

CRANFIELD UNIVERSITY



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**EFFECT OF PARTICLE SIZE ON SAND DEPOSITION IN
SINGLE-PHASE AND MULTI-PHASE PIPELINES**

Oil and Gas Engineering Centre
School of Water, Energy and Environment

PhD Thesis
Academic Year: 2013 - 2016

Supervisor: PROFESSOR HOI YEUNG

NOVEMBER, 2016

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ABSTRACT

Sand production in the life of oil and gas reservoirs is inevitable, as it is co-produced with oil and gas from the reservoirs. Sand deposition in petroleum pipelines poses considerable risk to the production of oil and gas. This study investigates the effect both of sand particle diameter and concentration on minimum transport conditions in single phase and multiphase horizontal pipelines through experimental methods. This study defines the minimum transport condition (MTC) for sand grains under stratified two-phase flow regimes, as the combined minimum gas and liquid velocities at which all sand particles have sufficient energy to keep them moving in the liquid phase along the pipe.

In this study, careful analyses based on experimental observations were made producing several conclusions. Based on the analysis, it was found that sand of different particle diameters and concentrations exhibits similar behaviours in single phase flow and stratified two-phase flow in horizontal pipes. Furthermore, in stratified two-phase flow, sand particles were transported within the liquid film and never observed crossing into the gas phase or transported across the gas-liquid interface; however, an increase in gas velocity tends to cause an increase in liquid velocity which in turn increases the velocity of the sand particles in stratified two-phase flow.

Studies carried out on the effect of particle diameter and concentration on MTCs in both single phase (water) and stratified two-phase flows (air-water) in horizontal pipes showed that MTC increases with increases in particle diameter for the same concentration and also increases as the concentration increases for the same particle diameter.

Sand sensors were used in this study for the purpose of sand monitoring and detection in single phase (water) and stratified two-phase flow in horizontal pipes. The sensors were flush-mounted at the bottom of the pipe. These sensors are commonly used to measure the thickness of a film in multiphase flow but have not been used before for monitoring and detecting sand both in single phase and multiphase flows. In this work the sensors were applied in monitoring and

detecting sand in single phase and multiphase flows; they were found to be capable of monitoring and detecting sand in a conducting liquid in both single phase and stratified two-phase flows.

Measured pressure gradients for sand-water flow at MTC were compared with measured pressure gradients for sand-air-water flow for the same particle diameter and concentration; it was found that there was a difference between the two pressure gradients. The pressure gradient of sand-water flow at MTC was higher than the pressure gradient of sand-air-water flow at MTC. For this reason, King et al.'s (2001) pressure gradient approach cannot be used to design wet gas pipelines.

Modified concentration (v/v) correction correlation is proposed to predict sand transport at MTC in air-water. The correlation accounts for low concentration of sand ($5.39\text{E-}05$ to $4.90\text{E-}04\text{v/v}$) in air-water flow. The proposed correlation predicted fairly when compared with the experimental results at MTC.

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NOMENCLATURE

Symbol	Description	Units
A	Cross-sectional area of pipe	m^2
A_b	Particle area projected in direction of motion	m^2
A_f	Cross-sectional area of liquid film in the pipe	m^2
A_G	Flow area occupied by gas	m^2
A_h	Cross-sectional area of heterogeneous slug in the pipe	m^2
A_L	Flow area occupied by liquid	m^2
B_o	Formation oil volume factor	bbl/stb
C_D	Drag coefficient	-
C_K	Lift coefficient	-
C_v	Sand volume concentration	v/v
D	Inside pipe diameter	m
D_{EQ}	Diameter of fluid section above sand bed	m
D_f	Hydraulic diameter of heterogeneous slug	m
D_{hh}	Hydraulic diameter of heterogeneous slug	m
d_p	Particle diameter	m
F	Fanning friction factor	-
F_B	Buoyancy force	N
F_D	Drag force on a particle	N
f_G	Gas-wall friction factor	-

F_G	Force due to gravity	N
f_i	Interfacial friction factor	-
f_L	Liquid-wall friction factor	-
F_L	Lift force	N
Fr	Froude number	-
Fr_L	Liquid-phase Froude number	-
f_s	Pseudo-average friction factor	-
g	Acceleration due to gravity	ms^{-2}
G_g	Gas mass flux rate	$\text{kgm}^2\text{s}^{-1}$
h_F	Liquid film thickness	m
$h_{F,a}$	Average liquid film thickness	m
H_G	Gas hold-up	-
h_L	Liquid level or gas cap	m
H_L	Liquid hold-up	-
H_u	Average liquid holdup of slug unit	-
L	Pipe length	m
L_s	Slug length	m
M	Mass	kg
P	Pressure	bar
P_D	Rate of dissipation of energy for Suspended Particles	$\text{J/m}^3\text{s}$
Q_d	Grain transport rate	$\text{m}^3\text{s}^{-1}\text{m}^{-1}$

