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Experimental Characterization of Solid Particle Transport by Slug Flow Using Particle Image Velocimetry

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Abstract. This paper presents an experimental study of gas-liquid slug flow on solid particle transport inside a horizontal pipe with two types of experiments conducted. The influence of slug length on solid particle transportation is characterized using high speed photography. Using combined Particle Image Velocimetry (PIV) with Refractive Index Matching (RIM) and fluorescent tracers (two-phase oil-air loop) the velocity distribution inside the slug body is measured. Combining these experimental analyses, an insight is provided into the physical mechanism of solid particle transportation due to slug flow. It was observed that the slug body significantly influences solid particle mobility. The physical mechanism of solid particle transportation was found to be discontinuous. The inactive region (in terms of solid particle transport) upstream of the slug nose was quantified as a function of gas-liquid composition and solid particle size. Measured velocity distributions showed a significant drop in velocity magnitude immediately upstream of the slug nose and therefore the critical velocity for solid particle lifting is reached further upstream.

1. INTRODUCTION
Many industrial processes, such as hydrocarbon production and processing, in the petroleum industry involve complex multiphase flows such as (oil/water, gas and sand mixtures). Understanding the mechanism of sand transport in multiphase flow lines has direct impact on estimation, design and detailed analysis of new generation of horizontal oil wells. For instance the increasing amount of sand in horizontal pipelines produces a stationary sand deposit which creates a pressure drop and affects 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 (Takahashi et al., 1989; Takahashi & Masuyama, 1991). The sand transport during the resuming operation can cause pipe blockage if the gas-liquid velocity becomes excessive (Takahashi & Masuyama, 1991). The frequently occurring gas-liquid flow situation appearing in pipeline is slug flow, classified as an intermittent flow of liquid and gas. The slug flow is defined as an intermittent phenomenon where a succession of long gas bubbles and liquid slugs appears in the pipeline, figure 1.
For near horizontal flow, the investigation of slug flow on sand transportation represents a key topic for design and improvement of production rate in oil and gas wells. The majority of studies published to-date on pipeline multiphase flows have focused on the dynamics of two-phases liquid-gas (Mandhane & Aziz, 1974; Fabre & Line, 1992; Manolis, 1995; Gopal & Jepson, 1998; Rosa, 2004, Woods et al., 2006;) or liquid-solid transport (Doron & Barnea, 1995; Ould-Dris et al., 1996; Matousek, 2001; Skudarnov & Lin, 2004; Ramadana et al., 2005). Limited studies exist on the simultaneous transport of three phase flow containing solid particles, gas-liquid flow inside horizontal pipes (Turian et al. 1987; Angelsen et al., 1989; Oudeman, 1993; Gillies et al., 1997; Salama, 1998; Stevenson et al., 2001; Stevenson & Thorpe, 2003; Oladele et al., 2005; Danielson, 2007; Orell, 2007). Stevenson et al., (2001) and Stevenson & Thorpe (2003) studied the dynamic of isolated particles in a multiphase flow line for a critical sand concentration C < 50 ppm. They predicted with good accuracy the sand particle velocity in intermittent slug flow by considering the slug flow as a hybrid between two steady flows: (i) stratified flow and (ii) simple hydraulic conveying. In addition they found that gas fraction does not influence directly the velocity of isolated sand particles. However their predictions are not appropriate for the present study which contains a high concentration of sand particles inside the pipeline. The influence of gas fraction for higher sand concentration has been studied by Oudeman (1993) for continuous feeding. Contrary to Stevenson et al., (2001) and Stevenson & Thorpe (2003); Oudeman (1993) found that the gas fraction influences greatly the sand transport. However few studies have focused on the influence of slug flow on sand migration with initial stationary sand bed geometry. At low flow rates below the critical velocity $U_c$, it is assumed that the sand bed is stationary (with no sand particle motion) and occupies the bottom of the pipeline with a specific height. At the critical velocity $U_c$ the sand particle is entrained from the stationary layer, transported along the pipe generating the bed load pattern.

