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Investigation of Effect of Sand Particles on Wave Velocity and Wall Shear Stress in Annular Flow in Horizontal Pipe

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ABSTRACT

Annular flow occurs in both upstream and downstream conduits, facilitating the transport of reservoir fluids to the surface via wells and flow lines. It is also present in nuclear power plants, chemical processing and refining facilities, such as reactors and heat exchangers. In this flow regime, high-velocity gas, along with entrained liquid droplets, flows through the core of the pipe, while a liquid film forms along the pipe walls. This study investigates sand transport in annular flow using a 2-inch (0.0504 m) flow loop measuring 28.68 m in length. Experiments were conducted with water, air and sand, incorporating sand particle sizes of 212 µm, 500 µm and 800 µm at concentrations of 200 lb and 500 lb. Conductivity ring sensors were used to measure liquid film thickness, while conductor probe sensors detected sand transport. The objective was to enhance understanding of sand particle effects in horizontal pipe flow, benefiting industries operating under such conditions. The results indicate that sand particle size and concentration have no significant effect on wave velocity. Superficial liquid velocities of 0.1252 m/s, 0.1256 m/s and 0.1286 m/s with sand particles of 212 µm, 500 µm and 800 µm at 500 lb/1000 bbl further confirm this observation. However, sand concentration was found to influence wall shear stress in annular flow within horizontal pipes. While sand particle size and superficial liquid velocity had negligible effects on wall shear stress, superficial gas velocity significantly impacted it. The analysis further revealed that an increase in superficial gas velocity amplifies the effect of sand concentration on wall shear stress in annular flow.

Keywords: Annular flow; Sand particles; Shear stress; Wave velocity; Superficial velocity

Introduction

Gas/liquid/sand multiphase flow in pipes involves different phases, with sand particles flowing together with the fluids at either the same or different velocities. As the flow develops along horizontal pipes, various flow regimes, including annular flow, emerge depending on the dominant phase, fluid properties, operating parameters and pipe geometry[1]. The mechanics of gas/liquid/solid three-phase flow is highly complex, with distinct flow behaviors that are of significant concern to several industries worldwide[2]. Annular flow behavior in horizontal pipes, particularly the effect of sand, was experimentally investigated in this study. This flow regime is commonly encountered in petroleum production systems, where reservoir fluids are transported from upstream gas wells to downstream facilities. Annular flow is also prevalent in oil wells dominated by the gas phase or gas pipelines with minimal condensation. Beyond the oil and gas industry, it occurs in nuclear power plants and chemical and refining processes, such as reactors and heat exchangers[3].

An extensive experimental investigation into annular flow behavior, with a focus on sand particle size and concentration, is essential for improving the understanding of sand transport in horizontal pipes. The presence of sand particles in high-velocity transported fluids can cause attrition and induce mechanical wear on pipeline walls. Sand particles are typically mobilized from the reservoir to the surface due to the drag forces exerted by flowing fluids within the porous formation. Several factors contribute to sand dislodgement, including drilling, water production, pore pressure reduction, unconsolidated formations, excessive drawdown and high production rates.

Drilling-Induced Sand Production: During drilling, mechanical stress from the drill bit creates a localized crushed zone near the wellbore, generating solid particles.

Water Production: In hydrocarbon reservoirs with strong water drive mechanisms, advancing water dislodges sand particles as it moves through perforations or fingering channels. Water weakens or dissolves the natural compaction bonds between sand grains, increasing sand production[4]. Additionally, water saturation affects capillary pressure, which holds sand grains together.

Pore Pressure Reduction: Reservoir depletion reduces pore pressure, increasing the stress exerted by the overburden. If the formation is poorly consolidated, sand production is more likely to occur[4]. Unconsolidated formations are typically younger, shallow formations (3,000–9,000 ft) with high porosity and permeability, whereas more consolidated formations (>10,000 ft) exhibit greater resistance to sand production.