Q_G	Gas flow rate	m^3s^{-1}
Q_L	Liquid flow rate	m^3s^{-1}
Q_T	Actual fluid flow rate	m^3s^{-1}
Q_w	Water flow rate	m^3s^{-1}
r	Distance from pipe centre	m
R	Pipe radius	m
Re	Reynold's Number	-
Re_G	Gas-phase Reynolds Number	-
Re_L	Liquid-phase Reynolds Number	-
s	Solid/liquid density ratio	-
S_G	Wetted perimeter by gas	m
S_h	Wetted Perimeter by heterogeneous Slug	m
S_i	Interfacial perimeter	m
S_L	Wetted Perimeter by Liquid	m
T	Time	s
u_f	Mean fluid velocity	ms^{-1}
u_H	Homogeneous suspension flow velocity	ms^{-1}
u_p	Particle velocity	ms^{-1}
u_t	Terminal settling velocity	ms^{-1}
V	Velocity of fluid in pipe	ms^{-1}
V_f	Solid Fraction	ms^{-1}

V_G	Actual gas velocity	ms^{-1}
$V_{G,c}$	Gas core velocity	ms^{-1}
V_L	Actual liquid velocity	ms^{-1}
V_m	Mixture velocity	ms^{-1}
V_p	Volume of a single particle in a fluid	ms^{-1}
V_S	Slippage velocity	ms^{-1}
V_{sg}	Gas superficial velocity	ms^{-1}
$V_{sg,c}$	Critical gas superficial velocity	ms^{-1}
V_{sl}	Liquid superficial velocity	ms^{-1}
w	Average velocity of the liquid stratum	ms^{-1}
w_c	Critical velocity of the liquid stratum	ms^{-1}
X	Lockhart-Martinelli Parameter	-
y	Denote position in the pipe	-
Z	Gas compressibility factor	-

Greek Letters

ρ	Fluid density	kgm^{-3}
ρ_c	Density of core flow	kgm^{-3}
ρ_G	Gas density	kgm^{-3}
ρ_L	Liquid density	kgm^{-3}
ρ_P	Particle density	kgm^{-3}
ρ_s	Density of slug body	kgm^{-3}
ρ_u	Density of slug unit	kgm^{-3}
μ	Fluid viscosity	$\text{Pa} \cdot \text{s}$
μ_g	Gas viscosity	$\text{Pa} \cdot \text{s}$

μ_L	Liquid viscosity	$\text{Pa} \cdot \text{s}$
μ_m	Viscosity of flow mixture	$\text{Pa} \cdot \text{s}$
τ	Shear stress	Nm^2
τ_i	Interfacial shear stress	Nm^2
τ_{WG}	Gas-wall shear stress	Nm^2
τ_{WL}	Liquid-wall shear stress	Nm^2
ϑ	Wetted wall fraction	-
θ_0	Central angle with flat interface	rad
σ_L	Liquid surface tension	Nm^{-1}
σ_w	Water surface tension	Nm^{-1}

ABBREVIATIONS

CR 1	Conductivity Ring 1
CR 2	Conductivity Ring 2
MTC	Minimum Transport Condition
PSD	Power Spectral Density
SS 1	Sand Sensor 1
SS 2	Sand Sensor 2

1 INTRODUCTION

1.1 Background

The prediction of minimum transport conditions (MTCs) for sand particles in multiphase flow, petroleum pipelines is an essential, ever-increasing topic in the petroleum industry. The majority of today's oil and gas reservoirs are prone to sand production due to the different activities performed on the oil and gas reservoirs to increase the production rate. These activities can be acid stimulation or fracturing to open up the well-bore (negative skin factor) for higher production rate. Furthermore, injection of water and chemicals during secondary and tertiary enhanced oil recovery (EOR) and also depletion of the oil reservoirs during production processes all contribute to sand production. However, there are some reservoirs that are poorly consolidated (i.e. reservoirs with low formation strength). According to Almedeij and Algharaib (2005), 70% of the world's oil and gas is produced from reservoirs with low formation strength or unconsolidated reservoirs formation. The existence of sand in petroleum pipelines or flowlines has caused a major setback for the oil and gas industry, which needs to be addressed.

Production of oil and gas from petroleum reservoirs usually involves sand being co-produced with petroleum fluids or formation fluids due to aging and the activities carried out on the reservoirs as already mentioned. During production, if the production rate of oil and gas is high, the movement or the impact of sand particles on the wall of the pipe will erode the inner surface of the pipe. On the other hand, if the rate of production of petroleum fluids with sand particles is low, sand deposition will become a problem within the flow-line. The deposition of sand particles in oil and gas flowlines can wreak havoc on the oil and gas production systems in such a way as to cause increased pressure loss, localized high velocities, reduction or loss of production when the pipe is partially or completely blocked, and expensive cleaning operations from time to time.