It has been shown in previous published studies (Stevenson et al., 2001; Stevenson & Thorpe, 2003) that particle transport in intermittent flow occurs primarily in “slug” phase rather than the film phase. The particle does not move immediately on the slug nose arrival. Instead the slug passes a distance ($l$) downstream before it entrains the first particle on the top of the bed. In this study the distance between the slug front and the first moving solid particles is referred to as the Slug Nose Inactive Length (SNIL), figure 1. The term inactive is related to static behavior of solid particle inside the SNIL. The importance of this distance ($l$) is significant for numerical simulation of particle transport. If this phenomenon is not taken into account, in simulation, prediction of particle transport will be over estimated. Previous studies (Stevenson et al., 2001; Stevenson & Thorpe, 2003) have observed this phenomenon but no existing study has quantified this parameter in terms of flow rate conditions. Stevenson et al., (2001) investigated the influence of the slug flow on particle transport in near horizontal pipeline. They assumed that the observed delay in pick-up of particles on arrival of the slug nose can be explained by considering the length required for the turbulence experienced in the slug nose to diffuse into the calmer region. They exposed an analogy based on a turbulent 2D jet flow where there is a region of turbulent, high-velocity fluid meeting a slower fluid. This analogy lead Stevenson & Thorpe (2003) to propose a range of 3 to 4 pipe diameters for the SNIL, without details about the flow condition. No further investigation has since been published on the influence of the flow conditions on the SNIL.
In order to understand the influence of slug flow on solid particle migration, it is essential to experimentally measure the velocity distribution inside the slug body and at bottom liquid layer. Previous experimental studies have measured local velocity distributions inside slug flow using Laser Doppler Velocimetry (Kvernvold et al., 1984), Hot-Film Anemometry (Sharma et al., 1998; Lewis et al., 2002), Photomatic Dye Activation (Kawaji et al., 1995), Nuclear Magnetic Resonance (Barberon & Leblond, 2001) and Digital Image Analysis (Gopal & Jepson, 1997). The local mean velocity profiles obtained from the various methods showed an axisymmetric behavior with highest velocity located at the upper region of the pipe. However, full 2D field velocity distribution is required to obtain fundamental insight into particle solid migration inside slug flow body. For vertical slug flow, a limited numbers of studies have presented 2D flow field measurements using techniques such as Particle Image Velocimetry (van Hout et al., 2002; Nogueira et al., 2003, 2006) and Advanced Electromagnetic Flowmetry (Kang et al., 2004). Nogueira et al. (2003, 2006) combined the Particle Image Velocimetry (PIV) with Pulsed Shadowgraphy (PS) and obtained the 2D velocity distribution behind rising Taylor Bubble inside vertical pipe. The same method has been performed by Carpintero-Rogero et al., (2006) for horizontal two phase flow. Experimental results obtained by Carpintero-Rogero et al., (2006) were focused on the validity of the method for measuring 2D velocity field. They concluded that the simultaneous PIV (using fluorescent particle as markers) and PS is suitable for the investigation of stratified wavy and elongated bubble flow and conditionally acceptable for slug flows. They also observed that measured velocity distribution decreases in accuracy if the gas phase is highly mixed with the liquid phase, as only a part of tracer particles can be seen. Consequently measurement of the velocity distribution is challenging near the gas-liquid interface.

The present study investigates the influence of gas fraction in slug flow on preloaded solid particle bed geometry during startup process. Two experiments are presented: (i) Influence of slug length on solid particle transportation using high speed CCD camera (multiphase air-water-solid particle loop); (ii) Measurement of the velocity distribution inside slug body using combined Particle Image Velocimetry (PIV) with Refractive Index Matching (RIM) and fluorescent tracers (two-phase oil-air loop). Combining these experimental analyses, the results provide an insight into the physical mechanism of solid particle transportation due to slug flow.

