EROSION IN SLUG FLOW

INTRODUCTION

Sand produced by oil and gas producers creates many problems such as accumulation of the sand in perforation tunnels, lines and pumps; and damage to production equipment, well tubing and fittings as well as inside walls of the reservoir. Sand screens or gravel packs are commonly installed in open hole well bores to avoid the passage of sand along with the reservoir fluids. However, this sand control approach may fail due to plugging of the screens with smaller particles causing an increase in the local fluid velocity at other portions of the screen causing damage. Upon failure, sand production occurs where this sand repeatedly impacts pipe walls removing material gradually. The mechanism of material loss depends on the type of pipe wall material. For example, the erosion in ductile materials is caused by localized pipe wall deformation resulting in cutting action caused by severe particle impacts. Other types of failure mechanisms include ploughing, fatigue and brittle fracture.

Prediction of solid particle erosion is extremely difficult because of its dependence on many factors. The important ones are flow pattern, sand distribution, flow geometry, fluid flow rates and particle properties such as size and shape. The complexity of erosion is increased in multiphase flow because of the different flow patterns that occur under different operating conditions. These different flow patterns affect the sand particle impact characteristics and cause different amounts of erosion. The geometries which are more susceptible to erosion are the ones which change the flow direction such as elbows, tee joints, and sudden expansion and

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contraction zones. Since erosion depends on multiple factors, developing a predictive tool for erosion is a challenging task.

The severity of erosion is clearly emphasized by the picture shown below. Figure 1 shows the location of a failure caused by erosion in a stainless steel pipe at a bend. This location of failure supports the statement already made that erosion failures commonly occur in locations where the flow direction changes. This failure was observed after conducting experiments in a laboratory setting for a period intermittently of 3 months.

![Figure 1: Multiphase Flow Stainless Steel Pipeline Failure as the Result of Erosion](image)

**Slug Flow – Literature Survey**

A major focus of this work is to show erosion measurements in the slug flow regime, so a brief description about slug flow is given here.

The study of intermittent flow has received considerable attention for the past 30 years due to its complex flow structure. Additionally, intermittent flow patterns are most commonly observed when liquid and gas phases are moving simultaneously inside a pipeline. In horizontal pipelines, two intermittent flow patterns are often seen: plug flow and slug flow. Plug flow is characterized by liquid plugs without gas entrainment, moving between the stratified zone of the gas bubble...
and the liquid film regions. Plug flow occurs at lower gas rates. If the gas rate is increased by maintaining a constant liquid rate, a three-dimensional mixing zone is observed at the front of the plug. This three-dimensional mixing zone results in entrainment of gas bubbles inside the liquid plugs, creating aerated plugs. These aerated plugs are commonly referred to as slugs.

Slug flow is characterized by slugs moving at a velocity approximately equal to the mixture velocity (mixture velocity is defined as the sum of superficial liquid and gas velocities) between the stratified gas and liquid film region. In the stratified zone, gas moves on top and the liquid film flows beneath it. The gas bubble seen in the stratified region is usually called the Taylor bubble. The combination of liquid slug body and the Taylor bubble region is called the slug unit. The various components of the slug flow are shown in Figure 2.

![Figure 2: Schematic of the Slug Unit (Note: Figure is not to Scale)](image)

Pseudo slug flow is a type of intermittent flow pattern which is seldom described in literature. In this type of flow pattern, there is entrainment of liquid droplets inside the Taylor bubble within the stratified region, in addition to the entrainment of the gas bubbles in the liquid slug region.

Many researchers have focused on the flow rates which result in the transition from stratified flow to slug flow. Two different approaches were followed by researchers. The first approach is to use classical linear stability analysis and the other is to examine the stability of the slugs travelling over the liquid layer. Dukler and Hubbard [7] first proposed the concept of a stable slug. They said that a fast moving liquid slug picks up slow moving liquid inside a liquid film and accelerates the liquid to the slug velocity. It then sheds the liquid back into the liquid film.
region. For a steady state slug flow, the rate of liquid picked up by the slug front is equal to the rate of the liquid shed at the slug back. Taitel and Barnea [14] developed a comprehensive model for slug flow by applying the momentum balance on the liquid film region. The final output of this model is to determine the pressure drop across the slug unit, where the slug unit is defined as the combination of slug body and the liquid film region. This model takes into consideration four types of closure relationships: translational velocity (interface velocity between Taylor bubble and the liquid slug body), slug body length, slug liquid holdup and velocity of gas bubbles entrained inside the liquid slug body.