Sand production from the oil and gas reservoirs formation has been a great concern in oil and gas field development and the common approach employed in

managing sand production problems is to put in place a down-hole sand exclusion system (such as gravel packs, screen/slotted liners, frac-packs etc.) and also inject chemicals to consolidate the reservoir formation. These can be effective; however, these solutions increase the cost of well completions. Moreover, once the production of sand from the oil and gas reservoir formation surpasses the threshold in the later stages of reservoir life, the virtue or integrity of the production tubing and pipelines will be degraded. Furthermore, it is impossible to produce oil and gas from the reservoirs without producing sand, even when sand exclusion systems are installed down-hole. This is because sand exclusion systems are designed in such a way that fine sands that are co-produced with petroleum fluids are allowed to pass through the opening of the sand exclusion systems.

Due to these various challenges and limitations associated with conventional sand management strategies, there will always be the need to produce oil and gas from the reservoir with sand but without affecting oil and gas production rates and the integrity of the production systems. Nevertheless, some challenges can be encountered with these kinds of operations, such as pigging problems, and also the inner surface of the pipelines or flow lines can be eroded if the production rate is high. Designing a robust production system and pipeline for sand to be co-produced with oil and gas will involve considering the presence of a solid phase with the multiphase flow of gas and liquid with the operating window to optimize production within the integrity limit.

Furthermore, demand for energy has greatly increased, which has increased the demand for oil and gas. Due to increase in demand for oil and gas to meet energy demands, the petroleum industry continues to search for adequate technologies to exploit reserves and co-produced sand with unprocessed petroleum fluids through multiphase pipelines to the surface facilities. The economic benefit of this, is to produce oil and gas successfully at less cost from those reservoirs that are more challenging (such as the offshore environment and aging reservoirs) so that the world's energy demand can be met.

In order to prevent sand particles being deposited within the pipelines and flowlines during the production of oil and gas, sufficient knowledge of basic design parameters is needed, such as minimum transport conditions (MTCs), sand hold-up, accurate prediction flow regimes and many more (Bello, 2008; 2009).

1.2 Previous Studies on Sand Transport in Pipelines at Cranfield University

Several studies have been carried out on sand MTC in single and multiphase pipelines in the Oil and Gas Engineering Centre (formerly called the '*Process Systems Engineering Group*') at Cranfield University. Yan (2010) investigated the effect of pipeline orientation, liquid viscosity (carboxyl methyl cellulose), and sand concentration on MTC in single phase and slug flow in 2 and 4-inch pipelines. He concluded that pipeline orientation slightly affects the MTC of sand in single phase water and air-water flows, and that the MTC of sand increases with increases in fluid viscosity. However, as the flow becomes laminar, the MTC of sand decreases as the fluid viscosity increases, and the MTC of sand increases with increases in sand volume concentration. Xiaozheng (2010) investigated sand behaviour in dips, Okeke (2012), studied sand transport in undulating pipelines and Osho (2013) studied the effect of pipeline orientation; they all concluded that the MTC of sand increases with a slight increase in pipeline orientation and the MTC of sand in the downhill is lower than in the uphill section. Ikeagu (2009) studied sand transport in stratified and stratified wavy flow in a horizontal pipeline. The effect of liquid viscosity (using carboxyl methyl cellulose as the liquid) on sand transport in stratified flow was investigated in a 4-inch horizontal pipe. He concluded that the liquid with higher viscosity has a greater tendency to transport sand, and also the MTC of sand for single phase liquid systems was higher than the MTC of the sand particles in stratified wavy flow (air-water).

In this study, the effect of sand particle diameter and concentration on MTC in single phase (water) and stratified (air-water) flows were investigated in a horizontal pipe. Furthermore, sand sensors (similar to those used to measure film

thickness in multiphase flow) were used to detect and monitor sand movement in both single phase and multiphase pipelines.

1.3 Research Objectives

The fundamental aim of this study is to investigate sand transport in single phase (water) and multiphase (air-water) flows in a horizontal pipe, in particular, to determine the effects of particle size and concentrations in water only and air-water stratified flow on the MTCs in a horizontal pipe. In order to achieve these stated aims, the following tasks were carried out:

1. Review of the literature on sand transport in single phase and multiphase (gas-liquid-solid) flows.
2. Design and modification of a three-phase (gas-liquid-solid) horizontal test facility with instrumentation to study sand transport in single phase and multiphase flow (stratified flow).
3. Comparison of the current experimental data with other experimental studies where appropriate.
4. Investigation of particle size effect on MTC in single phase (water) and multiphase (air-water, stratified) flows in a horizontal pipe with the aid of sand sensors.
5. Investigation of the concentration effect on MTC in single phase (water) and stratified (air-water) flows in a horizontal pipe.
6. Development of a new correlation to account for sand concentration effect in the Thomas Lower model.

1.4 Thesis Structure

Chapter 1: Introduction

This chapter discusses the problems caused by sand production in oil and gas pipelines and how these problems can be addressed without wreaking havoc on the production system. It also summarises earlier studies carried out on sand transport in pipelines at the Oil and Gas Engineering Centre at

Cranfield University. Furthermore, it discusses the aim of this study and outlines the tasks carried out to achieve it.