2. EXPERIMENTAL SETUP AND FLOW VISUALIZATION SYSTEMS

Particle transport and flow field measurements are undertaken in three-phase and two-phase flow loops, respectively. Solid particle transportation measurements are performed using digital image analysis. Slug flow velocity measurements are obtained using Particle Image Velocimetry (PIV).

2.1 Three Phase Flow Loop (Air-Water-Glass Beads)

The overall design of the horizontal multiphase flow loop was specified according to the laboratory space available to house the test facility. The test facility was limited to 3m in width and 6m in length. To optimize the utilization of this space constraint, a U-shape test facility was designed, with the layout shown in figure 2. The total flow length of the loop is 14 m, with the inner pipe diameter equal to 25.4 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 120 lpm (Re = 100,000) to the working section, measured by a digital mass flow meter range, 0 to 10 lpm (GPI 09 Series). The water reservoir tanks have capacity of approximately 450 liters each. Air flow is obtained from a utilities compressed air line that supplies clean air, free of lubricants, and measured by a digital flow meter, 0 to 50 lpm (Cole-Parmer CP5990). Two phase air-water composition is controlled by separate flow valves on the air and water lines. Air flow was injected downstream of
water flowmeter using a concentric annuli design. In order to remove potential surface curvature effects of the 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 $n = 1.48$. Three-phase flow measurements were realized at $24 \, ^\circ C$.

![Diagram of Horizontal Multiphase Flow Loop (Air-Water-Solid Particle).](image)

The gas-liquid flow structures were visualized in the vertical plane of the working section using high speed CCD camera (Flowsense M2/E 8bit). Mixture compositions were chosen to ensure that air-water flow was within the slug pattern zone (Mandhane & Aziz, 1974; Goharzadeh et al., 2008). Various slug air-water flow rate mixture compositions of 3 to 11 lpm (air) and 3 to 5 lpm (water) over preloaded solid particle bed were visualized. As outlined by Bain & Bonnington (1970), sand transport pattern classification in terms of particle size, density, and shape have a considerable influence on the particle bed geometry. It was therefore decided to investigate the behavior of glass beads with a mean diameter of 0.4 - 0.8 mm and 2.00 mm for the above flow compositions. A uniform glass bead bed of $h = 5$ mm thickness was laid in the test section over a 4 m length, which represents approximately 160 pipe diameters.

### 2.2 Two Phase Flow Loop (Air-Oil)

The test facility (figure 3) consisted of a 1.5m horizontal transparent cylindrical working section having an inner diameter of 25 mm. Made from Plexiglas, the working section is connected to a centrifugal pump ($Q_{\text{max}} = 30$ lpm) with a regulating valve and flowmeter. Air is injected through a 2 mm nozzle fitted to the top of the pipeline, downstream of the working section. To obtain steady laminar flow with the minimum of bubbles generated from air injection, a viscous silicon oil (Dow Corning 556) was selected as the working liquid. The kinematic viscosity of the silicon oil was measured to be $\nu = 18.6 \times 10^{-6}$ m²/s at the working temperature of $T = 34.7 \, ^\circ C$. As for the previous test facility, surface curvature effects of the pipeline were eliminated using a transparent rectangular box fitted around the working section and filled with the same silicon oil as the working liquid.
The Particle Image Velocimetry (PIV) was employed using fluorescent particles tracers (Rhodamine 6G) excited by a planar laser sheet from a pulsed YAG laser (NewWave Solo λ = 532 nm, P = 1.5 W) with a wavelength suitable for the absorption band of the dye (≈ 500 – 600 nm). The light is re-emitted with an emission maximum wavelength at approximately 650 nm. The planar laser sheet penetrated the central vertical plane of the working section, with the CCD camera (Flowsense M2/E 8bit) placed perpendicular to the laser sheet. To minimize the light scattering effect of traveling air bubbles at the top part of the pipeline the laser sheet was illuminated beneath the working section. In addition when recording visualization of two phase flow (air-oil), the CCD camera was fitted with a standard red interference filter to eliminate scattering light received from the two phase air-oil interface. A field of view of 85 × 25 mm was obtained using a focal length of f = 28 mm. Full-frame images of 1600 × 1186 pixels were acquired and transferred to a computer via a frame grabber.