There is a vast amount of literature available on studies of slug characteristics as they tend to be important in models which predict pressure drop. Several experimental techniques have evolved in the recent past to study details of slug flow such as its structure and length distribution and void fraction. Some of the instruments used by researchers are conductance probes, nuclear-densitometers, fiber-optic sensors, wire mesh sensors, piezo-electric sensors, hot-film anemometers and tomography techniques. Slug length measurements suggest that the slug body length is not constant and it follows a log normal distribution (Brill et al. [1], Scott et al. [10], Nydal et al. [8], Cook and Behnia [2], van Hout et al. [12], Wang et al. [13]). This suggests that the volume of liquid inside the slug body is continuously changing and over a certain period of time there will be stable, decaying and growing slugs passing by a particular cross-section inside the pipe which would be sufficiently far from the inlet of the pipe. Also, several correlations were evolved for the calculation of the mean slug length based on pipe diameter and orientation of the pipe. Recently, Sarica et al. [18] conducted a sensitivity analysis on the influence of slug length correlations on frequently used mechanistic models in the literature which are used to predict the pressure drop in the slug flow regime. They found that the
influence of slug length correlations is relatively small in the calculations of pressure drop and liquid holdup.

Slug liquid holdup and translational velocity measurements have also been conducted by many investigators. There are many slug liquid holdup correlations available in the literature. Gomez et al. [4] is a commonly used slug liquid holdup correlation as it is applicable to all inclination angles. Also, Zhang et al. [15] developed a unified mechanistic model which predicts slug liquid holdup by equating the kinetic energy possessed by the slug body to the surface free energy of the entrained spherical gas bubbles. Pereyra et al. [19] gathered huge data sets on slug liquid holdup from literature and compared the data with the published correlations. They improved the slug liquid holdup correlations by tuning them to the available data and finding new constant values for the correlations.

Slug flow characteristics are important for understanding and predicting erosion. Despite the literature available on slug flow, it is currently an active research area due to its vast appearance in many areas and enormous complexity.

Sand Distribution and Transport

In addition to the multiphase flow characteristics, sand location distribution and transportation characteristics also directly influence erosion behavior and magnitude. So, a general overview on the influence of sand characteristics on erosion is explained below.

Hill [20] examined the behavior of sand flowing in horizontal pipes and determined critical transport velocity. He observed the effects of particle concentration (0.01%, 0.1%, 1% by volume), particle diameter (20 µm, 150 µm, 300 µm), liquid viscosity (1 cP, 10 cP) and the pipe diameter (50.8 mm, 101.6 mm) on the critical flow rates for particle transport. Experiments were performed under single-phase (liquid and sand) and multiphase (liquid, gas and sand) conditions.
Hill found increasing particle concentration, particle diameter, liquid viscosity or pipe diameter increased the fluid flow requirements for particle transport. So, for similar particle size and fluid flow characteristics, the erosion for smaller pipe sizes may be higher than for larger sizes.