High Production Rates and Drawdown: Excessive production rates, often driven by arbitrary wellhead choke adjustments, can result in excessive drawdown across the near-wellbore region. This increases both water encroachment and sand production.

The interaction of sand particles with fluid flow generates friction between the fluid and the pipeline's internal walls. This leads to the formation of wall shear stress, which this study aims to investigate in annular flow conditions. While extensive experimental research has been conducted on gas-liquid and liquid-solid flows, limited studies exist on gas-liquid-solid multiphase flow, particularly in annular regimes. Previous research has primarily focused on slug, bubble and stratified flow regimes, as documented[5-16]. However, none of these studies specifically address sand behavior in annular flow.

To effectively analyze water/air/sand annular flow behavior, it is necessary to investigate sand transport mechanisms in gas/solid flows. Despite the limited availability of experimental data, some notable studies have explored gas-solid flow using computational fluid dynamics (CFD) simulations and laboratory experiments[17] conducted experiments on air-solid two-phase flow in horizontal pipes with a 30.5 mm internal diameter. They examined plastic particles (0.2 mm and 3.4 mm) with a density of 1000 kg/m^3, using a Laser Doppler Velocimeter (LDV) to measure velocity. Their results indicated that larger solid particles (3.4 mm) increased turbulence, while smaller particles (0.2 mm) reduced it. Furthermore, the probability density function (PDF) of gas flow deviated from a normal distribution and power spectral density (PSD) frequencies increased with solid concentration. Sommerfeld and Huber[18] presented a model for particle-wall collisions in horizontal gas-solid flow, validated through experiments in a 3 m-long, 30 mm-high, 300 mm-wide channels using 100–500 µm glass bead and quartz particles. Their findings demonstrated that rough wall surfaces and irregular particle shapes significantly influence collision behavior. Particles impacting rough structures at angles below 10° displayed size-dependent distribution patterns.

Akilli, et al.[19] examined gas-solid flow in horizontal pipes with 90° elbow sections. Their experiments, conducted with air velocities of 15–30 m/s and 50 µm pulverized coal particles, used fiber-optic probes to measure concentration and velocity. Results showed that larger solid particles concentrated near the bottom of horizontal pipes due to gravitational settling. Kesana[20] explored the effects of sand particle size on erosion in slug and annular flow using a 3-inch pipe with gas velocities of 25.2–45.7 m/s and superficial liquid velocities of 0.45–0.76 m/s. Sand particles (20 µm, 150 µm and 300 µm) were tested in continuous-phase (CMC) viscosities of 1 cP and 10 cP. Their findings indicated that sand particles transported in the gas core caused greater erosion in annular flow than those in slug flow, where sand remained within the liquid phase. McLaury, et al.[21] studied sand distribution in horizontal and vertical multiphase flow, highlighting the impact of sand on erosion. Their semi-mechanistic model for erosion in elbows accounted for orientation effects and demonstrated good agreement with experimental data. Zahedi et al.[22] developed a predictive model for liquid film thickness in pipe bends. Their analysis, based on control volume calculations and experimental data, showed strong agreement between predicted and measured film thickness variations. Shirazi et al.[23] conducted large-scale erosion experiments in 2-4-inch multiphase flow loops under various flow regimes, including slug, wet gas and annular flow. They improved existing erosion prediction models and validated them against CFD simulations for large-diameter, high-pressure conditions.

This study aims to evaluate the effect of sand particle size and concentration on wave velocity and wall shear stress in annular flow within horizontal pipes **(Figure 1)**. By conducting controlled experiments, the research will provide valuable insights for industries dealing with multiphase flow systems, particularly in mitigating pipeline erosion and optimizing flow conditions.