Using the Flowmap System software provided by the Dantec Dynamics, the 2-D PIV image is divided into 16 × 16 pixels sub-regions with 50% overlap and average particle velocities is calculated using 100 images with the cross correlation method. The time interval between each image couple was 125 ms. The pulse separation time was adjusted to 0.1 ms.

Two phase velocity profiles in the slug body were obtained using a fluid mixture composition of Q_{oil} = 6.7 lpm, corresponding to a Reynolds number Re = 306, and Q_{g} = 2.4 lpm.

3. RESULTS

3.1 PIV Validation

To verify the upstream single phase flow conditions as fully developed laminar flow, as well as PIV velocity measurement accuracy, the obtained velocity profile was compared with an exact analytical solution, Munson et al. (2006):

\[ u(r) = U_{max} \left( 1 - \left( \frac{r}{D} \right)^2 \right) \]  

(1)

where \( U_{max} \) is the maximum velocity at the center of the pipe, r and D are the radius and diameter of the pipe, respectively.
For a Reynolds number \( \left( \frac{U_{\text{mean}} \cdot D}{\nu} \right) = 306 \), excellent agreement was obtained between the measured velocity profile and corresponding analytical prediction, as illustrated in figure 4. As an additional error analysis assessment, the pipe volumetric flow rate \( Q \) was measured using a flowmeter (GPI 09 Series). Based on the measured volumetric flow rate, mean velocity \( U_{\text{mean}} \) was calculated to be 0.224 m/s. For the corresponding PIV analysis, the measured maximum velocity is \( U_{\text{max}} = 0.416 \) m/s, which corresponds to an averaged pipe velocity of \( U_{\text{mean}} = \frac{U_{\text{max}}}{2} = 0.208 \text{m/s} \). Thus the estimated error between the mean velocity measurements obtained using the flowmeter and PIV is approximately 7%. Combined, both measurement error assessment approaches provide confidence in the accuracy of the PIV velocity measurement technique employed in this study.

![Fig. 4 Comparison of measured and predicted velocity profiles for fully developed single phase laminar flow (Re = 306).](image)

3.2 Slug Nose Inactive Length

Measurement of SNIL \( (l) \) is illustrated in figure 5. The distinction between the inactive and active zones in terms of solid particle transport, upstream of the slug nose, is characterized by a disturbance at the liquid-porous interface.

![Fig. 5 Measured Slug Nose Inactive Length.](image)

The SNIL measurements given in figure 6 are average values for the number of slugs passing over the particle bed in the acquisition session. The SNIL results are presented in a non-dimensional ratio \( (l/D) \) with \( D \) the inner pipe diameter.
The SNIL range measured is between 1 and 6 times the pipe diameter (figure 6). This is contrary to Stevenson et al. (2001) who postulated that SNIL can be generally simplified to be a factor 3 and 4 times the pipe diameter.

It was found that the SNIL depends significantly on the air-gas flow composition. For a given water flow rate, SNIL decreases with increasing gas flowrate. This trends also holds for a given gas flowrate with increasing liquid flowrate. In addition the influence of the particle size has been highlighted in figures 6 (a) and (b). For a fixed mixture composition, SNIL increase with particle diameter increase, indicating lower solid particle transportation rate for the 2 mm diameter glass beads particles.
3.3 Velocity Distribution inside Slug Body