Al-lababidi et al. [21] studied the influence of pipe angle (+ 5 degree inclined) on the solid particle transport for single-phase water flow and air-water flow regimes. They conducted experiments using an average sand size of 200 µm and varied the particle volume concentrations. In the inclined pipe, the efficient means of particle transport was found to be in pseudo slug flow. It was found that the number of particles entrained in the pseudo slugs is higher, because of the increase in turbulence energy at the front of the liquid slug body. This result has a direct influence on erosion, since increasing the number of particle impacts at a specified location in the pipe increases the metal loss. Also, the particles entrained in the liquid slug body possess high kinetic energy causing severe impacts with the pipe wall. Al-lababidi et al. also mentioned that the change in gas throughput influences the minimum transport condition of the particle. The authors attributed this behavior to the change in turbulent intensities in the liquid by increasing the gas velocity. They have also emphasized that the change in the particle concentration has a significant impact on the particle transportation characteristics which is in agreement with the findings of Hill. Recently, Zeinali et al. [22] studied the influence of near wall turbulent structures on particle removal from a deposited sand bed. They found with increase in time, the concentration of the finer particles on the pipe bottom was increased, thereby coarser particles were removed by turbulent structures. The range of particle sizes they studied was from 0.1 µm to 50 µm. However, these experiments were performed in a single-phase liquid flow, and the influence of gas-liquid on the particle removal was not studied.
As mentioned earlier, sand distribution characteristics in multiphase flows along with the transport characteristics influences erosion. However, unlike the sand transportation data, the sand distribution data in pipelines operating under multiphase flow regimes is extremely limited. McLaury et al. [23] studied the influence of the distribution of sand particles in horizontal and vertical annular flow on erosion. They said that the location distribution of the particles and liquid are relatively uniform for the vertical pipe compared to the horizontal orientation. They found that the amount of liquid and sand collected at the centerline of the pipe increased by increasing the gas velocity. Particles travel in the gas core at higher velocities, so more particles near the centerline cause more erosion. The non-uniform distribution of the particles in the horizontal pipes was attributed to gravity. Also, they found that for a similar sand throughput the metal loss in the vertical pipe is higher than that for horizontal pipe which was attributed to the distribution of the particles. Entrainment of liquid and particles is less in horizontal flow, so more particles are in the slower moving liquid film than the gas core. Authors also tried to relate the liquid film thickness to erosion magnitude, stating that the increase in the liquid-film thickness in horizontal flow decreases erosion. However, the sand distribution behavior needs to be verified for the slug flow regime for which the sand transport characteristics are very different than other multiphase flow patterns.

**Slug Flow Erosion-Previous Studies**

The complexity in understanding erosion in slug flow is even more complicated than slug flow alone as an additional phase (solid) is introduced to the liquid and gas phases. There are very few studies in the literature studying erosion in slug flow.

Gundameedi [6] conducted erosion experiments using Electrical Resistance (ER) probes installed at a bend and in a straight pipe section in the slug flow regime. His main objective was
to study the performance of acoustic monitors and ER probes in slug flow. ER probes are intrusive instruments which relate the metal loss to the change in electrical resistance between sample and reference elements where the sample element is exposed to the flow whereas the reference element is protected from the flow. He concluded that ER probes are successful in detecting the metal loss in the slug flow regime and acoustic monitor output can be useful in detecting the sand rates. He also stated that acoustic monitor raw output increases by increasing the particle size and these monitors are ineffective in detecting particle impacts of 20 µm particles i.e., finer particle sizes. Odigie [16] extended the acoustic monitor study to detect the threshold sand rate for annular, slug and stratified flow regimes.

Rodriguez [9] developed a one-dimensional mechanistic model for erosion in slug flow using a stagnation length concept developed by Shirazi et al. [17]. In this approach, stagnation length is the distance away from the wall where viscous effects are important. He calculated particle impact velocities by applying a force balance on the particle which is used to compute erosion. Finally, he compared the predictions of the model with the experimental data and found good agreement with larger particle sizes. The model under predicted the erosion data collected using smaller particles.

Throneberry [11] conducted measurements with smaller particles using ER probes installed on a bend and in a section of straight pipe. He extended Rodriguez’s model to two dimensions thereby considering both normal and tangential impacts of the particles at the wall.

The prior erosion measurements under the slug flow regime were made at a maximum of two locations inside the bend due to the size constraints associated with the ER probes. Therefore, there is a need for a new measurement technology which enabled erosion inside the bend to be characterized in more detail.
Erosion Measurements

Previous reports (E/CRC report 2010 and 2011) have shown the erosion measurements obtained for variety of operating conditions. This report is more focused on the sand sampling study conducted and the future work associated with slug characteristics.

Sand Sampling Studies

In order to better understand erosion behavior in various multiphase flow regimes, it is necessary to examine the amount of sand at various locations in the pipe. It is important to mention that sand production is often unavoidable when producing oil and gas from reservoirs. Produced sand creates a multitude of problems. Some of them are listed as follows:

- Presence of the particulate phase increases the mixture density and viscosity and thereby increases the energy requirement for transport i.e., increases the pressure drop
- Sand particles may accumulate at the junction between the pipelines and the riser during offshore production. Under severe conditions, sand particles may pileup and block the passage resulting in less production and finally no production
- During the emergency shut-down of production, sand particles will settle down at the pipe bottom forming a sand bed. Formation of the sand bed leads to corrosion of the pipeline underneath the bed which is usually called sand bed corrosion or under-deposit corrosion
- Sand particles traveling at higher velocities inside the pipelines will impact the pipe wall and gradually remove the material from it resulting in erosion. Severe erosion of the pipe wall is unacceptable and can lead to failure

