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EXPERIMENTAL CHARACTERIZATION OF HYDRAULIC SOLID PARTICLE TRANSPORTATION IN HORIZONTAL PIPELINES USING PIV

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ABSTRACT

Solid particle transport in pipelines by fluids is encountered in a wide variety of industry processes, such as oil production, mining and chemical industry. In contrast to the intensive research effort that has investigated transport modes for suspended solid particles in pipeline flow, limited studies have been published on solid transportation mechanism generated from an initial stationary particle bed. Consequently the underlying mechanisms responsible for bed-load and saltation transport phenomena have not been extensively assessed, particularly for low velocity hydraulic conveying pipe flows.

This paper presents an experimental investigation into sand particle transportation from a stationary horizontal particle bed under hydraulic conveying flow for bed-load and saltation transport phenomena. Experiments were undertaken in a laboratory environment using a 14 m long transparent plexiglas loop of 24 mm internal diameter to permit optical access. High speed digital photography was employed to study the morphologic characteristics of sand bed transportation, with Particle Image Velocimetry (PIV) used to characterize the near surface flow structure at the fluid-solid interface. Experimental results characterize the influence of water flow on sand dune formation for one bed thickness and particle size. Flow field velocity distributions revealed the presence of vortex structures that strongly influence the dynamics of sand dunes. The results presented on the combined study of flow field and bed formation interaction provide a fundamental insight into the physics of fluid-solid interaction in a closed conduit that can also serve as benchmark data for computational fluid dynamics based predictions.

INTRODUCTION

Solid particle transport in pipelines by fluids is encountered in a wide variety of industry processes, for example, in the petroleum industry, solid and liquid flow is involved with drilling fluids, gas hydrates and oil transportation processes [1]. Understanding the mechanism of solid transport in multiphase flow lines plays a critical role for the development of modern oil and gas industry. For instance the increasing amount of sand in horizontal pipelines produces a stationary sand deposit which creates a higher pressure gradient and reduction of flow area which can affect the rate of production. The formation of a sand bed inside the pipeline during the shutdown process creates many engineering challenges particularly during the startup process [2,3]. The sand transport during the resuming operation can cause pipe blockage if the gas-liquid velocity becomes excessive [3].

To understand the mechanism behind solid transport, intensive experimental and theoretical research has been conducted over the past several decades. Due to the complicated interaction between solid and liquid phase, hydrodynamic parameters such as friction losses, pressure gradient along pipe and mixture velocity depend strongly on the flow pattern. From previous studies [4-6], a general flow regime classification is: (I) stationary bed flow mode, defined as the condition no solid particle movement occurs; (II) moving bed flow mode, defined as the condition solid particles mainly moving along the sand bed in a bed load mode; and (III) suspension flow mode, defined as the condition solid particles heterogeneously or homogenously suspending in the liquid phase. Based on different flow patterns, research in this field has covered a wide range of topics such as pressure drop [6-9], pickup velocity [10-13], solid transport efficiency [14] and model prediction [15-17]. However, as Matousek [18] pointed out in a review paper for pipeline transport of settling slurries, the complex behavior of solid-liquid flow is not yet fully understood, with existing tools for its simulation and prediction still far from accurate.

When solid particle is transported on the moving bed flow mode, experimental observations show that an unstable phenomenon usually occurs in the pipe that results in the formation of dune structures. From an operating point of view, it can be frequently encountered in the multiphase transport system, especially when a low liquid flow rate is involved. However, this phenomenon has received limited attention among previously published studies. Takahashi *et al.* [2] experimentally and numerically studied the unstable flow of hydraulic solid transport with dunes formed at the bottom of a horizontal pipeline. It was shown that dunes movement can cause a significant pressure fluctuation in the pipe. Takahashi and Masuyama [3] proposed a stability criterion for the fluid velocity at which dunes are formed on the surface of the deposit bed. Goharzadeh *et al.* [19] published a study on sand transport in horizontal pipeline with an initially stationary flat bed. Using high speed photography, the characteristics of sand transport such as velocity, height and frequency of dunes under hydraulic convening and gas-liquid flows were assessed. Quriemi *et al.* [20] recently presented their results on dune formation phenomenon in hydraulic sand transportation flow. Time series dune development information was measured by image recording. To explain the observation of the experiment and predict dune formation, they conducted linear stability analysis which leads to the conclusion that the dune formation appears to be controlled by the pipe Reynolds number.

