by the UVP instrument. The flow field of water and glass sphere particles (200 micron range) involves complex turbulence patterns. Different dunes flow regimes or geometrical patterns form depending on the actual flow rate. Of particular interest are dune regimes, where bed and overlaying fluid changes dynamics. In particular this involves bed roughness and particle lift, which are related to the particle transport rates, generation of macroturbulence and frictional pressure drop.

Keywords: PIV, UVP, liquid particle flow, particle beds, macroturbulence

1 INTRODUCTION

Moving particle beds occur as part of natural flow phenomena like in rivers and turbidites, as well as in engineering applications, like hydraulic conveying of coal and cuttings transport during oil well drilling. Trains of dunes are normally observed in long pipes [1]. It is important to measure flow profile and turbulence characteristics of the liquid and particle flow fields in order to determine the dynamics of such largely self-organized systems. In this work we combined two of the most promising techniques for measurement of liquid particle flows; ultrasonic based velocity profiling (UVP) and laser based particle imaging velocimetry (PIV). It is important to perform cross check and consistency analysis of the techniques, as well as to reveal strong and weak aspects of each technique for analysis of particle laden flows. A small flow cell was made to reveal flow structures of only a few dunes. It is complementary to a larger flow loop at our laboratory for study of long trains of dunes. The flow in this smaller cell reproduces most of the characteristics of the flow patterns in the larger pipe, while also easily allowing easier adaptation for the UVP and PIV measurements. The dynamics of dunes has been investigated extensively using numerical simulation [2-4]. Also experimental studies, e.g. of turbidites and river flows using both PIV and UVP have been carried out. Bennett and Best [5] made detailed measurement of flow velocity and turbulent fluctuations using LDA. They found that the dune-related macroturbulence emerges from the shear layer instabilities**.** Best [6] also traced the evolution of such macroturbulent events over dune-covered bed using PIV. Special attention was paid at the lee and stoss sides of the dunes. The results provided a mechanism that may explain the entrainment of sediment into both suspended and bed load transport.

However, no published reports have so far been found on the simultaneous use of UVP and PIV as done in this work. We have applied both techniques successfully in previous experiments. This made it simpler to perform the combination and determine the validity of the results.

2 EXPERIMENTAL SETUP

2.1 Flow rig – pipes and pump system

The flow rig is shown in Figure 1. A single glass pipe segment of 1 meter long and 4 cm inner diameter is placed inside a water filled optical cell 90x20x30 cm. Small glass particles form beds during flow inside the pipe. Water flow is supplied from two small pumps. The particles are initially fed through a hole in the rear flange via a rubber hose to form an initial bed. A self-organized bed shape will form readily during the flow. The particles will eventually reach the pipe outlet and are then trapped by a large pipe at the bottom to prevent them from circulating into the pumps. For these experiments the pump flow rate was approximately 0.2 l/s, equivalent to 0.18 m/s in the 4 cm glass pipe.

2.2 Ultrasonic measurements - UVP system

A UVP system (Met-Flow) allows instantaneous flow profiles to be recorded through the pipe wall from virtually any position above the bed, as shown in Figure 1.

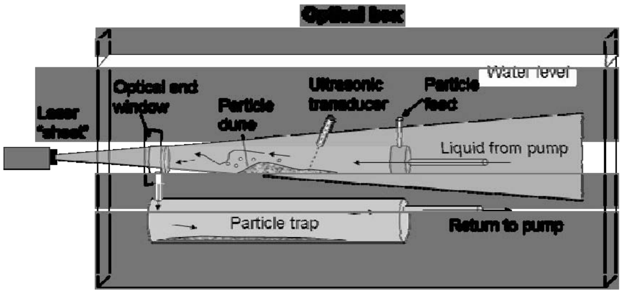

Figure 1: Flow rig with water filled optical box, transparent pipe and laser sheet setup.

Water in the optical cell works as contact fluid. A thorough description of the physical principle of UVP may be found in [7]. Three different frequencies are used in our arrangement; 1, 2 and 4 MHz. In essence the instrument measures the speed component along the ultrasonic beam axis, based on the backscattered signal from particles passing through the beam. We used the 4 MHz probe for these tests, requiring a particle diameter of approximately 93 microns.