Accordingly, monitoring the amount of sand inside the flow line and its distribution along the cross-section of the pipe is extremely useful to ensure safe production. One of the many ways to
understand the sand distribution is analyzing the sample withdrawn from the pipe iso-kinetically. Isokinetic sampling is a commonly used industrial technique to measure solid concentration, shape factor of solid particles and particle size distributions in the produced fluids. In this technique, the sampling tube is used to collect the sample where one end of the tube is fixed at the sampling location while the other is connected to a sampling tank where the pressure inside the tank is less than the pressure at the sampling location. For isokinetic sampling, the pressure should be the pressure that creates a velocity in the probe similar to the local velocity at the sampling location.

**Literature Survey:** Kaushal and Tomita (2002) measured concentration profiles of four different sized zinc particles along the vertical plane inside a 105 mm (4.13 inch) pipe with water as the fluid. The particle sizes they used to perform experiments ranged from 38 µm to 739 µm. They studied the influence of particle size, initial bulk concentration and flow velocity on the concentration profiles. Kaushal and Tomita found that the concentration profile is uniform along the vertical plane for the smaller particle sizes (38 µm) irrespective of the flow velocities; whereas for the larger particles, the concentration profiles are asymmetrically distributed and become more asymmetric as the flow velocity decreases. They said that the decrease in fluid velocity decreases the kinetic energy of the flow which affects the energy requirement for the particle suspension thereby causing the asymmetric distribution. Regarding the effect of the initial bulk concentration on the concentration profiles, they mentioned that the increase in initial bulk concentration decreased the asymmetry in the solids distribution due to the increase in interaction between the particles which further generating the lift force on the particles causing suspension. It is important to mention here that the initial bulk concentration for their
experiments ranged from 4% to 26%, and the measurements were performed using an isokinetic sampling probe.

Nasr-el-din et al. (1995) conducted sand sampling experiments inside a mixing tank along the impeller plane location and also at several other axial and radial locations. They calculated the errors associated with the orientation of the sampling tube by comparing the magnitudes of local solid concentration obtained from sampling tubes with the solid concentration measured using a conductivity probe. They said sampling errors were higher when using the smaller diameter sampling tubes and for larger particle sizes. Also, errors depend on sampling tube location, shape and orientation. They concluded that the solid concentrations were functions of the particle size, impeller speed and the location of sampling. They observed that the smaller particles (82 µm) were uniformly distributed along the radial location whereas the larger particles (410 µm and 1000 µm) were not.

Diez-Lazaro et al. (2005) mentioned the importance of sampling tube orientation, sampling tube geometry and sampling rate for obtaining a representative sample while conducting experiments. They mentioned that the sampling tube diameter should be greater than at least 6 mm (0.24 inch) in order to obtain a representative sample inside a mixing tank. Also, Diez-Lazaro et al. (2005) discussed that the particle bouncing effect is one of the reasons for withdrawing a non-representative sample. A particle that bounces off the wall loses its inertia and thereby will be sucked inside the sample tube which otherwise would not occur. In order to reduce its effect, authors suggested using a tapered sampling tube. Aguillon et al. (1995) compared different non-isokinetic sampling probes to measure solid concentration in upward and downward flowing circulated fluidized beds with rectangular column geometry with air as the fluid and cracking catalyst for particles. They found that the best results were obtained with the
larger radius probe with a square opening. However, their mean particle sizes were 68 µm, which one would assume to be uniformly distributed.

Isokinetic sampling was also conducted by a few authors to measure the droplet flux at various vertical locations inside the pipe for gas-liquid flows. Zhang and Ishii (1994) developed a method for droplet size measurements using both an isokinetic sampling tube and image processing technique in high velocity gas-droplet flows for application in a nuclear reactor. Tayebi et al. (1999) measured the droplet distribution above the stratified liquid layer for a two-phase (oil-gas and water-gas) flow using an isokinetic sampling technique. Their objective was to conduct droplet flux measurements for liquid droplets transported in a high pressure gas medium. Their study led to several important conclusions which are listed below:

- Deviation of ± 50% from the isokinetic conditions showed only ± 13% change in droplet flux measurements.
- Entrainment rate of droplets increased two times for oil/gas flows than water/gas flows.
- Thickness of the liquid layer flowing at the pipe bottom is predicted by observing the fluctuations in the stagnation pressure reading on the flow meter connected to the isokinetic instrument. These fluctuations are due to the periodic striking of the liquid waves on the sampling tube tip indicating the interface between the gas and liquid. However, they mentioned that the uncertainty in these types of interface measurements is considerably high.
- Droplet entrainment rate increased by increasing the superficial gas velocity and also by increasing the gas density. However, the influence of superficial gas velocity on droplet entrainment rate is stronger than gas density.
Sand Sampling in a Bend

It is also beneficial to perform sand sampling inside the bend to better understand the erosion behavior for slug flow conditions. Measurements of sand concentration using a protruding sample tube into the bend is not an ideal measurement approach. The flow in a bend is not unidirectional and the existence of secondary flows will not allow extracting the representative sample for analysis. So, wall mounted ports with diameters of 6.35 mm (0.25 inches) have been used. Eight wall mounted ports were placed around the 45 degree cross-section of the bend to obtain the local particle concentrations near the wall. Figure 3 shows the location of the wall mounted ports on the 76.2 mm (3 inch) standard bend. In order to compare the sand concentrations in the straight pipe to the bend, wall mounted ports were also placed in the straight pipe section upstream of the bend. Ports in the straight pipe were placed 3.05 m (10 ft) upstream of the bend. This distance was maintained in order to avoid any changes in the flow behavior before it reaches the bend. Figure 4 shows the location of the mounts on the straight section of the pipe.

Figure 3: Location of the eight wall mounted ports across the 45 degree cross-section of the bend
A slug characterization study was performed to improve understanding on erosion behavior. The instrument used for the measurement of slug characteristics is explained below:

**Wire Mesh Sensor (WMS):** WMS is the intrusive wire mesh technique used for the investigation of multiphase flows. WMS operates by measuring either conductivity or permittivity (capacitance) of the mixture at various electrodes. Figure 4 shows the WMS and its associated electronics that can be applied to multiphase flow through pipes. WMS can measure average liquid hold-up in the liquid slug and the entrainment fraction of liquid in the Taylor bubble region for pseudo slug flow and also the interface velocity. This information is useful to improve the current slug flow erosion model by developing a relationship between slug characteristics and erosion magnitude. WMS experiments were also performed after the standard bend to observe the influence of bend on fluid distribution.
Figure 5: Conductance Wire Mesh Sensor (Courtesy: HZDR, Dresden, Germany)

Sand Sampling Experimental Results

Figure 6: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 27.4 m/s and 0.67 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns
Figure 7: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 27.8 m/s and 0.44 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 8: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 33.5 m/s and 0.49 m/s with Liquid Viscosity of 1 cP and Particle Size of 300 Microns
Figure 9: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 27.4 m/s and 0.52 m/s with Liquid Viscosity of 1 cP and Particle Size of 300 Microns

Figure 10: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 35.7 m/s and 0.72 m/s with Liquid Viscosity of 10 cP and Particle Size of 300 Microns
Figure 11: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 35.7 m/s and 0.76 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 12: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 35.7 m/s and 0.73 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns (Repeatability Test)
Figure 13: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.76 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 14: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.76 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns
Figure 15: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 15.24 m/s and 0.30 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 16: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 30.5 m/s and 0.30 m/s with Liquid Viscosity of 1 cP and Particle Size of 150 Microns
Figure 17: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.76 m/s with Liquid Viscosity of 10 cP and Particle Size of 150 Microns

Figure 18: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.76 m/s with Liquid Viscosity of 10 cP and Particle Size of 150 Microns
Figures 6 to 19 show the ratios of the sampled liquid and sand quantities at various locations inside the cross section of the pipe. The observations made from this study are stated as follows:

- There is a non-uniform radial distribution of particles when the liquid viscosity is 1 cP. From the figures above, it is shown that the majority of sand particles travel along the bottom of the pipe.
- For the operating conditions examined, the majority of the liquid is collected at the bottom of the pipe. This is expected as gravity is a dominant factor for experiments in a horizontal pipe transporting fluids.
- The experimental data in Figures 12, 13 and 14 show the liquid and sand quantity ratios at different radial locations in the pipe for a nearly constant superficial liquid velocity of 0.76 m/s and superficial gas velocity ranging from 10.7 m/s to 35.7 m/s. The observed flow regime for all the operating conditions is slug flow. By comparing the amount of