A potential reason for the insufficient understanding on sand transport mechanism may be related to the poorly known flow information involved with complex solid-liquid and solid-solid interaction, due to the limitation of measuring techniques. Few studies have been performed on the acquisition of detailed flow structures for solid and liquid flows. Chen *et al.* [21] used non-intrusive Laser Doppler Velocimetry (LDV) to discriminate and measure the local solid and liquid velocities in a horizontal fully suspending slurry flow by matching the refractive index of the two phases. Goharzadeh *et al.* [22] and Morad *et al.* [23] measured the velocity profile at permeable interface in rectangle horizontal open channel respectively by employing Particle Image Velocimetry (PIV) combined with Refractive Index Matching (RIM) technique. The results were used to study the transition layer thickness. Martin [24] applied a 2D PIV system to characterize the flow structures above and within large sized, non-moving gravel bed in a large dimensional turbulent open channel flow.

Based on the authors' knowledge, no studies have been found that have investigated the flow field for a moving bed transport mode, especially when dune formation is involved. The present study seeks to contribute to this field by a novel PIV measurement approach. When regular PIV test method is used for characterizing the moving bed transport condition, an inevitable challenge will arise from the laser scattering light received from the solid-liquid interface. This is particularly difficult for the condition with high particle saltation, which makes the acquisition of the flow structure near the bed surface unachievable. Previous studies have successively used PIV technique to detect sand particle movement for the flow and mixing of granular materials [26,27]. For the solid transport conditions, it is possible to take the suspending solid particles as tracers for the PIV measurement, if suitable sized solid particle and appropriate flow velocity is achieved.

In this paper, the result of the nonintrusive optical approaches using two different PIV set-ups to investigate solid transport is reported, and for the first time, the detailed flow condition throughout the entire sand dune formation process is captured and studied. The objective is to investigate the flow field induced by dune formation and provide a physical insight into the fundamental mechanics of solid-liquid interaction for sand transportation in horizontal pipelines.

EXPERIMENTAL SET-UP

The overall design of the multiphase flow loop was specified according to the laboratory space available to house the test facility. The test facility was limited to 3 m in width and 6 m in length. To optimize the utilization of this space constraint, a U-shape test facility was designed, with the layout shown in Figure 1. The total flow length of the loop is 14 m, with the inner pipe diameter equal to 24 mm. Piping is constructed from Plexiglas to permit flow visualization, with the exception of the curved section which was made from copper to permit fabrication. Water is circulated using a centrifugal pump, which can supply single phase flow rate of up to 40 lpm (Re = 35,385) to the working section, measured by a digital mass flow meter range, 0 to 10 lpm (RS 511-3892). The water reservoir tanks fitted with particle filters have capacity of approximately 450 liters each. In order to remove potential surface curvature effects of pipeline for flow visualization, the working section was submerged inside a transparent rectangular box filled with silicon oil (Dow Corning 556) having a refractive index of n = 1.46 which is close to Plexiglas n = 1.48. Single and two-phase flow measurements were realized at 24 °C. Details on the commissioning of the flow loop are given in [19], which verified the water flow to be fully developed when entering the test section for the Reynolds number under analysis.

In order to acquire a flow condition that would permit both significant solid-liquid interactions and the application of PIV, the following test conditions were employed. A uniform 8.7 mm

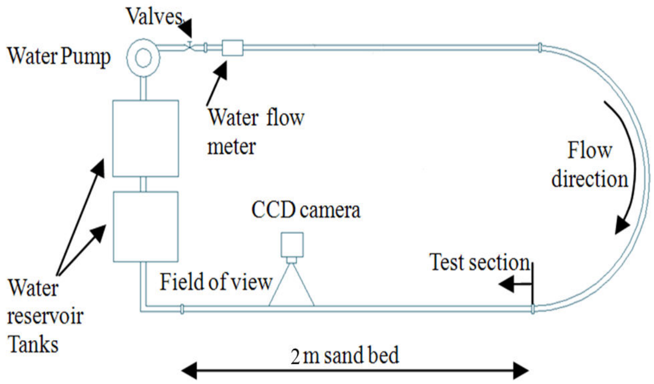


Figure 1: Experimental set-up.

thick sand bed was laid in the test section over a 2 m length, which occupied approximately one third of the pipe hydraulic cross section area. The sieve sand particle size and density were measured to be d < 125 μm and 2560 kg/m^3 respectively. A fixed water flow rate of 7.2 lpm (Re = 6,369) was applied over the sand bed, while the corresponding measured critical Reynolds number for moving bed transition and sand dune formation been Re_c = 2,990 and Re_d = 4,600, respectively. These Reynolds numbers correspond to the critical pickup and dune formation velocities, respectively.