Chapter 2: Literature Review on Sand Transport in Multiphase Flow

This chapter reviews literature that is relevant to the fundamentals of multiphase flow, such as flow regimes and flow maps in horizontal pipes. It also reviews previous research findings on the prediction and behaviour of sand transportation in single phase liquid flow and multiphase flow (gas-liquid flow), with discussions on the parameters which affect solid transportation in pipelines.

Chapter 3: Experimental Set-up

Chapter 3 discusses 2-inch horizontal flow loop design and outlines the instrumentation used for data acquisition and processing. It also discusses the experimental procedure and measurement. The final part of this chapter briefly explains sand distribution and the test methodology used in this work.

Chapter 4: Results and Discussion of Sand-Water Tests

This chapter discusses the experimental findings obtained in sand-water tests. The sand characteristics observed in single phase (water) flow in a horizontal pipe and analysis of the sand sensor with respect to sand behaviour are discussed. Furthermore, Chapter 4 also accounts for the actual liquid velocity at MTC for sand-water flow at various sand concentrations in a horizontal 2-inch pipe.

Chapter 5: Air-Water Experimental Results and Analysis

Chapter 5 presents a brief literature review on air-water flow parameters (such as hold-up and flow map) and the experimental findings obtained on a laboratory-scale for air-water multiphase flow in a 2-inch horizontal loop. Comparisons of parameters, such as hold-up and pressure gradient with established correlation, are also discussed. This chapter also discusses the experimental findings obtained in sand-air-water tests in a horizontal pipe.

Furthermore, the chapter discusses actual liquid velocities at MTC for various sand concentrations in a horizontal pipe in air-water flow.

Chapter 6: Analysis of Pressure Gradient for Pipe Design and Extension of Thomas Lower Model

Chapter 6 discusses the pressure gradient for pipe design, extension of the Thomas Lower correlation model and validation with experimental results from a horizontal 2-inch pipe. This predictive model will serve the purpose of predicting sand MTCs in a wet gas pipeline (horizontal).

Chapter 7: Conclusions and Recommendations

This chapter draws conclusions from this research work and outlines the recommendations for future research work.

2 LITERATURE REVIEW

2.1 Overview of Sand Transport

Sand production from oil and gas reservoirs is a common problem associated with the petroleum industry. Analysis of oil and gas reservoir formation through a drill stem test (DST) allows engineers to determine if sand will be produced with oil and gas in the early life of a field. If the analysis through a DST indicates that sand will be produced, a sand exclusion system such as a gravel pack can be installed. A typical sand exclusion system (gravel pack) is shown in Figure 2-1. However, some operators prefer to produce oil and gas with sand to the surface facilities; for this purpose, sand management strategies will be put in place by the operators in order to handle the sand production at the surface. Sand production from the oil and gas wells is caused by many factors. These factors are discussed in section 2.3.

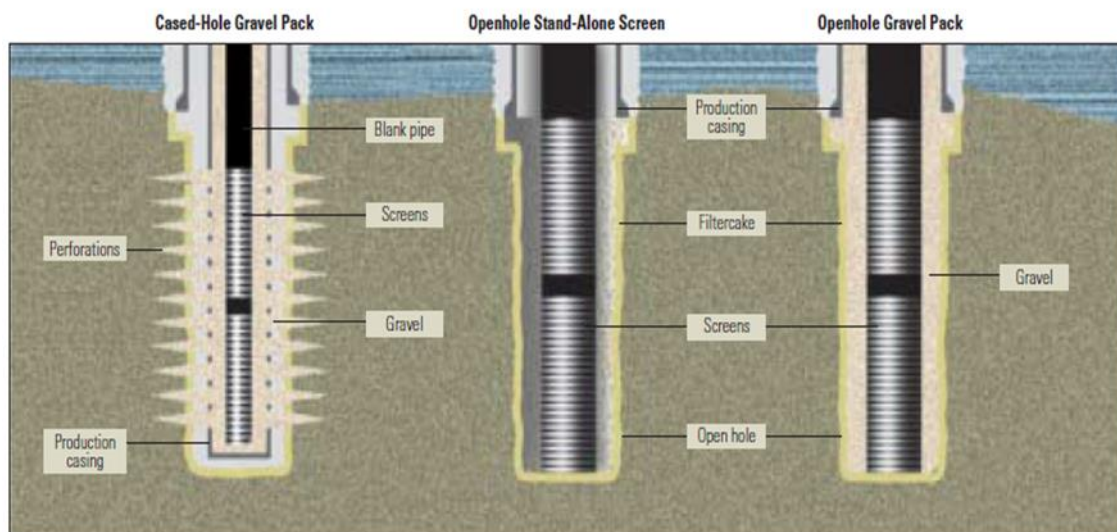


Figure 2-1: Sand exclusion systems (Acock et al, 2004)