Figure 19: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 51.8 m/s and 0.76 m/s with Liquid Viscosity of 40 cP and Particle Size of 150 Microns
liquid collected from the bottom of the pipe (position 1), it is observed there is more liquid flowing at the bottom as the superficial gas velocity increases. This is an indirect indication, that the amount of liquid associated with the slug body (liquid hold-up) decreases with an increase in the gas velocity. So, for the lower superficial gas velocities the liquid hold-up in the slug body is higher. The variation of sand flowing at the bottom of the pipe with an increase in superficial gas velocity under slug flow conditions is not as prevalent as the difference in the measured liquid. However, there is a slight increase in the number of particles flowing at the bottom of the pipe with an increase in the superficial gas velocity. The increase in the number of the particles flowing at the bottom of the pipe with the increase in superficial gas velocity, suggests that the majority of the sand particles are flowing with the liquid

- From all the experiments with liquid viscosity of 1 cP, it is observed that the sampled particle ratios are greater than the sampled liquid ratio only at the bottom of the pipe. At the other locations in the pipe cross-section, liquid is definitely the dominating medium. It is important to mention here that we haven’t observed any accumulation of particles in the pipeline. Due to the considerably high fluid velocities, the particles are always moving in the direction of the fluid flow

- With an increase in liquid viscosity, the magnitudes of liquid and sand quantity ratios become closer. Figure 10 and Figure 11 show the liquid and sand quantity ratios for similar operating conditions with a change in liquid viscosity (1 cP and 10 cP) and particle size (150 µm and 300 µm). Influence of liquid viscosity on liquid and sand quantity ratios can be compared from these two plots. The plots considered here for comparison are for two different particle sizes, but it is shown from the concentration
distribution plots that the influence of radial particle distribution on the particle sizes of 150 µm and 300 µm is negligible. From these figures, it is clear that amount of liquid flowing at the bottom of the pipe is higher for the 1 cP liquid viscosity compared to the 10 cP liquid viscosity. However, at the other sampling locations, the amounts of liquid and sand flowing are higher for the 10 cP liquid viscosity condition. This behavior also indicates that with an increase in the liquid viscosity there is more liquid entrainment. As the sand particles tend to stay with the liquid phase, there is also an increase in the sand entrainment with an increase in the liquid viscosity.

- Figures 17 and 18 also show the sampled liquid and sand quantities for the 10 cP liquid viscosity for different operating conditions. These data points were obtained by gathering the sampling measurements at 7 different radial locations inside the pipe instead of 5 locations. Irrespective of the superficial velocities (or) the sampling locations, the sampled liquid and sand quantity ratios are nearly the same. Also, the closeness of the sample liquid and sand quantities increases by increasing the liquid viscosity. Figure 19 shows the distributions for the 40 cP liquid viscosity and an observation was made that the closeness of the sampled liquid and sand quantities is more prominent. Also, a similar observation of increasing the amount of liquid flowing at the bottom of the pipe increasing with increase in the superficial gas velocity for 1 cP liquid experiments is also observed for the experiments with the liquid viscosity of 10 cP.

From the above analysis, it is understood that the majority of the sand is carried in the liquid film region. Also, as these experiments were performed at very high gas velocities, the slugs observed were highly aerated with less liquid content. From understanding gained through the sand sampling experiments, the majority of the sand particles are traveling with the liquid phase, so
only a small fraction of the sand is in the region where the fluid velocities are higher. However, these particles possess high momentum, which can create erosion damage to the pipe walls.