In figure 7 a visualized slug flow sequence with corresponding velocity field measurements in the liquid region is presented. The velocity distribution in the slug nose is shown in figure 7(a) where a significant change on the velocity magnitude is observed along the stream-wise flow direction. Corresponding vertical velocity profiles of the horizontal component at four different downstream positions (x coordinate) are plotted in figure 8. The velocity magnitude in the liquid film is half that in the slug nose region (figure 8(a)). The same phenomenon appears in the slug front region (figure 7(b)) with greater magnitude change. The velocity profile is significantly affected when the air bubble passes above the liquid flow. The local velocity profiles, obtained at four different stream-wise positions (figure 8(b)), shows that the velocity magnitude increases by factor of five at the upper region of the pipe. However, in the same locations the velocity magnitude changes smaller at the lower region of the pipe. Upstream from the air bubble (figure 7(c-d)), the velocity magnitude increases and a laminar velocity profile is observed in this single phase flow region (figure 8(c)). It should be noted that the averaged velocity profile reaches its maximum magnitude in the region furthest upstream of the slug front (figure 7(d)). In terms of assessing the SNIL, the velocity distribution shows a drop in velocity magnitude immediately upstream of the slug nose and therefore the critical velocity for solid particle lifting is reached further upstream.

The slug flow is characterized by the intermittent flow of slugs, and therefore the observed velocity profile formation is cyclic. This observation is confirmed by comparing the velocity profiles in figure 8(a) at x = 80 mm with figure 8(c) which are comparable in magnitude. In addition this mechanism results in intermittent solid particle transportation in slug flow (Goharzadeh et al., 2008).
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Fig. 7 Measured slug flow velocity distribution ($Q_{air} = 2.4$ lpm, $Q_{oil} = 6.7$ lpm).
a) In the liquid film (x = 20 and 40 mm) and slug nose (x = 60 and 80 mm) (t=0s).

b) In slug front body (x = 20 and 40 mm) and liquid film (x = 60 and 80 mm) (t=0.125s).

c) In the slug body for two different time (t = 0.25s and t = 0.375s).

Fig. 8 Measured vertical profile of horizontal velocity component in slug flow.

(Q_g = 2.4 lpm, Q_oil = 6.7 lpm).
4. CONCLUSIONS

Particle transport and flow field measurements are undertaken in two-phase and three phase flow loops, respectively. Solid particle transportation measurements are performed using digital image analysis. Slug flow velocity measurements are obtained using Particle Image Velocimetry (PIV). Combining these two experimental analyses, an insight was provided into the physical mechanism of solid particle transportation due to slug flow. It was shown that the slug body significantly influences solid particle mobility. The physical mechanism of solid particle transportation was found to be discontinuous. The inactive region (in terms of solid particle transport) upstream of the slug nose was quantified as function of gas-liquid composition and solid particle size. Measured velocity distributions show a significant drop in velocity magnitude immediately upstream of the slug nose and therefore the critical velocity for solid particle lifting is reached further upstream.

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NOMENCLATURE

\begin{align*}
C & \quad \text{Sand concentration [ppm]} \\
\text{d} & \quad \text{Sand particle diameter [m]} \\
D & \quad \text{Pipe diameter [m]} \\
f & \quad \text{Focal length of the camera [m]} \\
h & \quad \text{Height of glass bead bed [m]} \\
n & \quad \text{Refractive index n [-]} \\
\text{Re} & \quad \text{Reynolds number [-]} \\
Q_g & \quad \text{Gas flow rate [lpm]} \\
Q_w & \quad \text{Water flow rate [lpm]} \\
Q_{oil} & \quad \text{Oil flow rate [lpm]} \\
t & \quad \text{Time [s]} \\
U_{mean} & \quad \text{Averaged Velocity of liquid particles [m/s]} \\
U_c & \quad \text{Critical velocity for lifting solid particles [m/s]} \\
U_{\text{max}} & \quad \text{Maximum velocity of liquid particles [m/s]} \\
x & \quad \text{Axial coordinate [m]} \\
\lambda & \quad \text{Wavelength [nm]} \\
\nu & \quad \text{Kinematic viscosity [m}^2\text{/s]} \\
\end{align*}

REFERENCES