2.2 Challenge

One of the major problems facing the oil and gas industry today is the production of sand with the fluid that is produced from the reservoir to multiphase flow pipelines and surface facilities. A sand exclusion system such as a gravel pack

or screen may fail, which may lead to sand production within multiphase flow pipelines (Danielson, 2007). In contrast, the majority of operators prefer to produce oil and gas without installing a sand exclusion system down-hole. This is to enable operators to boost oil and gas production rates. In this type of operation production, sand production is inevitable (Danielson, 2007; Ibarra et al., 2014). Furthermore, it is not possible to produce oil and gas from the reservoirs without producing sand, even when sand exclusion systems are installed down-hole. This is because sand exclusion systems are designed in such a way that fine sand that is co-produced with petroleum fluids is allowed to pass through the opening of the sand exclusion system. Deposition of sand within multiphase flow pipelines wreaks havoc on oil and gas production systems. Sand deposition within the production pipelines causes complete or partial blockage of the multiphase flow pipelines, an increase in pressure loss, and localized corrosion or erosion (Danielson, 2007; Ibarra et al., 2014; Najmi et al., 2014; Salama, 2000).

Due to the damages that sand production can cause to oil and gas pipelines, there is always a need to design pipelines that operate above the sand MTC (velocity), so as to overcome the challenges of sand deposition along the multiphase pipelines.

2.3 Causes of Sand Production

Sand production from the oil and gas reservoirs to surface facilities is caused by several factors: (1) Production rate, (2) Degree of consolidation, and (3) Increase in water production.

2.3.1 Production Rate

When oil and gas are produced from the reservoir, drag force, as a result of friction and pressure difference, is generated in the oil and gas well. The combination of pressure difference and drag force within the reservoir sometimes exceed the compressive strength of the reservoir formation. When this exceeds the compressive strength, sand will be produced; however, there is a critical flow

rate for most oil and gas wells at which combined pressure difference and drag force within the oil well will not exceed the formation compressive strength. At this critical flow rate, sand will not be produced along with the fluid produced.

2.3.2 Degree of Consolidation

The mechanical properties of rock that consolidates rocks are referred to as the compressive strength. Investigations carried out on the compressive strength of rocks, have shown that poor or unconsolidated formation will exhibit low compressive strength. This can be less than 1000 pounds per square inch. However, a well consolidated reservoir formation can be altered by degradation of the matrix as a result of acid stimulation treatment and steam flooding. *Acid stimulation* is a process carried out around the wellbore of the reservoir formation to enlarge the pore spaces of the formation, while *steam flooding* is a method of enhanced oil recovery whereby oil can be recovered as a result of thermal processes such that steams are generated from the top (surface) and injected into the reservoir via specially distributed wells. The importance of these two approaches is to recover most of the oil and gas from the reservoir. Activities such as acid stimulation and steam flooding degrade the matrix of the formation which can lead to sand production during the production of oil and gas.

2.3.3 Increase in Water Production

Increase in water production during production of oil and gas from the reservoirs may lead to the following effects (Essam and Walley, 2007):

2.3.3.1 Chemical Reaction

The destabilization of formation water in oil and gas reservoirs leads to sand production. Formation water within the oil and gas reservoirs exists in a state of chemical equilibrium in the original environment. However, if formation water within the reservoir migrates to another environment which is different from the original environment, due to change in temperature, density, or active ion concentration of the formation water in the new environment, a new chemical equilibrium will be attained. For example, if quartz (SiO_2), which is one of the

common minerals found in sandstone reservoirs, comes into contact with new formation water, they will break loose from each other.

2.3.3.2 Capillary Pressure

Capillary pressure tends to hold sand grains together within the oil and gas reservoirs. The intrusion of water will facilitate sand production. Saturation of the reservoir rock with low water content indicates high pressure from the capillary while high water saturation of the reservoir rock signifies a low pressure capillary, and complete absence of water indicates no capillary pressure among the reservoir rock grains. At this point in time, only a single liquid phase exists. When high water saturation exists between the reservoir rock grains, the capillary pressure will collapse and the bonds between grains will break off; this will always lead to the production of sand from the reservoir.

2.3.3.3 Wettability Effect

The flow of water within oil and gas reservoirs destabilizes the fines that exist within them and also provides a good path for transport. The intrusion of water in the reservoirs causes sand or rock fines to flow, depending on their wettability. The majority of the fines are water wet; therefore, the intrusion of water will cause the reservoir formation fines to be transported.

2.4 Single-Phase Liquid Flow

Liquid single-phase flow is distinguished by a laminar flow regime and a turbulent flow regime; however, the boundary that exists between these regimes cannot be defined perfectly. Shear stress from fluid acting on the pipe wall is very important in determining the amount of energy required to maintain the desired flow within the pipe. Experimentally, all fluid flows within a cylindrical pipe are dependent on the Reynolds number (Re); *Reynolds number* can be defined as the ratio of inertia force to viscous force. It also determines if a flow will exist as laminar or turbulent. Equation 2-1 depicts the Reynolds number:

$$Re = \frac{\rho u_f D}{\mu} \quad (2-1)$$

where ρ represents fluid density, D is the pipe diameter, u_f is the mean fluid velocity and μ the fluid viscosity.