**Sand Sampling in a Bend Using Fixed Mount Ports**

![Graph showing ratio of sampled liquid and sand quantities](image)

**Figure 20: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.73 m/s in a Bend with Liquid Viscosity of 1 cP and Particle Size of 300 Microns**
Figure 21: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 32.9 m/s and 0.71 m/s in a Bend with Liquid Viscosity of 1 cP and Particle Size of 300 Microns

Figure 22: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.25 m/s in a Bend with Liquid Viscosity of 1 cP and Particle Size of 300 Microns

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Figure 23: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.25 m/s in a Bend with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 24: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.25 m/s in a Bend with Liquid Viscosity of 10 cP and Particle Size of 150 Microns
Figure 25: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.73 m/s in a Bend with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 26: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 50.3 m/s and 0.46 m/s in a Bend with Liquid Viscosity of 1 cP and Particle Size of 150 Microns
Sand sampling was performed using the fixed mount ports on the bend as well as the straight pipe. Eight ports at various locations on a 45 degree bend were mounted to extract the sand and liquid samples. Figure 20 to Figure 26 show the liquid and sand distributions at all the eight different locations inside the bend, for a variety of operating conditions. The following observations can be made from the figures above:

- Due to the centrifugal forces acting on the liquid and the particles, the quantities of particles and the liquid were nearly similar at all the locations in the outer wall of the bend, for the slug flow regime.

- We have found that the liquid and particles collected at sample locations 1 and 2 correspond to the liquid and particles associated with the liquid slug. Whereas, the liquid and particles collected at the remaining locations correspond to that of the film. We have observed that there is a thin liquid film surrounding the entire cross-section of pipe in the Taylor bubble region, for some of the operating conditions. However, we discard the liquid and particles contained in this region, by comparison with the amount of liquid and particles presented in the slug body and the liquid film region.

- In order to validate that the liquid and sand collected at sampling locations 1 and 2 are from the liquid slug, sand and liquid samples were collected at a various locations of the bend in the annular flow condition (see Figure 26). It is clear from this figure that there is no liquid (or) sand at the top of the bend (sample position 1). The liquid and the sand samples collected at position 2 may be from the entrained droplets and the sand in the gas-core region.
• From Figure 20 and Figure 21, it can be observed that with an increase in superficial gas velocity, the amount of liquid and sand collected at sampling locations 1 and 2 decreases. This is because the amount of liquid in the liquid slug body decreases.

• The influence of particle size on the distribution of liquid and particles was studied from Figures 22 and 24, and Figures 20 and 25. As observed from the intrusive sampling experiments, the influence of particle size (150 µm and 300 µm) is not significant for the sand size considered during these experiments.

• It can be observed from Figures 22 and 24 that there is the difference in the sand and the liquid samples collected. This is because that observed flow pattern during those experiments was a transition between stratified wavy and the liquid slugs. The frequency of the slugs was much less compared to that of the traditional slug flow operating conditions. Under this condition, the inertia associated with the liquid film is not strong enough to move more liquid and sand to sampling positions 3 and 4 from the bottom of the pipe, i.e., sampling position 5. Also, as there are very few slugs, the mixing phenomenon at the front of the liquid slug body may be absent.

• With an increase in liquid viscosity from 1 cP to 10 cP for the similar operating conditions as in Figures 17 and 18, it is observed that the flow pattern has changed to slug flow. This is due to an increase in liquid and sand entrainment from the film with an increase in the liquid viscosity, which is a similar kind of behavior observed from the intrusive sampling. Thus, it can be concluded that for the slug flow operating condition in multiphase transport pipelines that the sampled quantities of liquid and sand should be uniform for the samples collected on the outside bend.
Sand Sampling in a Straight Pipe Using Fixed Mounted Ports

Figure 27: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.71 m/s in a Straight Pipe with Liquid Viscosity of 1 cP and Particle Size of 300 Microns

Figure 28: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.74 m/s in a Straight Pipe with Liquid Viscosity of 1 cP and Particle Size of 150 Microns
Figure 29: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.74 m/s in a Straight Pipe with Liquid Viscosity of 10 cP and Particle Size of 150 Microns.

Figure 30: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.25 m/s in a Straight Pipe with Liquid Viscosity of 1 cP and Particle Size of 300 Microns.
Figure 31: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.25 m/s in a Straight Pipe with Liquid Viscosity of 1 cP and Particle Size of 150 Microns

Figure 32: Sampled Liquid and Sand Quantity Ratio’s for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.25 m/s in a Straight Pipe with Liquid Viscosity of 10 cP and Particle Size of 150 Microns
Sand Concentration Measurements Using Intrusive Pitot-Style Probes

Figure 33: Influence of Particle Size (150 µm and 300 µm) on Sand Distribution in Slug Flow for Superficial Gas and Liquid Velocities of 27 m/s and 0.46 m/s with Liquid Viscosity of 1 cP