Time dependent geometric characteristics of sand dune structure are illustrated in figure 2, which were measured using high speed CCD camera (Photron, Model FASTCAM SA3). The parameter h_0 is defined as the initial uniform sand bed thickness before dune formation, h_g is dune growth height and h_e dune erosion height, with total dune height been $h_g + h_e$. Measurement error was estimated to be approximately ±0.32 mm, corresponding to image resolution of one pixel.

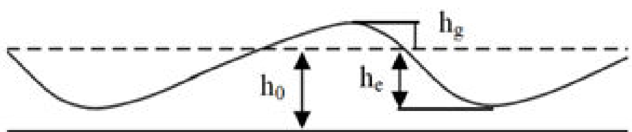


Figure 2: Dune structure geometric detail.

To obtain quantitative visualizations of both bulk flow field structures and fluid-particle interactions in conveying flow, two different measurement approaches for Particle Image Velocimetry (PIV) were employed. For regular flow field measurement, polyamide particles (Vestosint 2158) of diameter 20 μm were used as tracers, which are excited by a planar laser sheet of 1 mm thickness from a pulsed diode laser. However, due to strong scattering light at both water-sand interface and sand particles in saltation, this method was found suitable only for steady state stage of dune transport mode containing a small amount of sand particles in suspension. To investigate the flow field near the sand bed surface, sand particles were used as tracers. For this latter condition, employing appropriately sized sand particles with a suitable liquid flow rate triggered sand saltation with suitable suspending particle concentration necessary to permit PIV measurement. Most of the scattering light from the two-phase interface was eliminated by adjusting the intensity of the pulsed planar laser sheet. Consequently the suspended sand particles could be clearly discriminated, which made measurement of the near sand bed flow field possible. It should be noted that these two PIV measurements approaches could not be performed simultaneously, due to the reflected light intensities by the polyamide and sand particles been of different magnitudes.

PIV measurements were performed using the set up illustrated in figure 3. The planar laser sheet penetrated the central vertical plane of the working section with the CCD camera placed perpendicular to it. For each test, a field of view of 100 × 25 mm was obtained with a full frame image of 1280 ×1024 pixels. The pulse separation time was adjusted to 0.1 ms, and the time interval between each image couple was 200 ms, Using the DaVis Flowmaster software provided by the LAVISION, the 2-D PIV image was divided into 32 × 32 pixels sub regions with 50% overlap, single image couple was calculated to obtain the instantaneous particle velocity at different times, while the time averaged flow field was calculated using 20 images with the cross correlation method. The PIV technique employed has a typical uncertainty less than 7%.

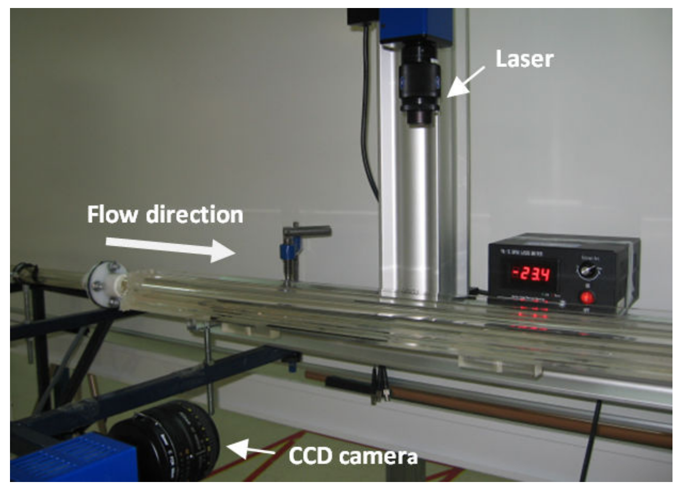
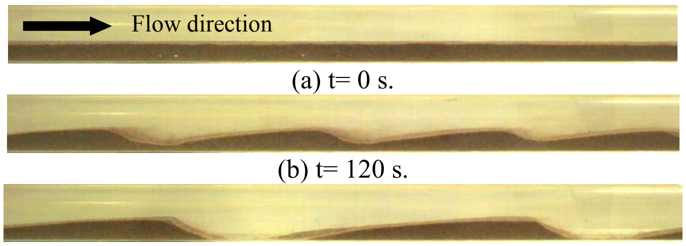


Figure 3: PIV system set-up.