Laminar flow can be identified or occur at the Reynolds number that is smaller than 2300 while turbulent flow will occur at the Reynolds number that is above 4000. *Transition flow* is the flow that exists between laminar flow and turbulent flow (between 2300 and 4000).

2.4.1 Laminar Flow

The laminar flow regime is a flow regime in which the fluid particle exhibits movement in layers or laminas. In this type of flow, a layer of fluid will glide regularly over an adjacent layer by molecular interchange of momentum. In a laminar flow pattern, particles of the fluid tend to move in layers of straight parallel paths. The governing law of laminar flow identifies shear stress in relation to the angular deformation rate (i.e., the product of fluid viscosity and velocity gradient): Equation 2-2 depicts shear laminar.

$$\tau_{\text{laminar}} = \mu \frac{du}{dy} \quad (2-2)$$

where τ is shear stress.

2.4.2 Turbulent Flow

This can be described as the uneven motion or movement of the fluid particle, with a disordered transverse interchange of momentum. The fluid particles in this regime tend to move in an apparently disordered fashion in every direction. Turbulence is greatly initiated by the irregularity of fluid particles, which transfer mass, momentum and energy from stream to stream.

2.4.3 Viscous Sub-Layer in Turbulent Flow

If fluid enters a rounded pipe with no initial disturbance, the velocity of the particles will be uniform across the diameter except for an exceedingly thin film at the wall. Velocity near the wall is always equal to zero. But as the flow progresses down the pipe, there will be changes in the velocity profile because

of the growth of a laminar boundary which continues until the boundary layer from the opposite sides meet at the axis and then there is fully developed laminar flow. As the boundary layer increases in thickness, a point is reached where a transition occurs and the boundary layer becomes turbulent. The turbulent boundary layer generally increases in thickness much more rapidly, and soon the two from opposite sides meet at the pipe axis and there is then a fully developed turbulent flow. No turbulence will occur next to the wall of the pipe because the velocity is zero in a near smooth solid boundary region. Therefore, immediately adjacent to a smooth wall, there will be a laminar or viscous sub-layer within which the shear is due to viscosity alone. The laminar sub-layer is extremely thin, i.e. only a few hundredths of a millimetre. It has great effect because of the steep velocity gradient and $\tau_{laminar}$. The viscous effect becomes negligible at a distance from the wall, but turbulent shear becomes large. The boundary layer in the rounded pipe is shown in Figure 2-2.

The height or thickness of the laminar sub-layer can be calculated using equation 2-3 (King et al., 2001):

$$\delta_{lam} = 62D \left(\frac{DV_{sl}\rho_L}{\mu_L} \right)^{-0.88} \quad (2-3)$$

where V_{sl} is liquid superficial velocity, ρ_L is liquid density and μ_L is liquid viscosity.

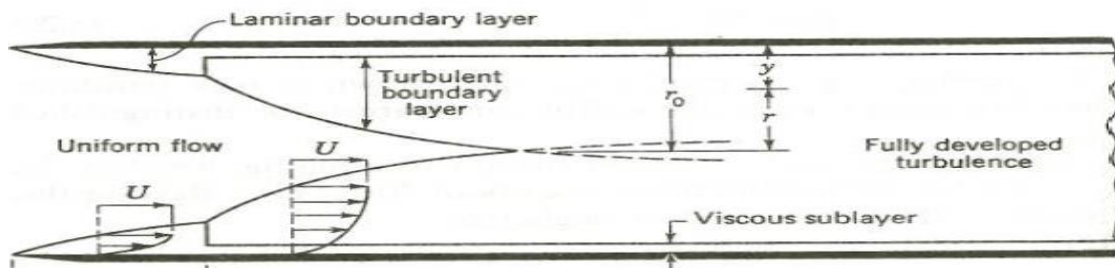


Figure 2-2: Boundary layer in a pipe (Daugherty et al, 1989)

2.5 Multiphase Flow

Multiphase flow can be defined as the concurrent flow of two or more material mixtures of different states, such as gas-liquid, gas-solid, liquid-solid or gas-liquid-solid in a pipe. Multiphase flow behaves differently compared to single phase flow because it is more complex. In multiphase flow, different phases will separate due to density difference. Furthermore, due to differences in the densities and viscosities of each phase, viscous resistances at the wall are different. The phases in multiphase flow tend to travel at different velocities. The gas-liquid multiphase can be classified into different flow regimes due to the different behaviours of gas with liquid in the pipeline. Furthermore, gas-liquid-solid regimes are called *flow patterns*. This section discusses in detail the gas-liquid multiphase flow variables that are crucial to sand transportation in horizontal pipelines, such as liquid hold-up, flow regimes and superficial velocities.