Figure 33 shows the distribution of sand from bottom to the top of the pipe for the particle sizes of 150 µm and 300 µm. It is clear from the figure, that the influence of particle size on location distribution is negligible for the particle sizes considered. Also, it can be understood for the horizontal flows that the majority of the particles tend to flow at the bottom of the pipe irrespective of the inertia associated with the liquid slug.
Figure 34: Influence of Liquid Viscosity on Sand Particle Distribution in Slug Flow for Superficial Gas and Liquid Velocities of 35 m/s and 0.76 m/s with 300 Micron Sand

Figure 34 shows the influence of liquid viscosity (1 cP, 10 cP and 40 cP) on sand distribution for the superficial liquid and gas velocities of 35 m/s and 0.76 m/s in a horizontal pipe. From the figure, it can be understood that the low viscosity liquids carry more sand at the bottom of the pipe, i.e., 1 cP viscous liquid carry more sand than the 10 cP viscous liquid, and 10 cP viscous liquid carry more sand than the 40 cP viscous liquid. Also, at the top of the pipe, the concentration of sand is higher for the high viscosity liquids compared to the low viscosity liquid. This result explains that the high viscosity fluids transported in the pipelines have more entrainment compared to the low viscosity liquids.
It was found from the previous measurements that there is a significant drop in the concentration of the particles from sampling location 1 (bottom of the pipe) to sampling location 2, especially when the liquid viscosity is 1 cP. Thus, two additional measurements were made very close to the wall for the operating condition where superficial gas and liquid velocities were 15.24 m/s and 0.3 m/s with a liquid viscosity of 1 cP, which is shown in Figure 35. It was observed that the particle concentration is reduced significantly by moving the sampling tube slightly away from the pipe wall. It is suggesting that the majority of the particles are traveling by contacting the bottom of the pipe, due to the influence of gravity. So, it is obvious that for horizontal pipes, the sample collected from the bottom of the pipe is not representative of the flowing concentration at least when the viscosity of the liquid is 1 cP.
Figure 36 shows the influence of superficial gas velocity on the sand profiles for the superficial liquid velocity of 0.3 m/s and with a liquid viscosity of 1 cP. From the experiments, it was found that the concentration of the particles is higher at every sampled location inside the pipe, for the lower superficial gas velocity. This behavior should be carefully analyzed with the study of the slug characteristics.

Figure 36: Influence of Superficial Gas Velocity on the Sand Distribution for the Superficial Liquid Velocity of 0.3 m/s and With Liquid Viscosity of 1 cP

Figure 36 and Figure 37 shows the sand distribution when the liquid viscosity is 10 cP. It is found that the distribution is nearly uniform for the two different operating conditions considered.
Figure 37: Sand Distribution for Superficial Gas and Liquid Velocities of 10.7 m/s and 0.76 m/s with Liquid Viscosity of 10 cP

Figure 38: Sand Distribution for Superficial Gas and Liquid Velocities of 17.7 m/s and 0.76 m/s with Liquid Viscosity of 10 cP
Conclusions

The preliminary conclusions for this study are listed:

- In horizontal slug flow, the metal loss is higher on the top of the elbow and lower at the bottom.
- Under the slug flow conditions examined, we did not observe a change in sand distribution in a straight pipe for 150 and 300 micron sand sizes
- Low viscosity liquids carry more sand at the bottom of the pipe compared to high viscosity liquids
- For the lower viscosity experiments, sand distribution varied more significantly from top to bottom of pipe than the high viscosity experiments

Future Work

The future work is shown below:

- Observe the influence of liquid viscosity (1 cP, 10 cP and 40 cP) on the liquid and sand distribution inside the bend
- Analyze gathered WMS data to determine
  - Slug Length Distribution
  - Translational (Interface) Velocity
  - Slug Frequency
  - Slug Liquid Hold-Up
- Obtain the radial velocity distribution for the liquid slug body
- Obtain the axial velocity distribution inside the liquid slug
- Improve the slug flow SPPS model with the understanding obtained through experiments
- Obtain the average liquid hold up in the slug body before and after the bend for different liquid viscosities
- Obtain the velocity profile of the liquid slug by analysis of the void fraction data from the dual wire mesh sensor

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• Develop a relationship between slug characteristics and erosion magnitude

References:


