

# Evaluation of Velocity Impact on Sand Particles in Two-Phase Annular Flow in Horizontal Pipes

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**Abstract:** Experimental investigations on sand particles in annular flow in horizontal pipes were presented. The aim is to enhance the knowledge related to sand transportation in the oil and gas industry. More so, to add values in facilitating the optimum design of oil and gas production systems where annular flow is often encountered. The experimental investigations were conducted using a closed-loop consisting of a horizontal pipe with an internal diameter of 2-inch (0.0504m). The experimental investigations covered both: water/sand flow and water/air/sand annular flow. The water/sand flow experiments were carried out to establish sand transport regime in liquid such as sand saltation, sand streak, and sand suspension. While, water/air/sand annular flow experiments revealed that the only the only sand transport regime in annular flow are saltation and suspension. Sand concentration profile in the annular flows were also estimated by using the sampling method. It was found that the bigger the sand particle size (500microns) leads to higher concentration of sand being transported at the bottom of the pipe because of gravity effect, while the smaller the sand particle size (212microns), leads to the higher sand concentration. Also, the sand concentration increased at the gas core as the superficial gas velocity increases.

**Keywords:** Sand Distribution, Sand Concentration, Annular Flow, Multiphase Flow, Flow Regimes

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## 1. Introduction

Gas/liquid/sand multiphase flow in pipes involve different phases and dislodged solids (sand) flowing together, either at the same or different velocity. As the flow develops along the horizontal pipes, different flow regimes are presented depending on the dominant phase, properties of each phase present (e.g. viscosity, density), flowing velocities and pipe geometry. The main flow regimes are: bubble flow, plug flow, slug flow, stratified flow, annular flow and mist flow. In this study, the focus is on annular flow in horizontal pipes.

Annular flow is encountered in petroleum production systems where reservoir fluids and sand particles are conveyed to the surface via wells, flowlines, nuclear power plants, chemical and refining processes like reactors, heat exchangers, etc. In annular flow, the gas, together with the entrained liquid droplets flow within the core in the pipe at high velocities, while the liquid flows as a film along the pipe walls [12]. However, the sand particles' distribution in the aforementioned is often not reported and this is the aim of this study.

Sand particles in the flow originates from the reservoir formation, where they are dislodged and being carried along with the fluids in the wells and flowlines/pipelines. According to Stevenson and Thorpe [19], sand production is a process that develops progressively in three stages: failure of the rocks surrounding an open hole or perforation from which free sand grains are generated, disaggregation of sand particles from weak formation and transport of those free grains by effluents into the wellbore.

Sand particles pose operational, safety and cost problems, depending on where in the production systems they are encountered, and the amount of sand dislodged from the reservoir. Therefore, there is need to present comprehensive experimental investigations on effects on velocity on sand particles in annular flow to compliment the dynamics of sand flow behaviours already researched on liquid/solid, gas/solid flow and the simultaneous transport of solid/gas/liquid flow in other flow regimes in horizontal pipes as also noted by Afshin et al., [1]. Among the existing sand transport in pipes

are: The experiments on solid transport in horizontal pipelines by Durand [6]. The experiments were conducted using pipes ranging from 1.5-inch to 28-inch with different solids such as coal, sand and gravel ranging from 0.05mm to 25mm. the solid flow regime were classified as homogeneous for solids such as (clay, fine ash, smooth powered coal), intermediate for solid like silt and heterogeneous for solids like gravel. More so, Newitt et al [13], investigated on flow regime and sand behaviour in horizontal pipes with internal diameters 1-inch and 6-inch. The solid particles used were in the range of 0.0625mm to 6.0mm. They presented homogeneous suspension, heterogeneous suspension, saltation and sliding bed flow regimes in water/sand flow. On solid transport, Ramadan et al [17] carried out investigations on solid transport in gas/liquid/sand flow in horizontal pipes. The experiments were carried out on bubble and slug flow on 1-inch and 2-inch horizontal pipes. They presented three sand flow regimes: settling flow which involves low liquid velocity (bubble and plug flow), not-fully suspended (exists in bubble flow) and fully suspended-for high velocity flow like slug.

Solid transport at low concentration in solid/liquid flow in horizontal pipes with internal diameters of 1-inch and 6-inch was investigated by Tsuji and Morikawa [22]. He presented solid flow regime in four distinct ways: migration to the pipe walls at stationary state under low velocities, at moderate velocity flow (rolling, slide and saltation), heterogeneous sand flow (across flow area and not uniform) and homogenous sand flow (across flow area uniformly). Likewise Oroskar and Turian [14], developed critical velocity models from descriptive analysis of particles terminal velocity in an unbounded flow conditions. While [21] presented experimental investigations on air/sand flow in horizontal pipe using a pipe with an internal diameter of 30.5mm, plastic particles of 0.2mm and 3.4mm and gas velocity ranging from 6m/s to 20m/s. At the end, Solid particle sizes were discovered to have impact on air flow turbulence. On sand flow regime, Angelsen et al [3] worked on stratified flow with sand/gas/liquid in both horizontal and near horizontal pipes. They presented sand flow regimes as sand bed, moving bed dunes, scouring and dispersed sand flow.

Experiments on sand/air/water flow was conducted by Oudeman [15] using a pipe with an internal diameter of 0.007m and sand particle sizes of 0.15mm to 0.30mm. He presented that liquid velocity aids sand transport and increases with gas fraction much than liquid velocity. However, Gillies et al [8] in their investigations, reported that gas injection at low superficial liquid velocity has little effect on laminar flow in sand particles transport. Also, experiments were conducted on particle-wall collision by Sunday and Andrew [20] using horizontal laden channel flow of 300mm wide, 3m long and 30mm high with glass bead particles of 100microns. They discovered that wall roughness and irregular shape of particles influences wall collision. While Akilli et al [2], presented in their experiments of air/sand flow, that solid particles spread across the entire pipe of the

horizontal pipe with the larger solids moving at the bottom of the walls. Meanwhile, Sergey et al [18], conducted experiments on sand particles in stratified flow with the particles in the range of (150 to 180) microns in horizontal pipe of 40mm and 70mm, culminated with critical velocity correlations. Also, Bello et al [4], investigated and developed predictive minimum transport velocity (MTV) models for suspended sand particles in multiphase flow in pipes. In developing their models, the concept of sand particle velocity profile was used on the following flow regimes (annular flow, bubble flow, slug flow, and stratified flow) to establish the models in highly deviated and horizontal pipes.