2.5.1 Liquid Superficial Velocity

In a gas-liquid phase flow regime, the liquid superficial velocity (V_{sl}) is the velocity that liquid has when it occupies the total cross-sectional area of the pipe. It can be expressed as equation 2-4:

$$V_{sl} = \frac{Q_L}{A} \quad (2-4)$$

where Q_L is the real liquid flow rate at the pipe condition (m^3/s) and A is the cross sectional area of the pipe (m^2)

2.5.2 Gas Superficial Velocity

Gas superficial velocity, (V_{sg}) is the velocity that gas will have when it occupies the total cross-sectional area of the pipe and is represented thus:

$$V_{sg} = \frac{Q_G}{A} \quad (2-5)$$

where Q_G is the real gas flow rate at the pipe condition (m^3/s) and A is the cross sectional area of the pipe (m^2)

2.5.3 Mixture Velocity

The mixture velocity (V_m) is the sum of liquid and gas superficial velocities. It is denoted as equation 2-6:

$$V_m = V_{sl} + V_{sg} = \frac{Q_L}{A} + \frac{Q_G}{A} \quad (2-6)$$

The actual fluid flow rate Q_T can be defined as

$$Q_T = Q_G + Q_L \quad (2-7)$$

then V_m becomes equation 2-8:

$$V_m = \frac{Q_T}{A} \quad (2-8)$$

2.5.4 Hold-Up

Hold up of a phase can be defined as the fraction of the pipe volume occupied by specific phase (for example gas or liquid).

2.5.5 Liquid Hold-Up

Liquid hold up is the original volume of the liquid phase when it is flowing in a pipe or fraction of the pipe occupied by the liquid.

2.5.6 Void Fraction

Void fraction is the *in situ* gas volume fraction in the pipe. It can also be defined as the volume occupied by the gas phase in a multiphase flow relative to the total mixture of the multi-components present in the pipe.

If the fractions of the pipe occupied by liquid and gas are H_L and H_G , then the real or actual liquid and gas velocities are given by equations 2-9 and 2-10 respectively:

$$V_L = \frac{Q_L}{H_L A} = \frac{V_{sl}}{H_L} \quad (2-9)$$

$$V_G = \frac{Q_G}{H_G A} = \frac{V_{sg}}{H_G} \quad (2-10)$$

When the liquid and gas velocities are equal, it is called *no slippage* ($V_L = V_G$)

$$\frac{V_{sl}}{H_L} = \frac{V_{sg}}{H_G} \quad (2-11)$$

2.6 Gas-Liquid Flow Regime

When gas and liquid flow at the same time (simultaneously), the gas and liquid are separated into different phases called flow patterns or regimes. Flow regimes in the pipes depend on the flow rate of gas and the liquid, physical properties of the fluid, pipe diameter and inclination of the pipes (Barnea et al., 1980; Mandhane et al., 1974; Taitel and Duckler, 1976).

The classifications of gas-liquid flow systems to regimes permit each of them to be treated separately so that a good and accurate model can be developed. In the history of the classification of two-phase flow regimes, they are classified by visual observation during experiments using transparent pipe. Furthermore, gas-liquid flow regimes can also be determined by the measurement and estimation of fluctuations of the normal flow variables, such as gas void fraction (Barnea et al., 1980; Costigan & Whalley, 1997; Vince and Lahey, 1982) or pressure fluctuation (Matsui, 1986).

Hubbard and Dukler (1966) determined flow regimes based on the spectra distribution of wall pressure fluctuations in horizontal and near horizontal pipelines. They classified flow regimes into dispersed, separated, and intermittent flows. However, their classifications do not distinguish gas-liquid flow regimes into stratified, annular flow, or dispersed liquid and dispersed flow regimes. Different gas-liquid flow regimes that exist in the horizontal pipelines are discussed below.

2.6.1 Flow Regimes in a Horizontal Pipe

When gas and liquid flow simultaneously in a horizontal or near horizontal pipe, the flow structures that occur, and are common in multiphase horizontal or near horizontal pipes, are shown in Figure 2-3 and can be classified into the following flow regimes below:

2.6.1.1 Dispersed Bubble

This flow regime occurs in horizontal pipes at a very high liquid velocity and low gas velocity. The gas flows occur as small bubbles within a continuous liquid flow. There is no uniformity in the gas bubbles, which mostly flow at the upper portion of the pipe due to the *buoyancy effect*. The bubbles' relative velocities are due to the difference in density between the gas and the liquid. *Disperse flow* can also be described as the flow regime that occurs at a high flow rate, in such a way that the flow of the fluid introduces turbulence that causes a thorough and homogeneous mixture of liquid and gas in a pipeline.

2.6.1.2 Stratified Smooth Flow

This flow structure occurs at a lower flow rate of liquid and gas. The gas phase and liquid phase segregate in the flowline by gravitational force in such a way that gas travels in the upper part of the pipe and the liquid phase flows in the lower part of the pipe; the interface between gas and liquid is smooth.