RESLUTS

CCD camera observations showed that for an initially stationary sand bed, with the flow condition corresponding to the moving bed transition Reynolds number (Re_c = 2990), sand particles were entrained from the stationary bed layer, mainly rolling and sliding along the bed surface. For this condition, sand bed surface remained flat. Increasing the flow rate to the sand dune formation Reynolds number (Re_d = 4600), sand dune formation with saltation phenomenon were observed. The dune structures grew from the initially flat water-sand interface with sand particle erosion at the upstream side and deposition at the downstream side. Typical images obtained for the evolution of sand dune formation are presented in Figure 4.

Using CCD images, typical of figure 4, a time evolution sequence of sand dune formation was obtained in terms of dune



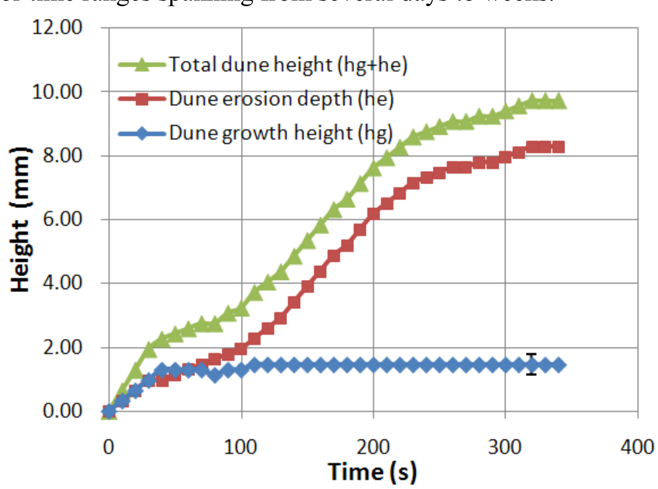
(a) t= 0 s.

(b) t= 120 s.

(c) t= 300 s.

Figure 4: Dune formation process.

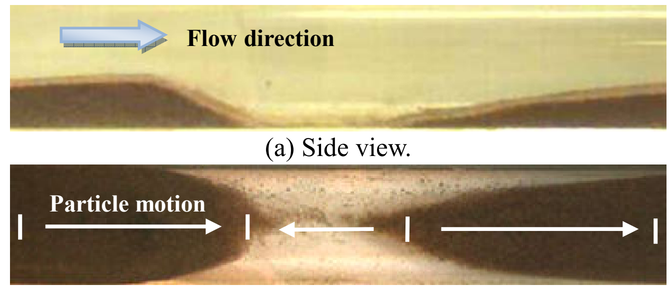
height, dune growth and erosion, which are presented in figure 5. In this study, it is observed that sand dune formation depends more on the erosion process than growth for the experimental conditions investigated. For the first 40 seconds, the dune growth and erosion heights increase at approximately the same rate, which results in a rapid transformation of sand bed structure from flat to non-regularity. After this time period, dune height growth does not significantly increase; instead dune erosion height rises in a stable manner until the sand bed is completely eroded between the dunes. A reason why dune growth height is constant after a time period of 100 seconds may be related to the reduced liquid flow hydraulic cross section area, which results in a higher free stream liquid velocity, hence shear stress over the sand bed surface. Thus when equilibrium between dune peak height and shear stress is achieved, sand dune height remains at constant elevation as shown in figure 5. Quriemi *et al.* [20] have indicated under the operating condition applied, dune mode transport can continue for time ranges spanning from several days to weeks.



Note: Geometry parameters h_e and h_g are defined in figure 2.

Figure 5: Time evolution of sand dune formation.

Figure 6 shows the visualized movements of the sand particles along the liquid-solid interface from both side and top views. It was observed from CCD images that sand particles were not always moving in the main flow direction. Between the sand dunes, sand particles were observed to move in an upstream direction in a discontinuous and irregular manner. The reason for this phenomenon may be related to affect of the dune induced vortex flow in this region [2,19,20]. However, no previously published studies have been found that experimentally investigated flow vortex interaction on solid particle movement, which plays an important role in the dune formation process. In this context the following PIV measurements provide such insight.



(a) Side view.

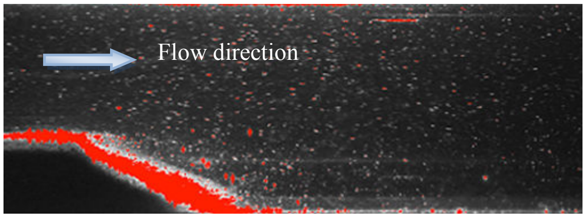
(b) Top view.

Figure 6: Direction of sand particles motion (t = 300s).

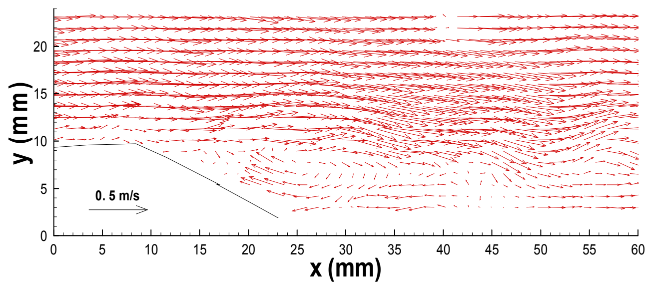
In figures 7, a visualized dune front with corresponding velocity field measurements are presented. Figure 7(a) shows a typical PIV image of the local field over the sand dune front. Figure 7(b) shows the corresponding instantaneous velocity vector field calculated using a single image couple. The corresponding time averaged velocity vector and magnitude distribution are shown in figures 7(c) and 7(d) respectively. As illustrated in Figure 7(b,c), separating and reattachment phenomenon is evident. The vortex located downstream of the sand dune is approximately 1.5 times the pipe diameter in length. In figure 7(c) an observable flow demarcation at x = 40 mm can be considered to be the reattachment point as in sudden expansion flow. In addition, the velocity fluctuations caused by dune and sand movement can be obtained by comparing the instantaneous and average velocity maps, the impact of these fluctuations will be discussed later.

Figure 8(a) shows the velocity distributions in the stream-wise (x-axis) direction for four different transverse (y-axis) positions, extracted from flow field data given in figure 7. Transverse locations y = 14.4 mm and y = 21.8 mm are located above the sand dune. These profiles show that velocity decreases in the stream-wise direction due to the flow expansion downstream of the dune peak. The velocity profile at y = 21.8 mm is lower due to pipe surface boundary layer interaction. At y = 8.3 mm, the velocity profile is taken through the vortex core flow region, and shows strong velocity fluctuation which may serve as a possible explanation for the strong pressure fluctuation measured by Takahashi *et al.* [2].

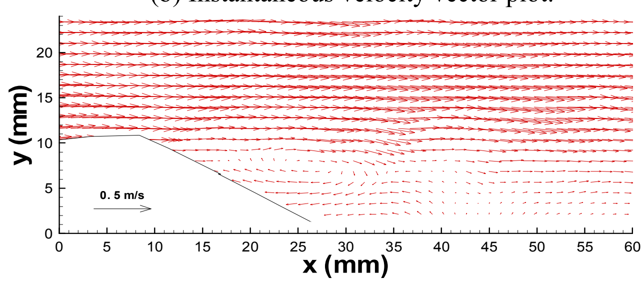
At y = 2.2 mm, flow reversal is observed between x = 25 and 40 mn in terms of negative velocity, and therefore supports the previous observations presented in figure 6 which identified sand particle movement in an upstream direction. However the magnitude of the time averaged back flow may not be strong enough to provide the necessary shear stress required for the entrainment of the stationary sand particles. A possible key point therefore maybe the existence of strong velocity fluctuations in both the stream-wise and transverse flow directions. Thus stream-wise fluctuation can contribute to a higher shear stress at the liquid-sand interface and therefore enhance the transportation force, with transverse fluctuations counteracting the gravity force leading to a reduction in total resistance. In addition, the randomness of these velocity component fluctuations could explain why sand particle move in the upstream direction is in the vortex region along the bed surface in a discontinuous and irregular manner.



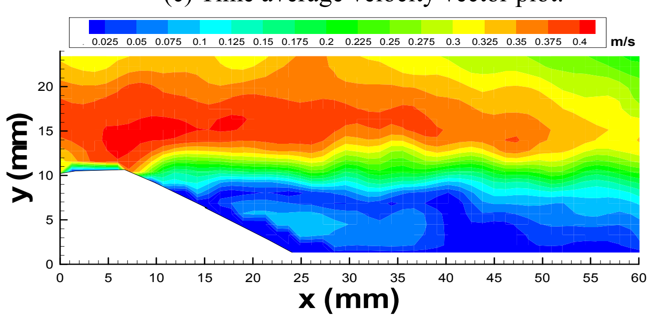
(a) PIV image.



(b) Instantaneous velocity vector plot.



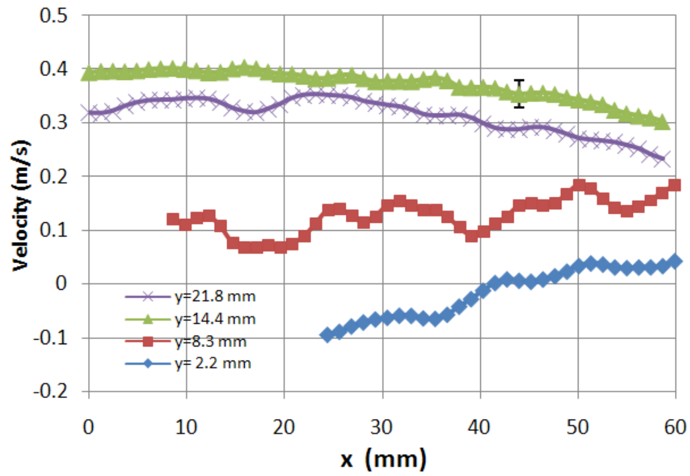
(c) Time average velocity vector plot.



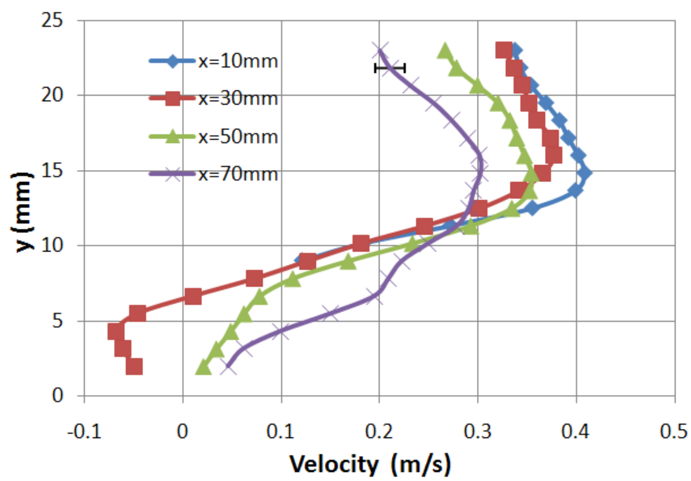
(d) Time average velocity magnitude distribution.

Figure 7: Measured flow field of dune front (t ≈ 600s).

Transverse velocity profiles for four different downstream positions are presented in Figure 8(b), with back flow detected in the region of the dune front. In the flow region above the dune (y = 10 mm) velocity decreases in the stream-wise direction. Below the dune peak, velocity magnitude increases reflecting typical flow expansion characteristics.



(a) Axial direction.



(b) Transverse direction.

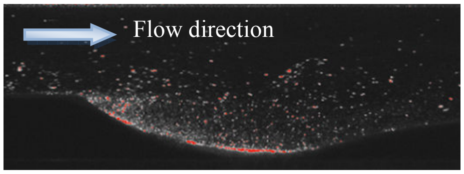
Note: Measurement taken in central vertical plane of the working section.

Figure 8: Measured flow field velocity profile (t ≈ 600s).

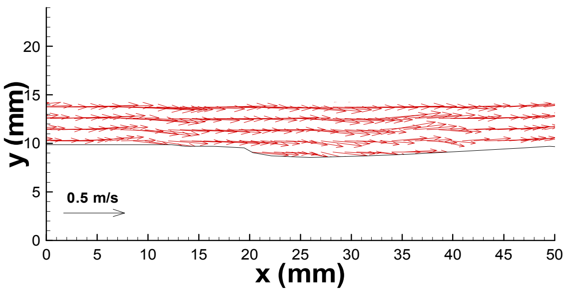
Due to the effects of laser light scattering at the liquid-sand interface, which can be observed in figure 7(a), additional PIV measurements are presented in figure 9 based on sand particles acting as the flow tracers. However due to insufficient concentration of suspended sand particles in flow region above sand dune, the PIV flow measurements are masked 4 mm above the sand dune to avoid unreliable data generation.

Figure 9 shows both the sand dune evolution process and corresponding flow field interaction in near liquid-sand region.

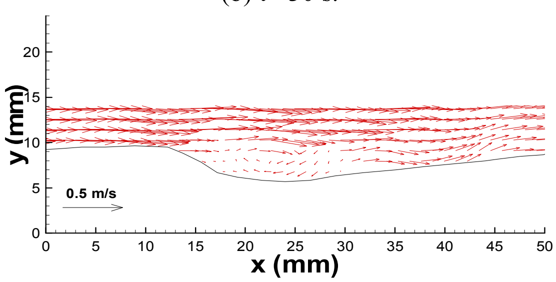
As previously discussed, when the flow rate exceeds the sand dune formation Reynolds number (Re_d = 4,600), small surface curvatures first appear at the liquid-solid interface due to sand particles rolling and sliding along the upstream side of the sand dune and depositing on the downstream side. As the dune height increases, higher shear stress is achieved and when of sufficient magnitude induces sand particle saltation. During the initial dune formation process (for example t = 30 seconds), dune altitude is not sufficiently high enough, and therefore the velocity field presented in figure 9(b) shows no significant flow separation structure in the region of dune front. During this time period, the flow affects the bed surface profile more than the bed surface influences the local flow structure. After this period, figure 9(c), the generation of a vortex can be clearly observed. As previously discussed, dune induced vortex generates upstream transportation of sand particles, which enhances the erosion process, thereby making dune altitude increase more rapidly. In parallel, the increasing dune altitude gives rise to a stronger and larger vortex expansion region. As illustrated by figure 9(c-e), both the evolution of sand dune and flow structures are now strongly coupled. This trend can also be observed in figure 4, which shows a rapid growth of dune erosion height between 100 and 200 seconds. Finally, the interaction between flow field and sand dune achieve a near equilibrium state, where *quasi* steady flow conditions are gradually achieved (figure 7).



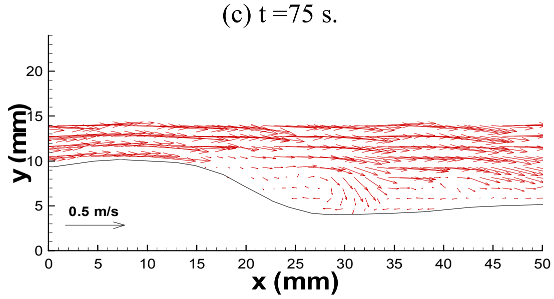
(a) PIV image.



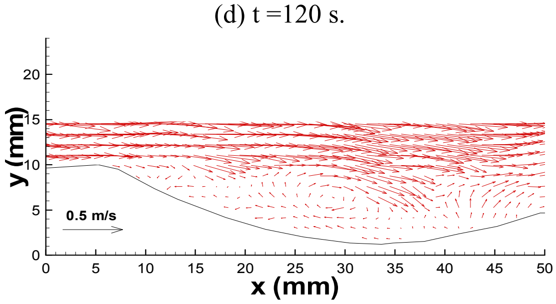
(b) t =30 s.



(c) t =75 s.



(d) t =120 s.



(e) t =200 s.

Figure 9: Time evolution of dune induced flow field.

CONCLUSION

In this study, Particle Image Velocimetry (PIV) analysis was undertaken to investigate both sand dune formation and local flow field interaction under hydraulic conveying conditions. Dune front vortex induced flow structures were captured, with time series analyses of particle-liquid interaction on the sand dune formation process presented.

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