Experiments were conducted by Kesana et al [12] to find out particles' size effect on erosion with respect to slug and annular flow in horizontal pipes. The experiments were achieved using a pipe internal diameter of 3-inches with flow matrix ranging from superficial gas velocities of 25.2m/s to 45.7m/s and superficial liquid velocities of 0.45m/s to 0.76m/s. The sand particle sizes were 20microns, 150microns and 300microns with CMC of 1cp and 10cp for liquid viscosities. Their key interest, was the impact of the sand particles' sizes on erosion. In conclusion, they found that in annular flow, sand particles which were discovered to be transported in the gas core created erosion more, than the sand particles in the slug flow. Investigation of hydraulic transport of large particles above (5mm) in horizontal solid-liquid flow in pipes were conducted by Oudeman [15]. Effects of specific mass, solid particle size on velocity and pressure drop were investigated using a glass pipe with an internal diameter of 100mm and 10m long. In summary, three flow regimes were observed in their work as a function of critical velocity ( $V_{crit}$ ) and mixture velocity ( $V_{mix}$ ). The flow regimes are: stationary bed, moving bed, solid bed suspension,

Solid particles' transport in a gas-liquid stratified flow was done by Franklin [7]. Though, it was a mathematical modelling without an experiment conducted, he was able to model solid particles' (bed-load) transport in a stratified gas-liquid flow. The special emphasis and considerations were on mean thickness of the granular layer and mean thickness of the liquid layer while experiments on hydrodynamic sand transport in a sand-gas-liquid stratified flow in horizontal pipes at low concentrations were conducted by Ibero et al [9]. The experiments were carried out using a 4-inch horizontal pipe with an average liquid density of 2475kg/m<sup>3</sup> and particles' diameters ranging from 211 to 297microns on stratified flow to develop a critical sand deposition velocity model. Observed in the experiments, were sand flow behaviours in three distinct manners, in line with the investigations of sand flow regime by Doron and Barnea [5] as: suspension, moving bed and stationary bed. Kamy and Hill [11], investigated the effects of physical parameters on sand transport in gas-liquid flow in horizontal pipes. The experiments were carried out using pipes with internal diameters of 0.1m and 0.05m and with special considerations on physical parameters like; sand sizes, sand shapes and sand concentration. Experimental studies were carried by Jiang et

al [10], on particle collision in a pseudo two-dimensional gas-solid fluidized bed using an optimized particle tracking velocimetry (PTV). The experiments were conducted using: alumina 1.8mm with a density of  $945\text{kg/m}^3$ , minimum fluidization velocity of 0.56m/s, 3.0m/s, 2.5m/s and 2.0m/s. The particles' temperature, impact velocity and particle collision frequency were the focus of the study. In summary, particle-particle collision was presented from the experimental studies with further observations that particles' temperature increases with increase in superficial gas velocities.

In all these reviews, experimental study on sand particles and its effect on annular flow in horizontal pipes are yet to be harnessed. Therefore, presenting sand transport in annular through extensive experimental investigations will progress the fundamental understanding of sand in such flow, which will enhance the knowledge base of the oil and gas industry, the nuclear power plants, the chemical and refining industries, where it is often encountered.

## 2. Experiments Setup

The experiments were conducted using a 2-inch (0.0504m) horizontal pipe. The pipeline was a 28.68m closed-loop system with water inlet pipe connected to a water storage tank and the outlet pipe connected back to the same water storage tank. The plastic fibre water storage tank with a capacity of  $4.4\text{m}^3$ , was designed with double chambers: suction chamber that acts as water source to the experimental test flow loop and returning chamber that retains the returning water. The flow loop had 2-pairs of pressure transducers installed at 2.13m apart, light emission diode infrared sensors (LED), two double pairs of conductivity rings sensors installed at 0.07m apart, pairs of conductance probes installed at 0.20m apart and temperature sensors. The gas (air) was delivered using a 2-inch (0.0504m) air pipe from a compressor with a capacity of  $400\text{m}^3/\text{h}$  and a maximum discharge pressure of 10bar. The air was metered using a gas flowmeter (vortex) with temperature and pressure sensors installed on the air flow line as presented in Figure 1.

Sand was supplied to the 2-inch flow loop from a sand hopper with internal diameter of 0.8m and a height of 1.35m. The water/sand mixture (slurry) from the sand hopper was delivered through a flexible pipe with an internal diameter of 0.00635m. In metering, a KROHNE magnetic flowmeter (OPTIFLUX, 2300) was used in metering the slurry from the sand hopper. The metering is done before the slurry, flows into the 2-inch flow loop.

On the sketch of the experimental 2-inch flow loop facility in Figure 1, the red flow line represents the air supply pipe, green line is for sand/water slurry pipe, the blue shows the water pipe flow and the pink represents multiphase flow to the delivery water tank. From the flow loop, there are also the conductance probe sensor and sand sampling equipment installed.

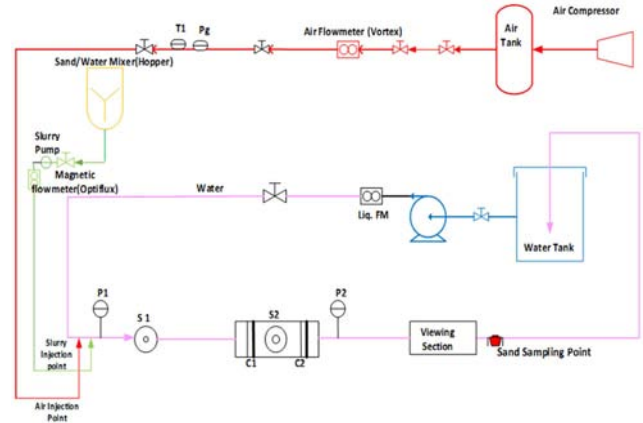


Figure 1. A Sketch of Experimental 2-inch Flow Loop Facility used.

### 2.1. Conductance Probe Sensor

Conductance probe sensors were used to detect sand transport in the film or liquid phase based on the conductivity of sand relative to water. The sand sensors have two electrodes, a central circular plate electrode of 10.25 mm in diameter (inner conductor) and the outer circular plate of 1.80 mm (outer conductor). The circular insulator of 2.40 mm is separated by two circular plates as presented in Figure 2. The probe sensor detects sand based on change in resistance as sand particles impinges on the surface of the probe sensitive inner and outer conductors.

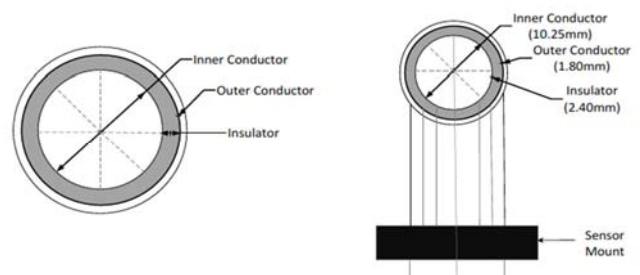


Figure 2. A Sketch of Conductance Probe Sensors Used.

### 2.2. Sand Sampling Procedures

The sand sampling pipe with an internal throat of 2.92mm (0.00292m) was properly flush mounted at the base of the pipe where the samples were collected. After each sampling was completed, the sampling throat was properly flushed/draind. The experiments were achieved by adjusting the pipe throat from zero to 1.5cm, 2.5cm and finally the top wall (5cm) of the pipe internally.

The sand samples collected with water were weighed with a known container properly labelled and stored for 24hours to enable the sand particles to settle. After 24hours, it was filtered into a known beaker for final drying using a Hot Air Tool, Leister - 230V (50/60Hz) which was adjusted to a temperature of  $300^\circ\text{C}$ .

### 2.3. Experimental Procedures

The water/air/sand annular flow experiments conducted

could be categorised into:

Water/sand only (212microns, 500microns)

The experiments on water/sand were presented in this study, to progress the understanding of flow regime in sand transport in pipes. Below are the properties:

**Table 1.** Water/Sand Flow Properties used in the Experiments.

Properties	Range	Units
Temperature	17.9-19.1	°C
Pipe internal diameter	0.0504	m
Air flow line internal diameter	0.0126	m
Superficial liquid velocity	0.0502-0.2009	m/s
Sand Diameter [200, 500] microns	0.000212, 0.000500	m

Water/air/sand annular flow (Probes)

The two conductance probes were installed at 0.20m apart at the bottom (flush mounted) in the pipe. The sand concentration used were: 200lb/1000bbl and 500lb/1000bbl, and below are the experimental properties and the ranges considered.

**Table 2.** Water/Air/Sand Flow Properties used in the Experiments.

Properties	Range	Units
Temperature	18.9-21.7	°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	8.4749-15.2251	m/s
Sand diameter [212,500,800] microns	0.000212, 0.000500, 0.000800	m

Water/air/sand annular flow (Sand Sampling Approach)

Sand sampling experiments were conducted to investigate physical modes of sand distribution in annular flow. The investigations, involved the use of a small pipe with sampling throat of (0.00292m), flush mounted at the internal diameter of the 2-inch (0.0504m) flow loop. The sand sampling pipe was adjusted internally from zero height, to 1.5cm, 2.5cm and to top pipe-wall in the experiments with sand sampling properties as:

**Table 3.** Water/Air/Sand Flow Properties for Sampling Experiments.

Properties	Range	Units
Temperature	17.9-20.5	°C
Pipe internal diameter	0.0504	m
Air flow line internal diameter	0.0504	m
Sampling throat (pipe diameter)	0.00292	m
Superficial liquid velocity	0.0713-0.1025	m/s
Superficial gas velocity	11.2481-18.0185	m/s
Sand diameter [212,500] microns	0.000212, 0.000500	m

### 3. Results and Discussion

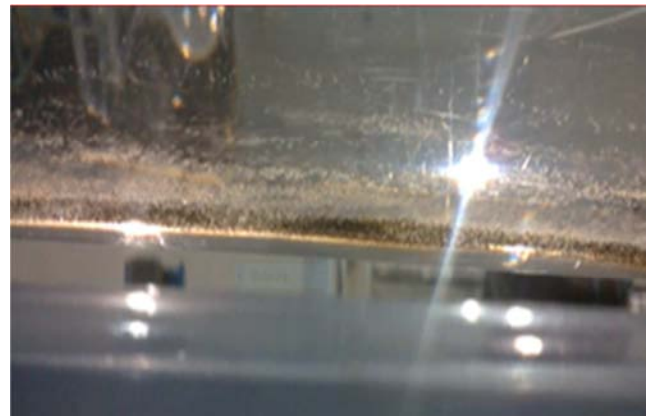
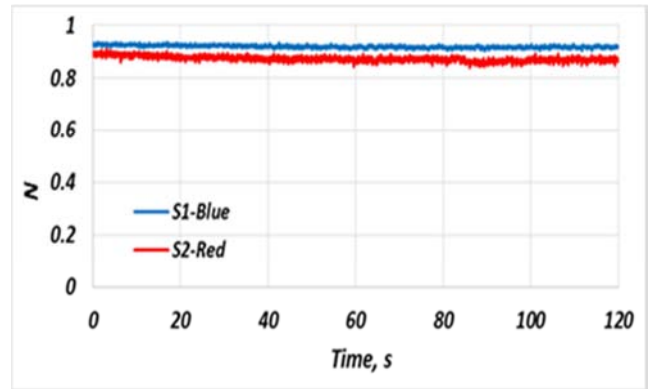
In the experiments, empty pipe and full pipe with water were recorded for normalizing the experimental results. This was indeed repeated on every experiment carried out on daily basis and mathematically expressed as:

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

Where  $V_{two-phase}$  is the voltage of the two-phase experiments,  $V_{empty}$  is for voltage of empty pipe and  $V_{full-pipe}$  is for full water voltage of the calibration pipe.

#### 3.1. Water/sand Flow

Sand saltation is presented in the graph of Figure 3 with sand particles' size of 212microns and sand concentration of 200lb/1000bbl in the pipe. The sand particles are close, though bouncing or jumping in motion along the bottom of the pipe as presented also by [22]. Again, from Figure 3, the upstream probe (S1, blue) and the downstream probe (S2, red) were presented with little spikes in a straight-line manner with little dip along spikes which justifies saltation in the flow regime in sand transport in pipes.



**Figure 3.** Saltation,  $V_{sl}=0.1775\text{m/s}$  (212microns, 200lb/1000bbl) - both are same.

Sand saltation was more pronounced in Figure 4 compared to Figure 3, because of the particles' size used. 500microns exhibited more gravity effect compared to the particle size of 212microns, hence more of the sand particles were detected by the probes compared to Figure 3 where the dips on the graph were less. Thus, more sand particles were found bouncing at the bottom of the pipe, hence the dip recorded by both probes.

As superficial liquid velocity increases from 0.1783m/s to 0.1967m/s, the flow regime changes from saltation to sand streaks. This means that majority of the sand particles came in proximity along the bottom of the pipe. Again, from the graph of Figure 5, you could easily point out the difference



from that of saltation. In this graph of figure 5, the spikes on both probes (S1, blue) and (S2, red) are with little or no dip.

In the case Figure 6 with a superficial liquid velocity of 0.2427m/s, the spikes from both probes (S1, blue) and (S2, red) became more fused together. From graph of Figure 6, the sand particles became fully suspended in the liquid flow in horizontal pipe.

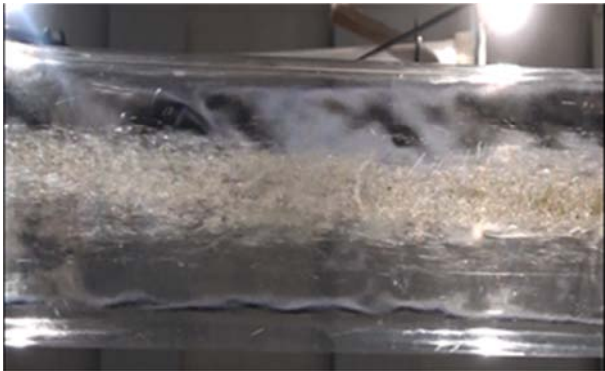
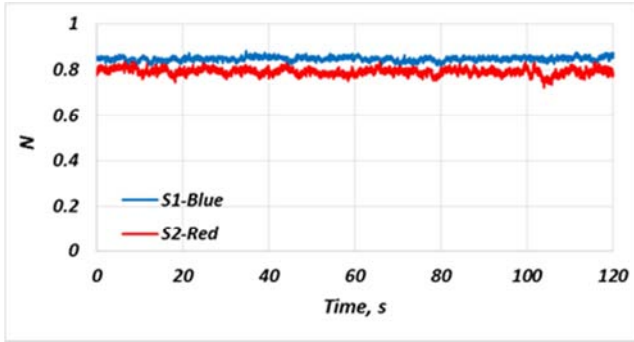


Figure 4. Saltation,  $V_{sl}=0.1783\text{m/s}$  (500micron, 500lb/1000bbl).

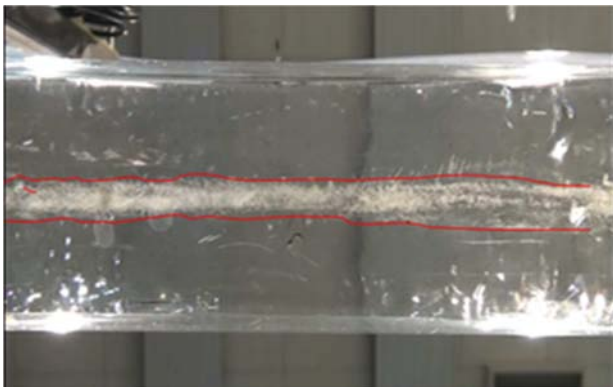
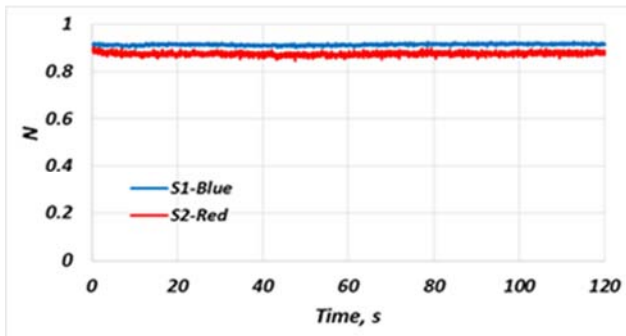


Figure 5. Sand Streaks,  $V_{sl}=0.1967\text{m/s}$  (212microns, 200lb/1000bbl).

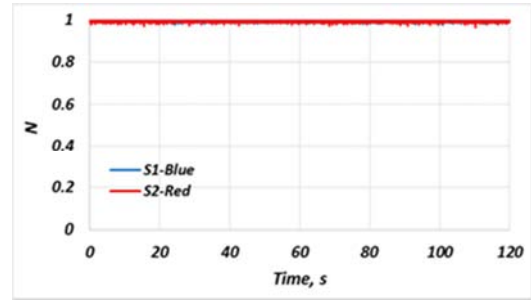
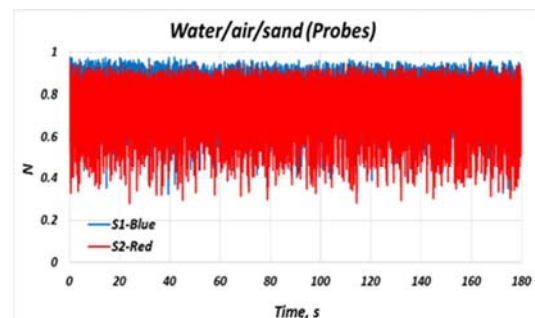


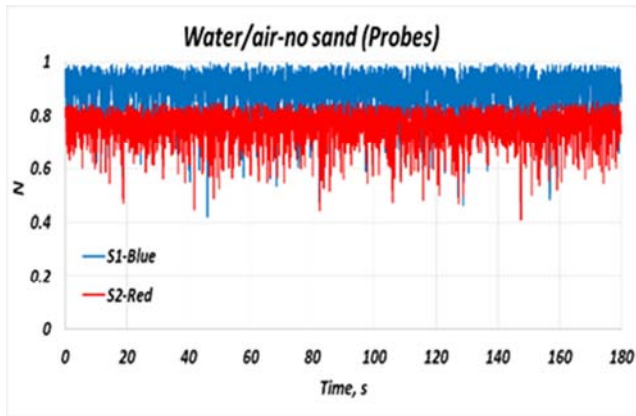
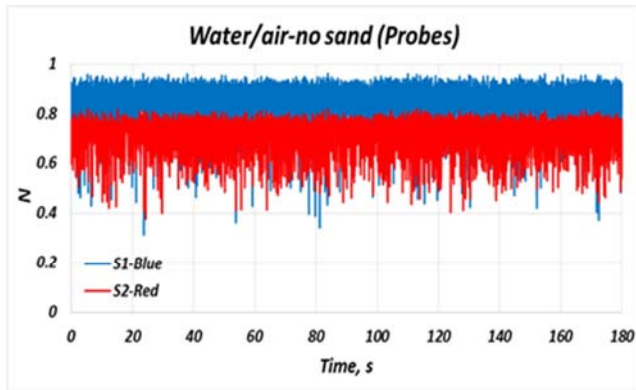
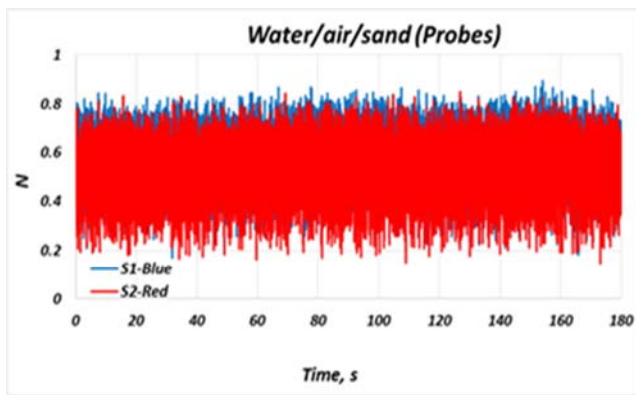
Figure 6. Suspension,  $V_{sl} 0.2427\text{m/s}$  (212microns, 200lb/1000bbl).

### 3.2. Water/Air/Sand Annular Flow (Probes)

From the experiments, the two probes S1 (blue) and S2 (red) results appeared to be widely spread with spikes across the graphs of Figures 7-12. This is because of the effect of superficial gas velocity which is the dominant phase in annular flow. The liquid and the sand in the pipe with the aid of the dominant gas phase, tends to behave like bubble of gas across the walls of the pipe thereby resulting to the broad spread of spikes seen on the following graphs of Figures 7 and 12 unlike figures 3-6 for water/sand flow only.

The graph of Figure 7 (a) is that of water/air/sand in annular flow. The sand particles were 212microns with sand concentration of 200lb/1000bbl, while Figure 7 (b) is that of water/air without sand. From the superficial velocities of both graphs of figure (a) and (b) which seems similar, the normalized volts of the probes S1 (blue) and S2 (red) against time should have also shown similar spikes hence both were from the same probes at the bottom of the pipe. This is to show that the probes detected sand transport that is the reason while Figure 7 (a) has a different signals/spikes from Figure 7 (b) even when the superficial velocities were almost the same. Irrespective of the high superficial gas velocity, the sand particles were detected to be moving as sand saltation/suspension.



(a)  $V_{sl}=0.1126\text{m/s}$   $V_{sg}=9.3775\text{m/s}$  (b)  $V_{sl}=0.1275\text{m/s}$ ,  $V_{sg}=9.3771\text{m/s}$ **Figure 7.** (a) Saltation/Suspension (212microns, 200lb/1000bbl) (b) Water/air-no sand.(a)  $V_{sl}=0.1145\text{m/s}$   $V_{sg}=14.9179\text{m/s}$  (b)  $V_{sl}=0.1269\text{m/s}$ ,  $V_{sg}=14.2926\text{m/s}$ **Figure 8.** (a) Sand saltation (212microns, 200lb/1000bbl) (b) Water/air-no sand.

The graph of Figure 8 (a) still shows that the probes were detecting sand saltation in the liquid film at the bottom of the pipe. Though, Figure 7 (a) had little spikes which also depicts sand saltation, but it's more pronounced in Figure 8 (a) even with dips on the upper surface of the plot which indicates that sand saltation was detected by the probes. Thus, Figure 8 (b) should have been the same with Figure 8 (a) if the probes were not detecting sand particles at the bottom of the pipe, but both plots were different even when the superficial liquid and gas velocities were close to have shown similarities in the signals/spikes. This has proven that the probes detected

sand particles (saltation) irrespective of the high superficial gas velocity in Figure 8 (a).

The graph of Figure 9 (a) has sand particle size of 212microns with sand concentration of 500lb/1000bbl. The trend is not different from the previous ones seen in Figures 7 and 8 respectively. The sand flow regime is that of saltation/suspension in liquid film at the bottom of the pipe.

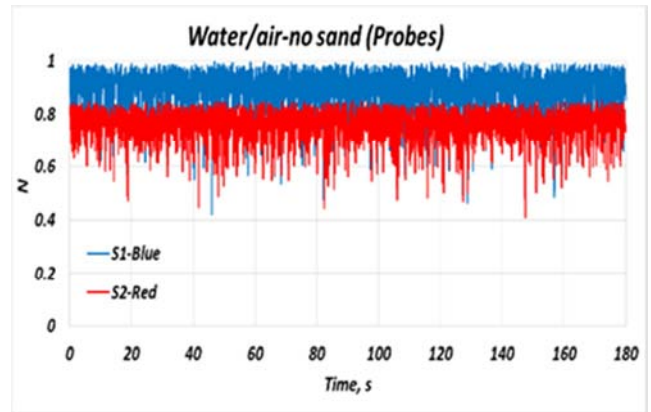
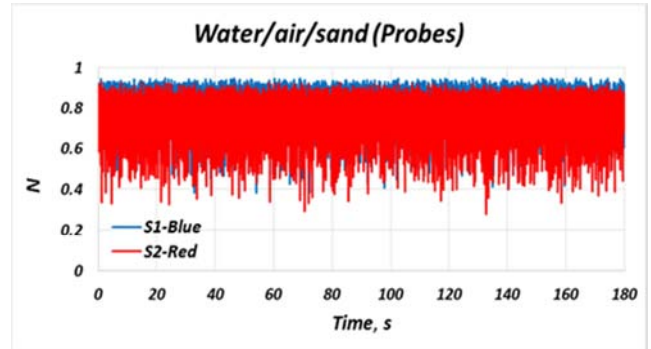
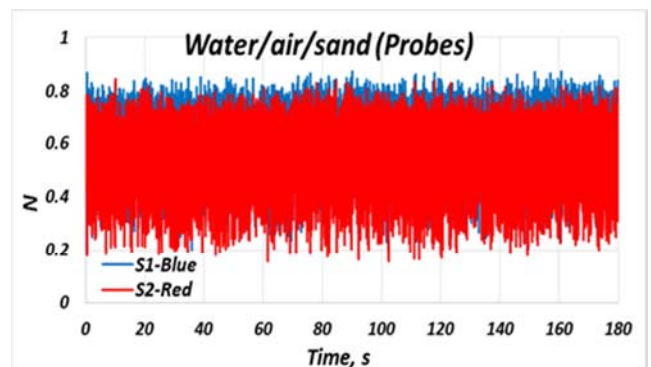
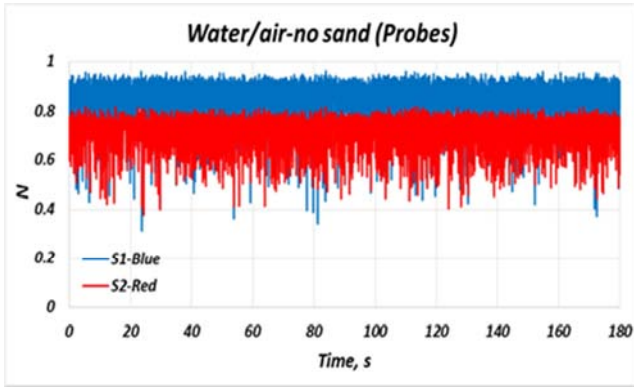
(a)  $V_{sl}=0.1252\text{m/s}$   $V_{sg}=8.9535\text{m/s}$  (b)  $V_{sl}=0.1275\text{m/s}$ ,  $V_{sg}=9.3771\text{m/s}$ **Figure 9.** (a) Saltation/Suspension (212microns, 500lb/1000bbl) (b) Water/air-no sand.

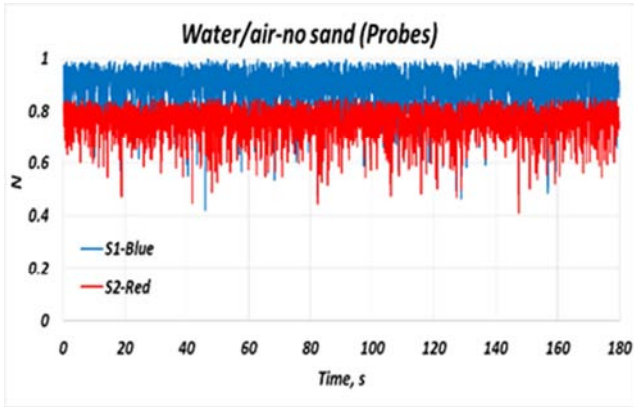
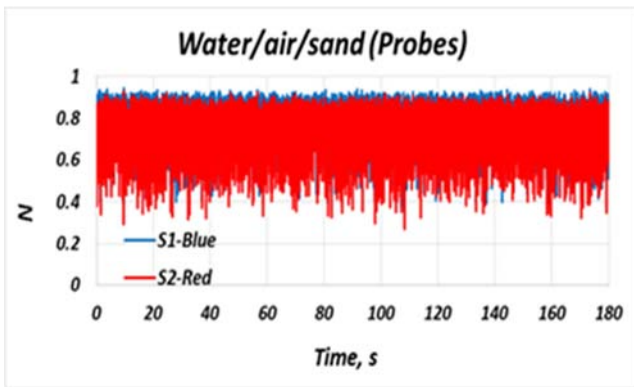
Figure 10 with sand particles of 212microns and sand concentration of 500lb/1000bbl shows more pronounced signals/spikes on the upper surface compared to Figure 9. Though, the difference could be attributed to more superficial gas velocity in Figure 10 which must have led to more bouncing or jumping of sand particles at the bottom of the pipe.





(a).  $V_{sl}=0.1248\text{m/s}$   $V_{sg}=14.5936\text{m/s}$  (b)  $V_{sl}=0.1269\text{m/s}$ ,  $V_{sg}=14.2926\text{m/s}$

**Figure 10.** (a) Sand saltation (212microns, 500Ib/1000bbl) (b) Water/air-no sand.



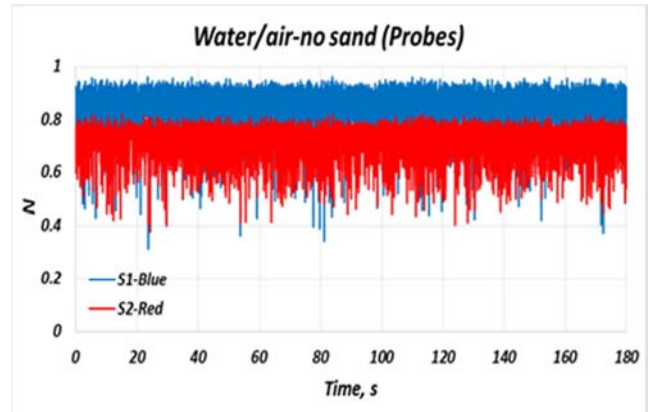
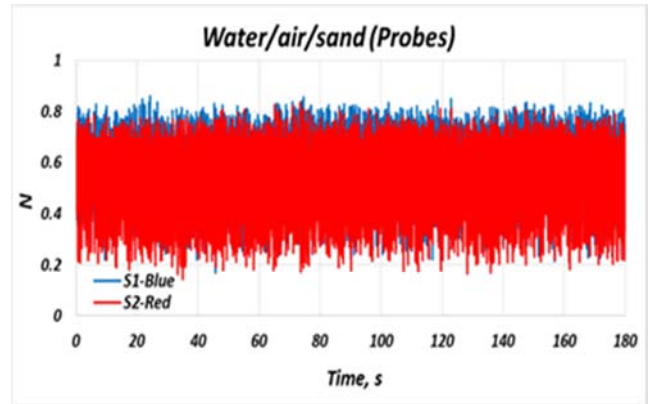
(a).  $V_{sl}=0.1256\text{m/s}$   $V_{sg}=8.7601\text{m/s}$  (b)  $V_{sl}=0.1275\text{m/s}$ ,  $V_{sg}=9.3771\text{m/s}$

**Figure 11.** (a) Saltation/Suspension (500microns, 500Ib/1000bbl) (b) Water/air-no sand.

From Figure 11, the plot of water/air/sand also presented a typical suspension spikes at the upper part in the flow, while the bottom signals present a typical sand saltation. Again, comparing Figure 10 and Figure 9 or Figure 11 shows that there are two sand flow regimes of saltation and suspension being detected in the flow. It shows that, in as much as the particles were bouncing (saltation) and floating (suspension), they were still connected by particle-particle collision.

Figure 12 (a) and (b) have also further proven sand transport in annular flow. Again, Figure 8 (a) exhibited similar trends with Figures 11, 10, 9, 8 and 7, as the spikes

look different from the spikes on Figure 12 (b) for water/air only. This has further shown sand effect on the conductance probes as Figure 12 (a) represents sand saltation in annular flow.



(a).  $V_{sl}=0.1236\text{m/s}$   $V_{sg}=14.4325\text{m/s}$  (b)  $V_{sl}=0.1269\text{m/s}$ ,  $V_{sg}=14.2926\text{m/s}$

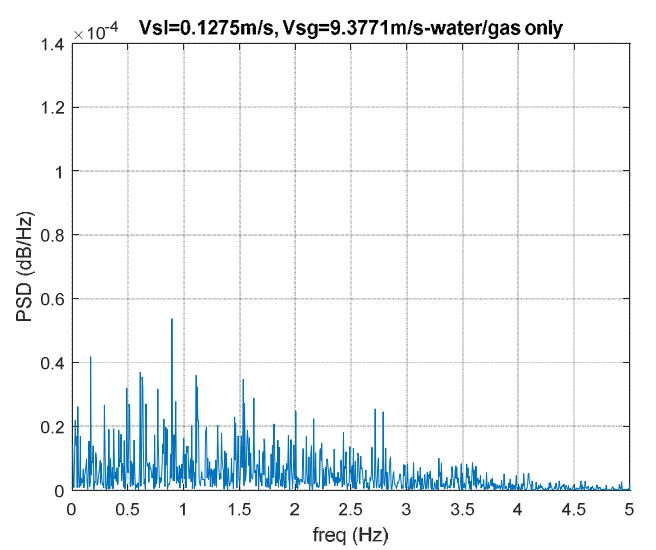
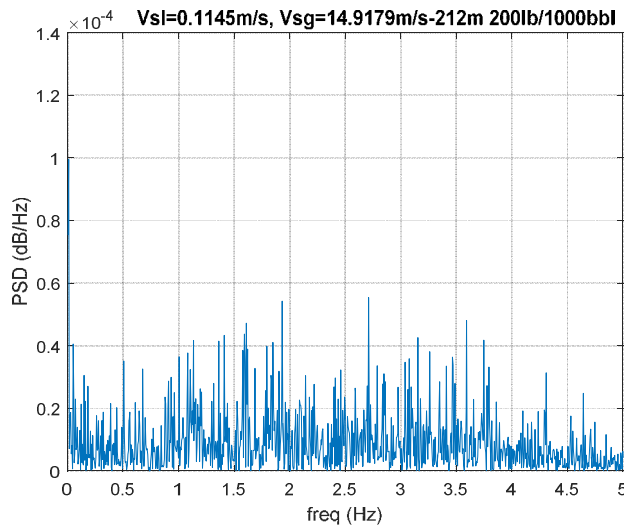
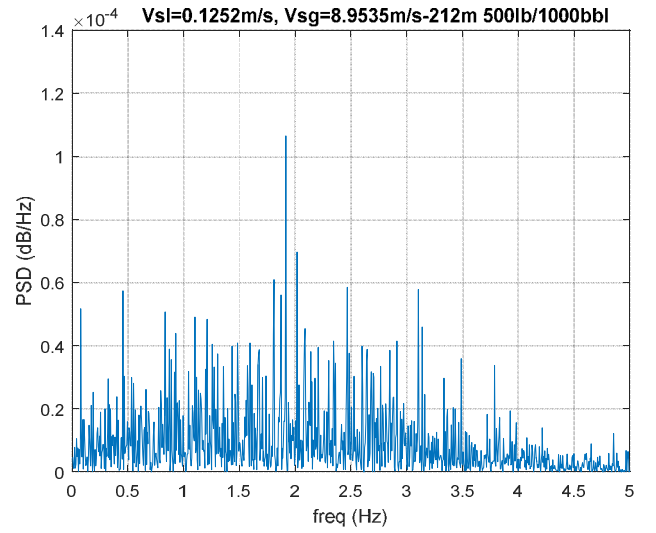
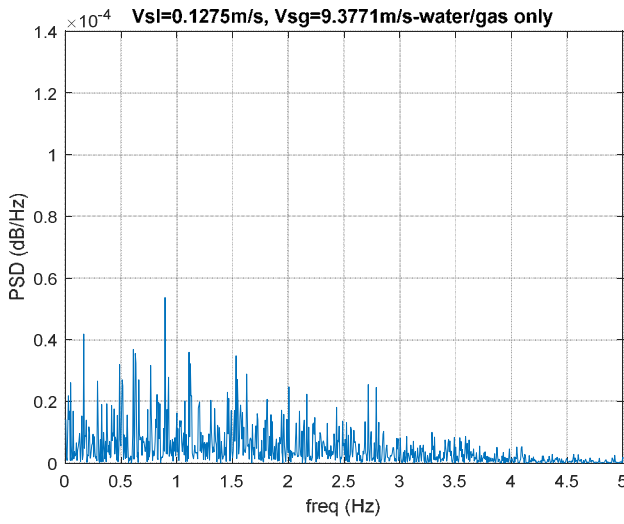
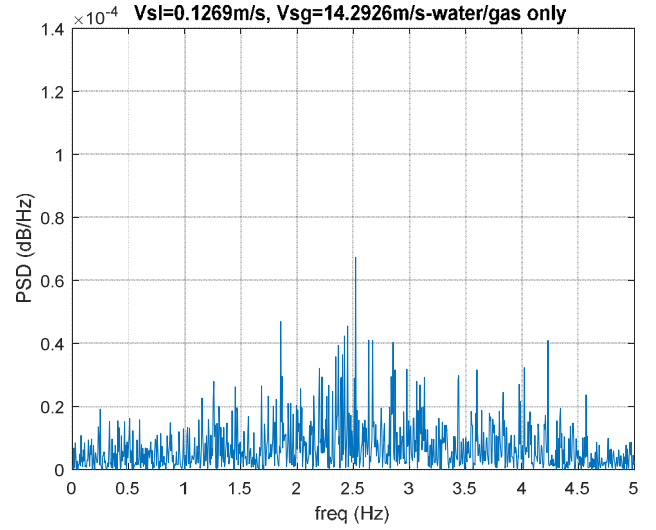
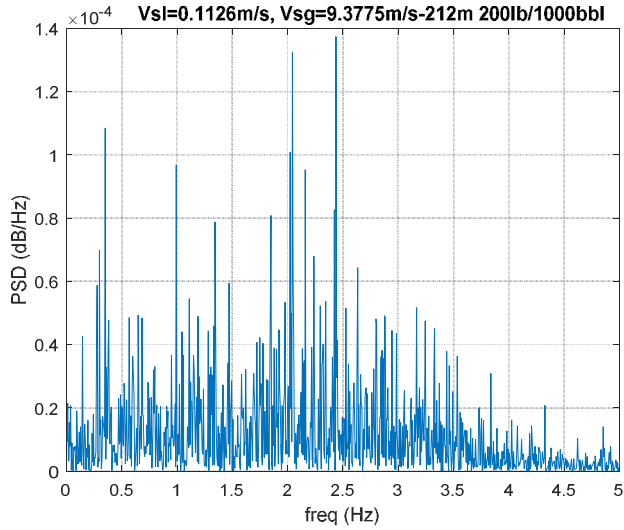
**Figure 12.** (a) Sand saltation (500microns, 500Ib/1000bbl) (b) Water/air-no sand.

### 3.3. Power Spectral Density (PSD) of Sand in Annular Flow

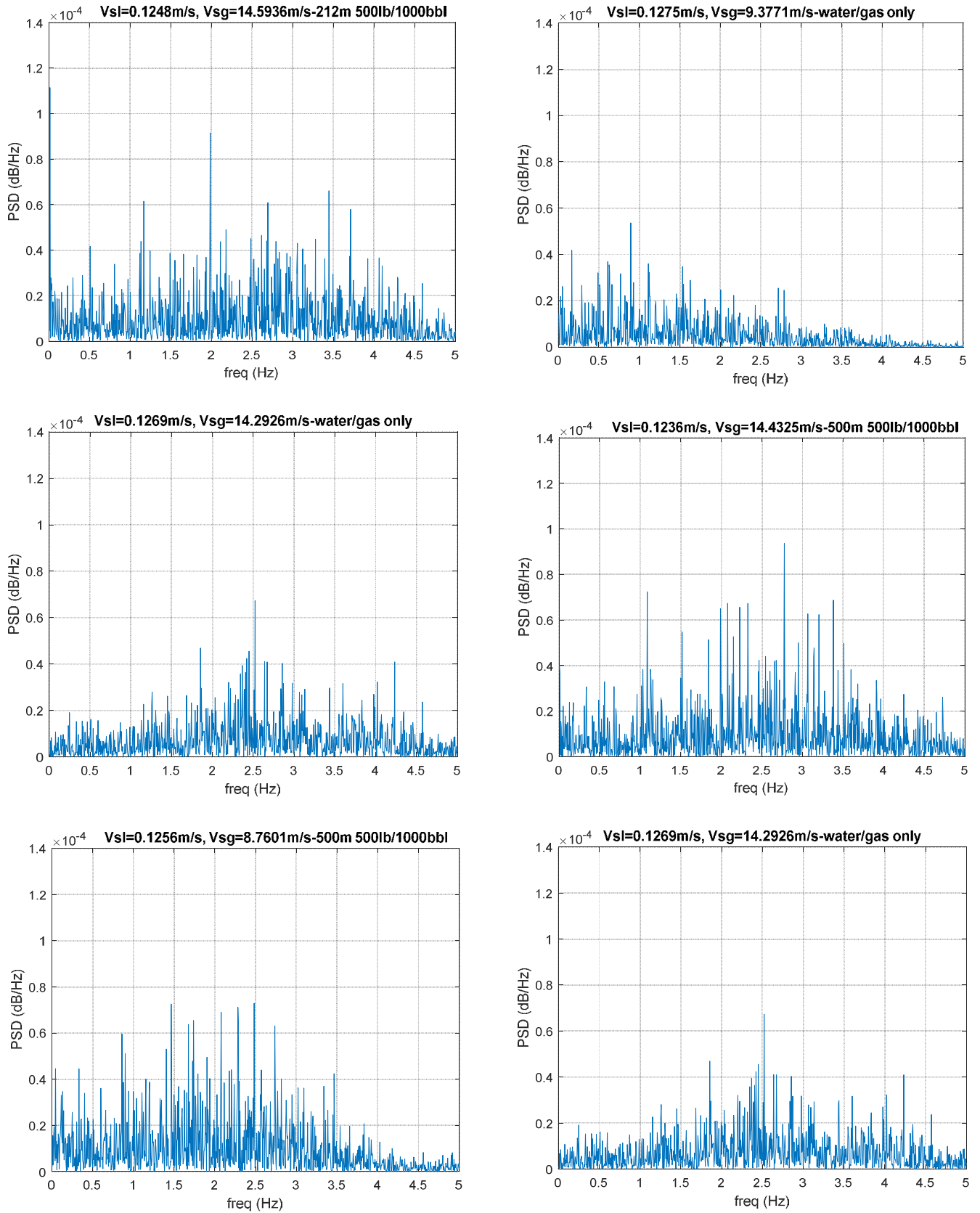
The power spectral density (PSD) of sand transport in annular flow on Figures 7-8 were further analysed to present the effect of sand on annular flow behaviour in horizontal pipes. It was observed after the analysis, that sand particles in liquid film aids in increase of wave amplitude as more energy were dissipated from the gas phase to keep the wave in motions as presented in Table 4.

The power spectral density of  $V_{sl}=0.1126\text{m/s}$ ,  $V_{sg}=9.3775$  with 212microns-200Ib/1000bbl has presented a distinct difference from that of  $V_{sl}=0.1275\text{m/s}$ ,  $V_{sg}=9.3771\text{m/s}$  without sand. This has shown, that more energy was dissipated in  $V_{sl}=0.1126\text{m/s}$ ,  $V_{sg}=9.3775$  with 212microns-200Ib/1000bbl. Therefore, sand particles are proven to be transported in the liquid film in annular flow as also presented in Figures 13 and 14 which were presented from the sand sampling experiments. Again, PSD has further proven the results of Figures 7-12, that sand particles were transported likewise at the bottom (liquid film) of the pipe.









**Figure 13.** PSD of Sand in Annular Flow compared with Annular Flow without Sand.

**Table 4.** Summary of Most Sand Transport, Phases, Flow Pattern and Model developed in Multiphase Flow Experiment over the Years.

Author	Phase	Model	Flow Pattern	Particle Sizes	Pipe Size
Durand (1952)	Solid/Liquid	Critical Velocity	-	0.05mm-25mm	1.5inch-28inch
Newitt et al (1955)	Solid/Liquid	Critical Velocity	-	0.0625mm-6.0mm	1 inch & 6inch
Scott & Rao (1971)	Solid/gas/liquid	Saltation Velocity	Bubble, Slug	(100,500) microns	1 inch & 2inch
Wicks (1971)	Solid/Liquid	Measured	-	Not mentioned	1 inch & 6inch
Oroskar & Turian (1980)	Solid/Liquid	Critical Velocity	Used SRC (1973) Report data of (V, IV, II, VI, VII)	And also Wasp et al (1970) experimental data	-
Tsuji and Morikawa (1982)	Air/Solid	-	-	0.2mm, 3.4mm	30.5mm
Angelson et al (1989)	Sand/Air/Water	Based on Wicks (1970) model	Slug, Elongated Bubble, Stratified	(30, 100, 200, 550) microns	1 inch & 4inch
Oudemans (1993)	Sand/Air/Water	Sand Transport Rate	Stratified, Slug	0.15-0.30mm	0.007m
Gillies et al (1997)	Solid/gas/liquid	Sand Transport Rate	Intermittent Flow	0.2mm, 0.1mm	52.5mm
Salama (1998)	Solid/Liquid	MMFV	-	< 400microns	-
Sommerfeld and Hubber (1999)	Solid/Gas	Particle-Wall Collision	Gas Flow	(100 & 500) microns	(300) mm Laden Channel Flow
Akilli et al (2001)	Solid/Gas	Particle Velocity	Gas Flow	50microns	0.154m
Stevenson & Thorpe (2002)	Sand/air/water	Critical Velocity	Intermittent Flow	150 – 180 microns	(40 & 70) mm
Ramadan et al (2005)	Solid/gas/liquid	Mean Velocity	Stratified Flow	-	70mm
Bello et al (2011)	Solid/gas/liquid	MTV	bubble, Annular, Slug,	-	4-inch
Kesana et al (2012)	Solid/gas/liquid	Effect on Erosion	Slug, Annular Flow	(20, 150, 300) microns	3-inch
Ravelet et al (2013)	Solid/liquid	Terminal Velocity	Intermittent,	(5, 5.5, 6, 8.5, 10, 10.515, 16) mm	100mm
Franklin (2013)	Solid/gas/liquid	Bed-load Transport	Stratified Flow	-	-
Ibarra et al (2014)	Solid/gas/liquid	Critical Velocity	Stratified Flow	211-297microns	4-inch
Kamayar et al (2015)	Solid/gas/liquid	Critical Velocity	-	Silica (20, 150, 300) microns	0.1m & 0.05m
Jiang et al (2017)	Solid/Gas	PTV	Gas Flow	Alumina-1.8mm	-
This Study	Sand/Air/Water	Sand Flow Regime	Annular Flow	212,500microns	2-inch (0.0504m)

#### 4. Physical Modes of Sand Distribution in Annular flow (Sampling Method)

The physical modes of sand distribution were investigated using sand sampling approach. The experiments on sand sampling shows that the higher the velocity, the higher the sand transported in the pipe. This simply means, increase in superficial gas velocity increases both the sand movement and concentration.

Figure 14 results were quite different from Figure 15 results presented. Figure 14, was conducted using  $V_{sl}=0.0732\text{m/s}$  with 212microns-200lb/1000bbl. The results illustrated that, small particles are transported more in the gas core than in the liquid film thickness. This means the smaller the particles, the lighter they are easily lifted and transported with respect to high gas velocities. At a height of 2.5cm (0.025m) internally where the gas core was dominant in the horizontal pipe, more of the sand particles were transported. Again, at a height of 1.5cm (0.015m) internally, more sand particles were also detected from the sampling experiments. While at the bottom of the pipe were the sampling throat was flush mounted, the sand particles were detected and increasing with the superficial gas velocity. At the upper walls of the internal pipe diameter, negligible sand particles were transported.

At the bottom of the pipe, more sand transportations were presented in the graph of Figure 15. At 2.5cm (I. D-0.025m) the results showed an increase in sand transport in the gas core from  $V_{sg}=15.0122\text{m/s}$  to  $18.0010\text{m/s}$ . Reasons for having more sand particles being transported at the liquid

film could be because of gravity. This was also noted by [2] on gas/solid experiments conducted. The sand particles are bigger in size compared to 212microns in Figure 14, therefore gravity impacted more on the sand particles hence the results presented in Figure 15.

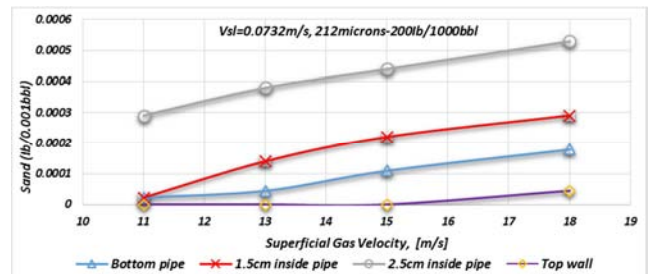


Figure 14. Sand Distribution in the Pipe for  $V_{sl}=0.0732\text{m/s}$ , 212microns.

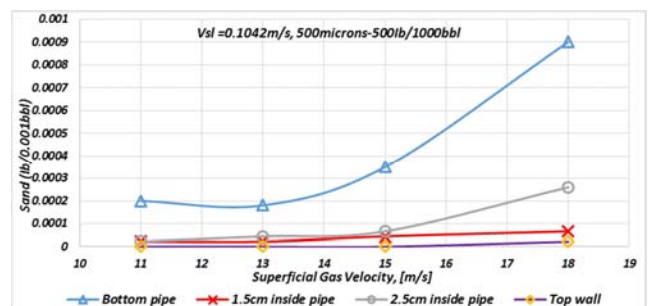


Figure 15. Sand Distribution in the Pipe for  $V_{sl}=0.1042\text{m/s}$ , 500microns.

#### 5. Conclusion

The experimental investigations have presented sand

transport in annular flow using conductance probes and sampling approach. At first, was the water/sand test which was the preliminary test conducted to progress the understanding of sand behaviour in flow.

The water/air/sand annular flow experiments with sand particles of 212microns and 500microns, presents saltation and suspension as the flow regime in annular flow. In confirmation, sand sampling experiments proved it as follows: that bigger sand particles (500microns) are transported more at the bottom of the pipe meaning saltation. While, the smaller particles of 212microns are transported more as suspension in gas core with traces of saltation from the experiments.

Figures 8, 10 and 12 (a), had bigger sand particle of 500microns under high superficial gas velocity of above 14m/s. The spikes on the graphs, had presented the influence of high gas flow and gravity impact as the conductance probes, detected more sand particles jumping (bouncing) which represents sand saltation than in Figures 7, 9 and 11 (a). While the spikes on graphs of Figures 7-12 (b) were gas bubbles in form of droplets in the film, which were likewise detected by the conductance probes. The difference between the Figures 7-12 (a) and (b), are the spikes' spreading and the S1 (blue) and S2 (red) colour differentiations.

Also, power spectral density (PSD) which was used to further analyse the signals from the water/air/sand annular flow experimental data, proved the presence of sand particles at the bottom of the pipe. The power spectral density of  $V_{sl}=0.1126\text{m/s}$ ,  $V_{sg}=9.3775$  with 212microns-200lb/1000bbl has presented a clear difference from that of  $V_{sl}=0.1275\text{m/s}$ ,  $V_{sg}=9.3771\text{m/s}$  without sand. This has proven, that more energy was dissipated in  $V_{sl}=0.1126\text{m/s}$ ,  $V_{sg}=9.3775$  with 212microns-200lb/1000bbl. Therefore, sand particles are proven to be transported in the liquid film in annular flow as presented by conductance probes' results, sand sampling results and PSD analysis in Table 4.

## Nomenclature

PSD=Power Spectral Density  
LED=Light Emission Diode infrared.  
 $S_1$ =Sand Probe (Upstream)  
 $S_2$ =Sand Probe (Downstream)  
 $T_1$ =Temperature Sensor (Upstream)  
 $T_2$ =Temperature Sensor (Downstream)

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