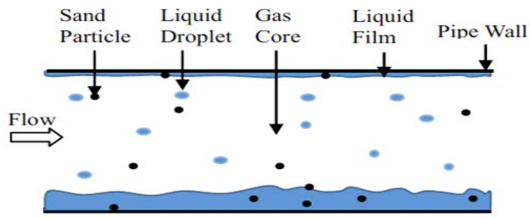

Figure 1: Sand Particles in Annular Flow.

Wave Velocity

Wave velocity is the displacement per time delay as wave travels through space or medium. Wave velocity could be obtained from the signals of the conductivity ring sensors or conductance probes in annular flow using Matlab. If the sensors' distance apart and time delay are known, the wave velocity could be presented as a ratio of distance per time delay from cross-correlations. The downstream sensor (sensor 2) is delayed by several milliseconds compared to sensor 1[24].

Shear Stress

Shear stress in two-phase flow can be classified into wall shear stress and interfacial shear stress.

Wall Shear Stress arises due to the frictional forces exerted by the flowing phases-liquid, gas and solid particles-on the internal walls of the pipe. This stress significantly influences pipeline integrity and erosion, particularly in multiphase flows involving solid transport.

Interfacial Shear Stress occurs at the boundary between the liquid and gas phases as they flow together. This stress results from velocity differences between the phases, creating resistance at the interface and affecting overall flow behaviour. In this study, wall shear stress was determined using the pressure gradient and superficial liquid velocity, with respect to the pipe diameter. This approach provides insight into how sand concentration and gas velocity impact shear forces in annular flow within horizontal pipes.

Sand Particle Sizes

Sand particle size, diameter, shape and concentration have an impact in multiphase flow in pipes depending on fluid velocity and forces acting on the sand (e.g. gravity, lift, buoyancy and drag). In horizontal flow, small sand particles are easily suspended in fluid flow under high velocity, while the larger and heavier sizes are often scoured along the bottom of the pipes due to gravity, depending on the fluid flow velocity. According to Ravelet et al., grains size and specific mass have strong effects on flow regimes, mostly between a stationary bed and suspended flow. **(Table 1)** below illustrates sand classification and sizes.

Table 1: Sand Particle Sizes, converted to microns in this study.

Classification	Size (mm)	Fraction	Microns
Very Fine Sand	0.0625-0.125	$\left(\frac{1}{16}-\frac{1}{8}\right)$	6.25 – 125
Fine Sand	0.125-0.25	$\left(\frac{1}{8}-\frac{1}{4}\right)$	125 – 250
Medium Sand	0.25-0.5	$\left(\frac{1}{4}-\frac{1}{2}\right)$	250- 500
Coarse Sand	0.5-1	$\left(\frac{1}{2}-1\right)$	500 – 1000
Very Coarse Sand	1-2 and above	-	1000 – 2000

Materials and Methodology

The experiments were conducted using conductance probes to detect sand particles in water/air/sand annular flow with sand particle sizes of 212microns, 500microns and 800microns. The superficial gas and liquid velocities used are presented in **(Table 2)**.

Table 2: Water/Air/Annular Flow Test.

Properties	Range	Units
Temperature	18.9-21.7	^{0}C
Pipe internal diameter	0.0504	m
Air flow line internal diameter	0.0504	m
Superficial liquid velocity	0.0922-0.1343	m/s
Superficial gas velocity	8.4749-15.9312	m/s
Sand diameter [212,500,800] microns	0.000212, 0.000500, 0.000800	m
Density of Sand Particles	2650	Kg/m^3

Conductivity Ring Sensors

Flow values were obtained by injecting an electric current into the pipes through the outer pair of electrodes and measuring the corresponding electric potential drop between successive electrodes[25]. A 2-inch (50 mm) plexiglass horizontal pipe test tube, with a length of 154 mm, was used for annular flow bench calibration.

The experimental setup included two pairs of conductivity ring sensors, designated as C1 (upstream) and C2 (downstream), installed 70 mm apart on the external surface of the pipe. Additionally, a conductance probe sensor was flush-mounted inside the 2-inch pipe test tube. The probe consisted of a central plate electrode (inner conductor) with a diameter of 10.25 mm, an outer circular plate (outer conductor) measuring 1.80 mm and a circular insulator of 2.40 mm separating the two conductive plates.

Both the conductivity ring sensors and the conductance probe sensor were connected directly to the receiver using black-coated flexible wires, as illustrated in **(Figure 2)**. The receiver transmitted the signals to the central processing unit, where they were recorded in LabVIEW during calibration.

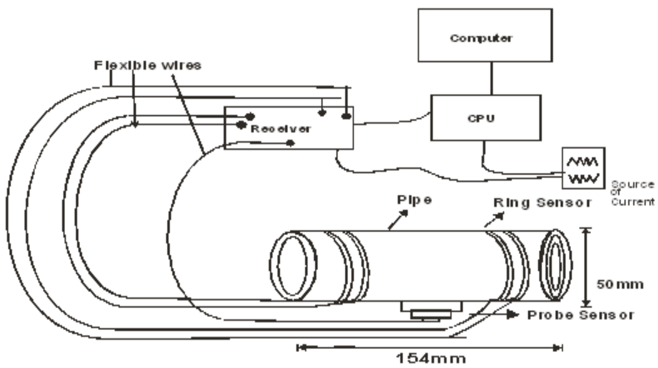

Figure 2: Conductivity Ring Sensors for calibration in experiment.

Conductivity Rings Calibration for Liquid Hold-up/ Film Thickness

The annular flow calibration using a horizontal pipe test tube was conducted with water of a known volume and five different acrylic rod inserts with diameters of 49 mm, 48 mm, 47 mm, 46 mm and 45 mm, each measuring 154 mm in length. The 50 mm test tube was filled with a measured volume of water for each test and the corresponding voltage values were recorded. For each acrylic rod insert, the annular space between the rod and the inner diameter of the 50 mm test tube was filled with water, which was measured and the corresponding voltage was recorded. During the experiment, voltage readings were also taken for both an empty pipe and a fully water-filled pipe to facilitate normalization of the experimental results. The recorded voltage values from different acrylic rod inserts were then normalized using equation (1).

$$N = \frac{V_{two-phase} - V_{empty}}{V_{fullpipe} - V_{empty}} \quad (1)$$

where N is for normalized Voltage of (S_1, S_2 or C_1, C_2) as shown in **(Figure 4)**, $V_{two\text{-}phase}$ is the voltage of the two-phase flow, V_{empty} is the voltage of the empty pipe and $V_{full\text{-}pipe}$ is for full water voltage of the calibration pipe.

Conductor Probe Sensors

In this study, conductance probe sensors were used as sand probes to detect sand transport within the 2-inch (0.0504 m) pipeline. These flush-mounted sand probe sensors were arranged in two pairs, designated as S1 and S2 and installed 0.21 m apart along the flow loop. Each sand probe sensor featured a central circular conductive plate with a diameter of 10.25 mm and an outer circular conductive plate measuring 1.80 mm, separated by a 2.40 mm circular insulator, as illustrated in **(Figure 3)**. The presence of sand was detected by the sensors through a decrease in voltage output.

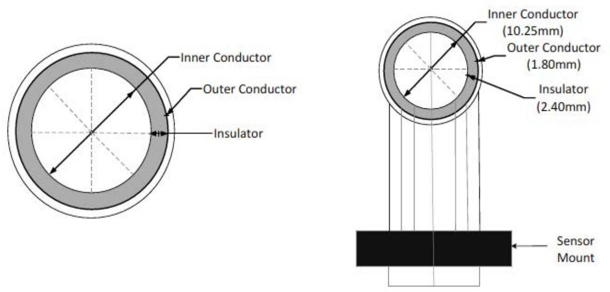

Figure 3: A Sketch of the Sand Probe Sensors used.

Experimental Set-Up

The experimental setup consisted of a 2-inch closed flow loop (pipeline) with a total length of 28.68 m from the water storage tank. The following apparatus were used:

- A high-speed Olympus camera
- Two pairs of Druck-PMP 4070 pressure transducers (P1, P2) installed 2.13 m apart
- Temperature sensors
- Infrared (IR) LED sensors
- Conductivity ring sensors (two pairs, installed 1.3 m apart)
- Conductance probes

As shown in **(Figure 4)**, the 2-inch horizontal pipeline test loop received water from a cubic-shaped plastic fiber water storage tank with a capacity of 4.4 m³. The tank was connected to the loop through a progressive cavity pump (PCP) with a 90 m³/h capacity and a maximum discharge pressure of 5 bar. The entire system operated in a closed-loop configuration.

The water storage tank was internally divided into two chambers:

- **Returning chamber:** Where the water, initially pumped into the test facility, returns.
- **Suction chamber:** Located on the side of the tank, this chamber retains the returned water and serves as the source for the pipeline test facility.

Air supply for the experiment was provided by a compressor located in the PSE laboratory, with a capacity of 400 m³/h and a maximum discharge pressure of 10 barg. The gas was metered using a vortex gas flow meter with a full range of 0–70 m³/h and an uncertainty of ±1%. The compressor could supply gas (air) through a 2-inch (0.0504 m) air pipeline to the flow loop, achieving a maximum superficial gas velocity of 30 m/s.

In **(Figure 4)**, the flow loop components are represented as follows:

- Red line: Air (gas) supply
- Green line: Sand/water slurry pipeline
- Blue line: Water flow pipeline
- Pink line: Multiphase flow to the delivery water tank

Experimental Procedures

Water/air/sand annular flow experiments were carried out using superficial gas velocity between 8.4749m/s to 15.9312m/s and superficial liquid velocities (0.0922m/s-0.1343m/s) respectively. The sand particle sizes and concentration used were: 212microns-200lb/1000bbl, 212microns-500lb/1000bbl and 500microns-500lb/1000bbl with their density as 2650kg/m3.

From the experimental set up, the 2-inch sand flow loop was used with two conductor probe sensors of S1 (upstream) and S2 (downstream) installed at the bottom of the pipe to detect sand transport and behaviour in the horizontal pipe. The sensors were linked to a LabView with the following conditions been applied: scan rate (1000Hz), sampling rate (200Hz) and scan duration (180s). Scan duration of 180s was used to enable the flow attain steady-state flow conditions in the pipe.

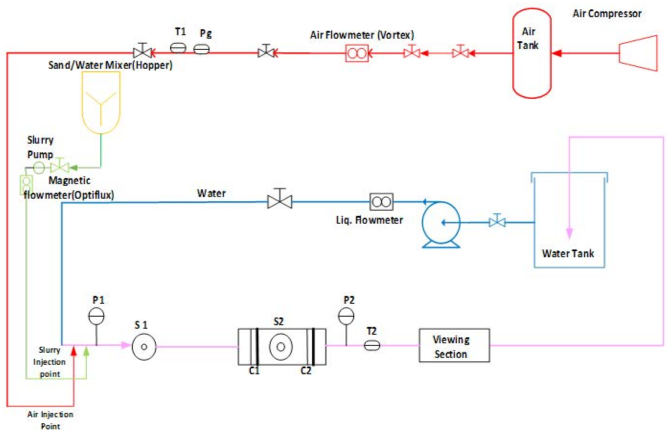

Figure 4: A sketch of experimental 2-inch loop Used.

Table 3: Instrument used, Functions and Ranges.

Instruments	Functions	Accuracy- [Full Range]
Gas Flowmeter Vortex	Air/gas Flow Metering	± 1% [0~70m³/h]
Magnetic Flowmeter [Opti flux 2300]	Sand Flow Metering	±0.2% [0~21m³/h]
Liquid flowmeter	Liquid Flow Metering	± 0.8% [0~20m³/h]
Pump	Water/sand pump	[0-300L/h]
Pressure Transducer [P1]	Pressure Measurement	± 0.04% [0-6bara, 0-100psi]
Pressure Transducer [P2]	Pressure Measurement	± 0.06% [0-6bara, 0-100psi]
Conductivity Probe Sensor [S1]	Film thickness, Sand detector	±3.6% [0-3.8mm]
Conductivity Probe Sensor [S2]	Film thickness, Sand detector	±3.6% [0-3.8mm]
Conductivity Ring Sensor [C1]	Liquid hold-up	±2.3% [0-1]
Conductivity Ring Sensor [C2]	Liquid Hold-up	±2.3% [0-1]
Thermocouple [Temperature Sensors T_1-T_2]	Temperature Measurement	± 0.5% [0°-100° c]

Results and Discussions

Sand Particle Sizes and Sand Concentration on Wave Velocity

The effects of sand particle size and sand concentration were analyzed and presented. As shown in **(Table 4)**, these factors had a negligible impact on wave velocity in annular flow within a horizontal pipe, whereas superficial liquid velocity had a significant influence. For instance, sand with a particle size of 212 microns (500 lb/1000 bbl) at Vsl = 0.0983 m/s and Vsg = 8.9651 m/s exhibited the same wave velocity (0.0175 m/s) as 200 microns (800 lb/1000 bbl) at Vsl = 0.0922 m/s, as shown in **(Table 2)**. Similarly, for 212 microns (500 lb/1000 bbl) at Vsl = 0.1248 m/s and Vsg = 14.5936 m/s, the wave velocity (0.0247 m/s) was identical to that of 200 microns (800 lb/1000 bbl) at Vsl = 0.1155 m/s and Vsg = 15.1954 m/s. This similarity occurs because the superficial liquid and gas velocities were close in value. These results confirm that sand particle size and concentration have no measurable effect on wave velocity. Instead, superficial liquid and gas velocities—particularly superficial liquid velocity—are the primary influencing factors.

Table 4: Test Model Specifications and Test Results with Grains (212microns) and Low Vsg.

Ib/1000bbl	Vsl [m/s]	Vsg[m/s]	Wave Velocity[m/s]
500	0.0983	8.9651	0.0175
500	0.1252	8.9535	0.0200
500	0.1343	8.9811	0.0210
200	0.0961	10.4769	0.0191
200	0.1126	9.3775	0.0200
200	0.1264	8.9792	0.0210

Table 5: Test Model Specifications and Test Results with Grains (212microns) and High Vsg.

Ib/1000bbl	Vsl [m/s]	Vsg[m/s]	Wave Velocity[m/s]
500	0.1024	14.4564	0.0221
500	0.1248	14.5936	0.0247
500	0.1304	14.8428	0.0262
200	0.0951	14.9132	0.0221
200	0.1145	14.9179	0.0233
200	0.1209	14.9517 0.0262	

Table 6: Test Model Specifications and Test Results with Grains (500 microns) and Low Vsg.

Ib/1000bbl	Vsl [m/s]	Vsg[m/s] Wave Velocity[m/s]
200	0.1017	9.0558 0.0175
200	0.1152	9.1572 0.0200
200	0.1243	9.2351 0.0210
500	0.1087	8.4749 0.0168
500	0.1256	8.7601 0.0200
500	0.1288	9.2246 0.0200

Table 7: Test Model Specifications and Test Results with Grains (500 microns) and High Vsg.

Ib/1000bbl	Vsl [m/s]	Vsg[m/s] Wave Velocity[m/s]
200	0.1003	15.2251 0.0221
200	0.1184	14.5038 0.0233
200	0.1289	14.4386 0.0262
500	0.1003	15.2251 0.0233
500	0.1236	14.4325 0.0247
500	0.1265	14.6875 0.0248

Table 8: Test Model Specifications and Test Results with Grains (800microns) and Low Vsg.

Ib/1000bbl	Vsl [m/s]	Vsg[m/s] Wave Velocity[m/s]
200	0.0922	8.8898 0.0175
200	0.1178	9.0353 0.0191
200	0.1263	8.7283 0.0210
500	0.1014	9.2332 0.0183
500	0.1209	9.0533 0.0191
500	0.1289	8.9116 0.0200

Table 9: Test Model Specifications and Test Results with Grains (800microns) and High Vsg.

Ib/1000bbl	Vsl [m/s]	Vsg[m/s] Wave Velocity[m/s]
200	0.1155	15.1954 0.0247
200	0.1239	15.1237 0.0262
500	0.1039	14.5006 0.0221
500	0.1179	15.1651 0.0247
500	0.1257	15.0489 0.0262

From the above tables average superficial liquid velocities of 0.1252m/s, 0.1256m/s, 0.1289m/s with sand particles of 212microns, 500microns, 800microns on 500Ib/1000bbl respectively, proved that sand particle sizes and sand concentration have negligible impact on wave velocity as shown on **(Tables 4,5,6,7,8,9)**. Irrespective of the differences in sand particle sizes and sand concentration, the wave velocity (0.0200m/s) were close together. The little gap observed is the difference on the superficial gas velocities.

Sand Particle Sizes and Sand Concentration with respect to Wall Shear Stress

Effect of sand particle sizes and sand concentration on wall shear stress were also investigated in annular flow in horizontal pipe. The sand particle sizes used were: 212microns, 500microns with sand concentrations of 200Ib and 500Ib. **(Figure 5)** for wall shear stress against film thickness shows the dominant effect of superficial gas velocity on wall shear stress in annular flow. At superficial liquid velocities of 0.0951m/s, 0.1145m/s and 0.1209m/s with superficial gas velocities of 14.9132m/s, 14.9179m/s and 14.9517m/s, we observed wall shear stress of 0.0097kPa, 0.0115kPa and 0.0129kPa respectively. This has shown that the higher the superficial liquid velocity, the higher the film thickness with respect to high superficial gas velocity, the higher the wall shear stress. This submission is in accordance with presentation of Manzar and Shah (2009) that the magnitude of shear stress shows an increasing trend with flow rate.

(Figure 6) shows a plot of wall shear stress against film thickness with sand concentration of 500Ib/1000bbl at different sand particle sizes of 212microns and 500microns. The superficial gas and liquid velocities where slightly different. The plots were observed to have a good match indicating that the sand particle sizes have negligible impact on the wall shear stress in annular flow from the experiments.

(Figure 7) was wall shear stress against film thickness with same sand particle size of 212microns but different sand concentrations of 200Ib and 500Ib. Again, the superficial gas and liquid velocities were slightly different. When Figure 7 was compared with Figure 6, a slight difference was observed. Figure 7 has shown that film thickness between 0.15mm and 0.23mm with particle size of 212microns with respect to sand concentration of 200Ib and 500Ib, impacted slightly on wall shear stress. However, one should have expected the film thickness and wall shear stress to be superimposed on one another as seen in Figure 6. This was not so because of the increase in superficial gas velocity between 8.9792m/s to 10.4769m/s. This is to illustrate the impact of sand concentrations on wall shear stress in annular flow in horizontal pipe when there is increase in superficial gas velocity.

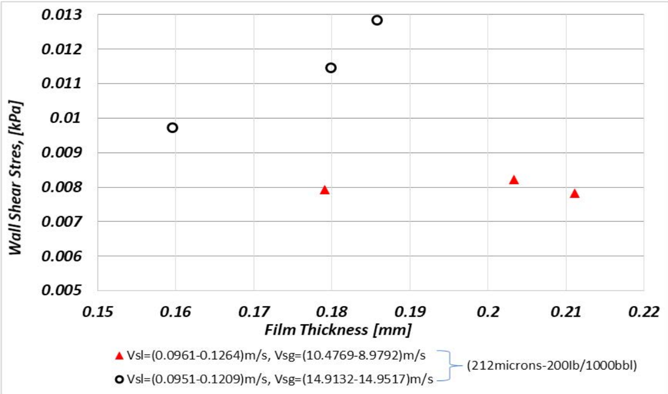

Figure 5: Wall Shear Stress against Film thickness- Effect of Gas Velocity Felt.

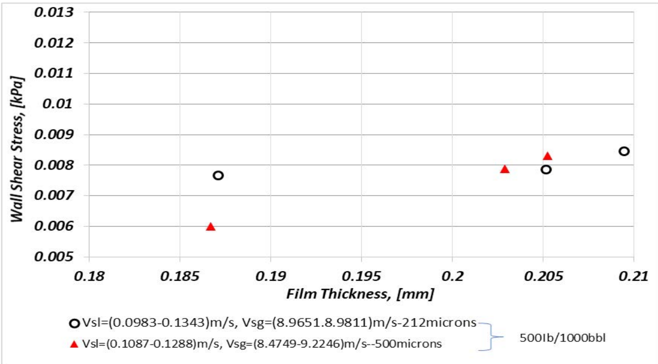

Figure 6: Wall Shear Stress against Film thickness- No Effect of Particle Sizes Felt.

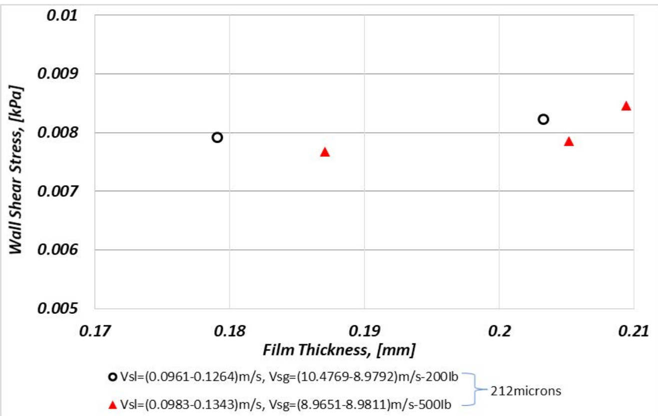

Figure 7: Wall Shear Stress against Film thickness- Effect of Sand Concentrations Felt.

Conclusion

This study experimentally investigated the effects of sand particle sizes and sand concentrations on wave velocity in annular flow in horizontal pipes. The impact of shear stress on film thickness at varying sand sizes and concentration as well as the effects of superficial liquid velocity on the wave velocity were investigated. It was observed that sand particle sizes and concentrations have negligible impact on annular flow in horizontal pipes. Also, the sand particle sizes have negligible impact on wave velocity and film thickness, although, increase in the superficial gas velocity increased the sand impact on the wall shear stress.

Nomenclatures

CFD = Computational Fluid Dynamics
LDV = Laser Doppler Velocimeter
PDF = Probability Density Function
PSD = Power Spectral Density
CMC = Carboxyl Methyl Cellulose
PCP = Progressive Cavity Pump
IR LED = Infar Red Light Emission Diode
S1 = Sand Probe Sensor (upstream)
S2 = Sand Probe Sensor (downstream)
P1 = Pressure Sensor (upstream)
P2 = Pressure Sensor (downstream)
Vsl = Superficial Liquid Velocity
Vsg = Superficial Gas Velocity

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Author's Contributions

The research was made possible by authors. The authors contributed immensely to the preparation and finishing of the work.

Data Transparency

Authors assured that all data and materials support claims and complied with field standard.

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Declarations

Competing Interest

The authors declare that they have no competing interest whatsoever.

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