2.3 Laser based velocity profiles based on PIV

A PIV system (Dantecdynamics) supplies a 1mm thick lasersheet (Solo ND:YAG laser 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 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. 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.

2.4 Bed and "seeding" particles

The particles added to the flow serves two main purposes; creation of sedimentary beds, and acting as seeding particles for flow visualization and ultrasonic beam reflectors. A combination of two different particle sizes is used; 10 micron Sphericel® Hollow glass spheres (Potters Industries Inc.) as PIV seeding particles, and 200 micron glass particles for bed formation. Electron microscopy images of the particles are shown in figure 3.

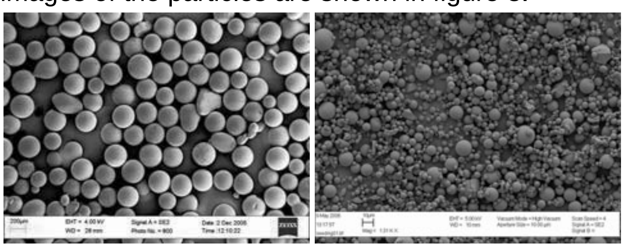

Figure 3: SEM pictures of bed particles (left) and seeding particles (right).

3 TESTS

Three different PIV planes were used for the tests. For each test plane UVP was also applied for comparison of results. Each PIV test consisted of a series (10 pairs) of pictures.

3.1 Axial velocity profiles

The experiments show that a shear layer develops from the dune crest. The shear layer delimits the recirculation zone below and the main flow above, as shown in Figure 4.

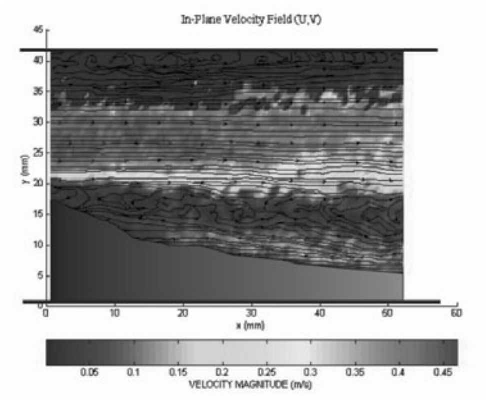

Figure 4: Development of shear layer between the main flow and the recirculation zone. The direction of the flow is from left to right. Flow rate is 0.2 l/s.

In Figure 4 the velocities on top of the main stream appear to be almost zero. This artifact, also appearing in Figures 6 and 7, is caused by particles attaching to the inner pipe wall at the top.

The results using UVP for the same flow as in Figure 4 are depicted in Figure 5. Zero velocities observed here (approximately between channels 2 and 8), are associated with the pipe wall. The plot is based on 1000 profiles in time, each with 128 channels representing depth. The time between successive profiles is 132 ms, and channel 128 is at depth 99.7 mm

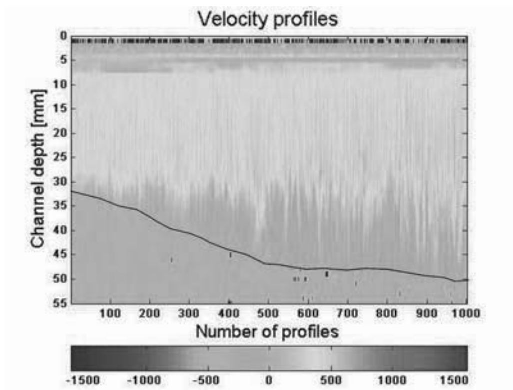

Figure 5: UVP velocity profiles above the dune. The UVP transducer is placed streamwise on top of the pipe at 12^o from horizontal. The flow direction is from left to right. Mean flow velocity U = 0.18 m/s. Colorbar in mm/s.

The velocity profile of primary interest for transport purposes is the axial profile, since most of the kinetic energy, shear and lift are in the axial z-direction. However flows involving particle beds do not have radial symmetric flow profiles as in single-phase pipe flow. Thus there are two other interesting profile planes; the transverse profile and profiles parallel to the bed surface. From flow over plane walls it is well known that rolling hairpin vortices develop in the plane parallel to the wall. The rollup sequence depends on local wall geometry and particles will modify the process.

The PIV velocity profile derived from the same image underlying Figure 4 is shown in Figure 6 below. Both the shear layer development, represented by the zero velocities sandwiched between the main stream and the bottom flow reversal can be seen from Figure 6.

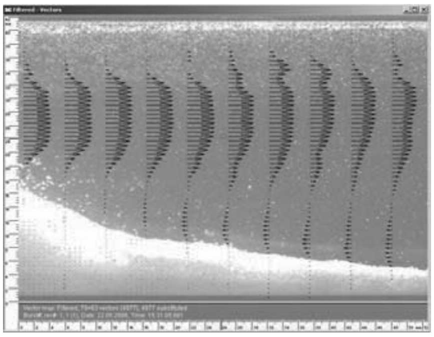

Figure 6: A close-up of an example of the axial velocity profile superimposed on the picture of the sand dune. The flow direction is from left to right. The image grayscale is inverted for clarity. U = 0.18 m/s.

Particles attached on top of the pipe wall as previously mentioned can also be observed. By increasing the mean flow, the velocity profiles became more flat as shown by PIV in Figure 7.

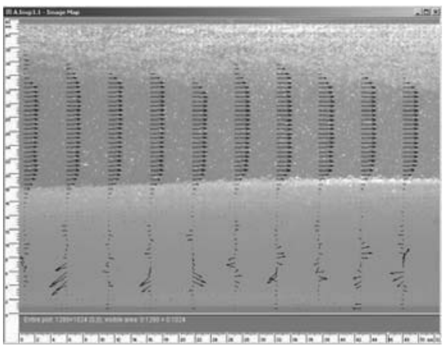

Figure 7: PIV velocity profiles above the dune stoss. The flow direction is from left to right. The image grayscale is inverted for clarity. U = 0.22 m/s.

3.2 Transverse cross sectional velocity profie

The transverse profile typically contains numerous large and small vortices. The PIV reveals such structures as shown in Figure 8. In contrast the UVP works along a line heading from the pipe surface. It can be difficult to adjust the UVP properly since direct wall reflections may survive several back and forth reflection and thus interfere will the pulse sequence. In many cases it is necessary to reduce the pulse repetition rate, thus limiting the use to only low speed flows. In general however, the transverse velocities are normally also quite small, and the limitation of measurement range is not so crucial. Letting the reflected beam hit the bed for dampening is often a useful method to avoid multiple passes of the beam.

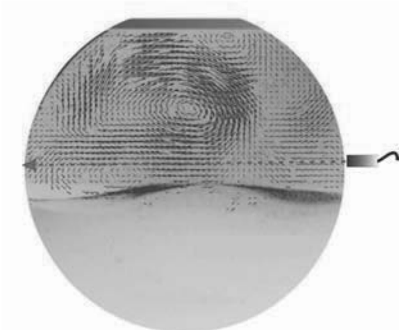

Figure 8: Velocity profile in cross section transverse to the pipe axis. The position of the UVP probe is indicated at the right. The image grayscale is inverted for clarity

3.3 Velocity profile parallel to the bed surface

Regarding flow details and shear layer generation, planes parallel and close to the crest is of interest.

An example is shown in Figure 9. The UVP transducer line was in the same position and direction as shown in Figure 8. In Figure 9 the velocity profile plane is taken approximately 5 mm above the bed surface. However, it is difficult to screen the laser sheet completely from secondary stray light hitting the bed surface.

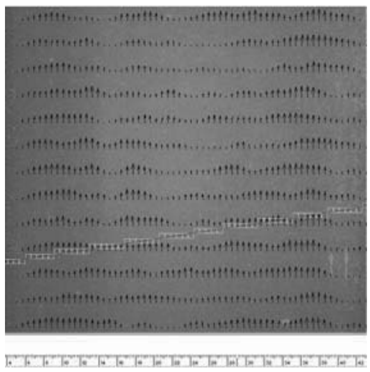

Figure 9: Time-averaged velocity profile in a plane 5 mm above and parallel with the bed surface. The transducer path line (red line) is also shown. The flow direction is from bottom to top. The image grayscale is inverted for clarity.

4 DISCUSSION

Based on the PIV recordings even very weak transverse rolls can be determined in the plane perpendicular to the pipe axis, as shown in Figure 8. The UVP instrument has only limited value for measurement lines parallel to the bed surface, due to the one-dimensional nature of the measurements. However, also another line direction lies in this plane; shooting from the top of the pipe onto the bed surface. This direction is also in accordance with the PIV plane along the pipe in the vertical direction. Note that the UVP method yields only the velocity component along the beam. Thus different particles having the same absolute speed crossing the beam at the same azimuthal angle will give identical speed. This is illustrated in Figure 10.

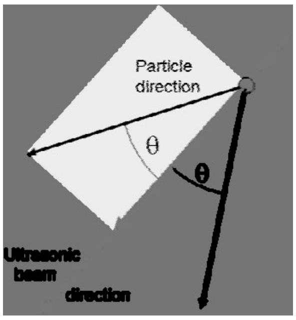

Figure 10: The axial symmetric nature of the UVP measurements may cause different particle directions to yield the same velocity component.

The validity of interpretation is very important. The UVP velocities may be interpreted both as the component in axial (z) direction related to Figure 5, but also as the velocity in the transverse cross section (Figure 8) if the transducer is pointing slightly in the z-direction.

In addition to particles attaching to the pipe wall (as in Figures 4,6 and 7), a difficult aspect with PIV arises in connection with velocity profiles parallel to the bed surface in Figure 9. Although the recorded PIV picture has only a limited focal sharpness, it may pick up some details from the stationary bed surface just 5 mm below. Thus stationary structures can become superimposed the moving particles and thus cause a bias in the PIV estimate.

A direct comparison of the measurements from UVP and PIV is in principle possible, since the test involved simultaneously triggered recordings. The UVP measurements apply to the velocity component along the ultrasonic beam. For direct comparison with PIV, the analysis program (Flowmanager 4.1) must calculate the corresponding vector along the same beam direction. It is not advisable to compare e.g. the u (horizontal) or v (vertical) components in the PIV picture with the corresponding decomposed values of the UVP profile. The comparison may be based both on instantaneous recordings with single profile versus pairs of single frames, and on time (ensemble) averages. The instantaneous method was found to have a fairly large amount of scatter, most likely due to the fast changing character of the ultrasonic signal. The PIV frames and the UVP profiles are not synchronized on individual basis, only the start of the recordings is simultaneous. On a time averaged basis there is a much better agreement between the two techniques. An example is shown in Figure 11. The analysis is based on average of 10 picture pairs and average of

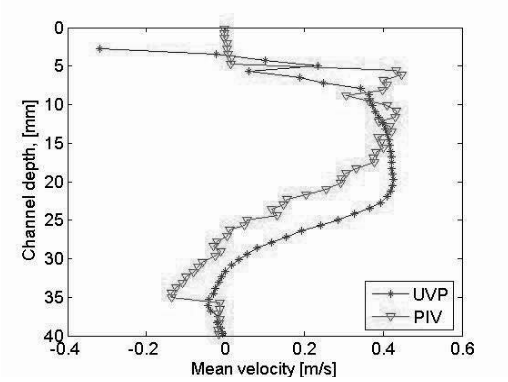

Figure 11: Direct comparison of UVP and PIV estimate, calculating the PIV component along the ultrasonic beam.

all UVP profiles during the corresponding time interval. Inflection point and flow reversal zone at the bottom can be seen from 30 mm and down. Flow rate is 0.2 l/s.

5 CONCLUSION

Both UVP and PIV measurements provide very useful measurements of particle laden flows. Clearly PIV is superior in optically perfect systems. UVP has an advantage in opaque systems where PIV cannot be used. However, single beam UVP is a one-dimensional technique and proper care must be done not to draw invalid conclusions in three-dimensional flows. PIV on the other hand is limited to transparent systems and care must be taken to avoid “contamination” of the images from particles on the walls or from flow structures illuminated outside the laser sheet.

6 SUMMARY

A comprehensive study was carried out to investigate liquid-particle flow with dunes formation in pipe flow, using combined UVP and PIV techniques. However both methods have traps and limitations that must be accounted for. The methods are complementary in use, but give consistent results if correct interpretation is made.

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