2.6.1.3 Stratified Wavy Flow

In this flow regime, at increased gas velocity and low liquid flow rate, ripples will form on the liquid phase. The liquid will mount or climb the pipe wall to form a curved sickle-like shape (crescent). The level at which the liquid phase mounts the surface of the pipe and the height of the wave of the liquid phase depends on the gas superficial velocity. Sometimes some of the liquid phase will separate from the wave to form a liquid film and travel some distance within the gas core

before being deposited into the moving liquid. As the gas velocity increases, the gas-liquid interface of the stratified smooth flow regime becomes wavy

2.6.1.4 Plug Flow

This flow regime in a horizontal pipe is an intermittent flow with moderate liquid superficial velocity and low gas flow rate. The majority of the gas travels as large bubbles dispersed inside a continuous liquid phase. Liquid plugs are mostly free from gas bubbles and separated partially by elongated bubbles. Plug flows are like slug flows but the bubbles in plug flows are small and travel slowly unlike the slugs where the bubbles travel fast.

2.6.1.5 Slug Flow

This flow regime occurs when the gas flow rate increases. The interface grows larger and covers the cross section of the pipe. The liquid plug becomes aerated with small entrained bubbles within the liquid phase. The bubbles in the liquid coalesce to form larger bubbles which intermittently bridge some of the pipe length. The flow structure of this regime is complex. It can also be described as the flow regime that occurs when the amplitude of the waves transiting along the liquid phase is large enough to bridge the top of the pipe. It is distinguished by a series of liquid plugs separated from one another by large gas pockets.

2.6.1.6 Annular Flow

In annular flow, the liquid phase flows as a film around the pipeline wall in such a way that the gas core with high velocity that may contain entrained liquid droplets is surrounded by a liquid film. The liquid film at the lower part of the pipeline is

usually thicker when compared with the liquid film that occurs at the top of the pipe. This is dependent on the liquid and gas flow rate.

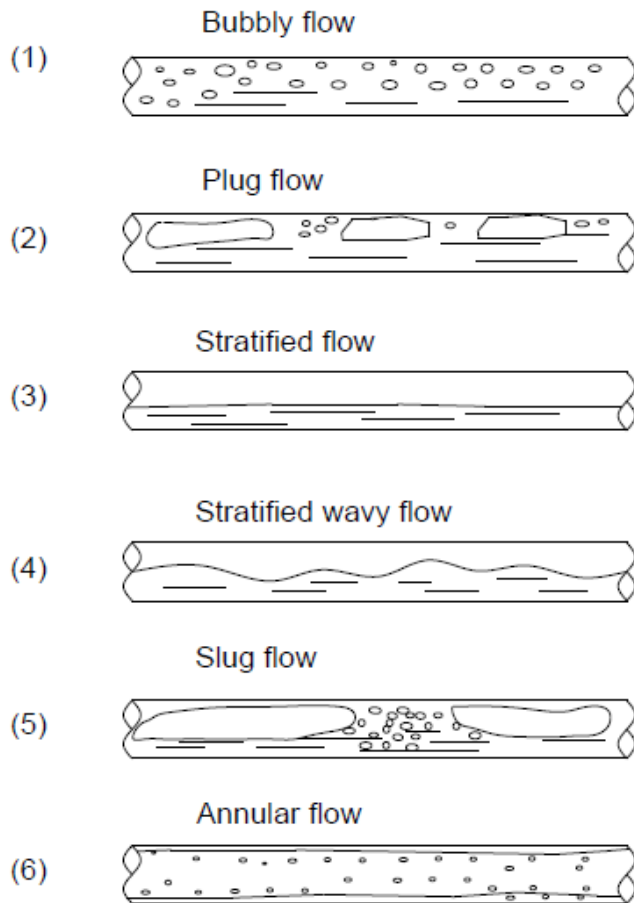


Figure 2-3: Flow regime in horizontal pipe (Perez 2007)

2.7 Flow Regime Maps

A flow regime map can be defined as a graphical representation of known flow rates or superficial gas and liquid velocities which are introduced as a graph and also as the flow pattern observed in order for boundaries to be produced when one flow configuration transits to another. Many researchers have in the past devised different flow regime maps. Each of these flow regime maps is different due to the parameters plotted on the axes and the flow direction, such as upwards, downwards, inclined, horizontal and near horizontal. These flow regime maps are developed based on theoretical analyses and experimental data.

2.8 Study of Sand Transport in Pipelines

2.8.1 Forces Acting on a Sand Particle in Liquid Flow

The movement of a single particle, such as sand in a liquid within the pipe as a suspension, is influenced by different body forces as shown in Figure 2-4. These forces are (1) Gravity (2) Buoyancy (3) Lift and (4) Drag force. The forces of gravity and buoyancy are constant, while lift and drag forces change with flow conditions, which are dependent on fluid inertial and viscous forces. At low fluid flow rates, particles will settle at the bottom of the pipeline to form a layer of sediment due to the predominance of forces of gravity and buoyancy. Sand particles settle at the bottom of the pipe and form a layer of stationary bed at the lowest fluid flow rate. In order for particles to be suspended from the stationary bed, the forces acting on a single particle must be such that the total sum of the buoyancy, lift and drag forces is greater than the force of gravity ($\text{Drag} + \text{Lift} + \text{Buoyancy} > \text{Gravity force}$).

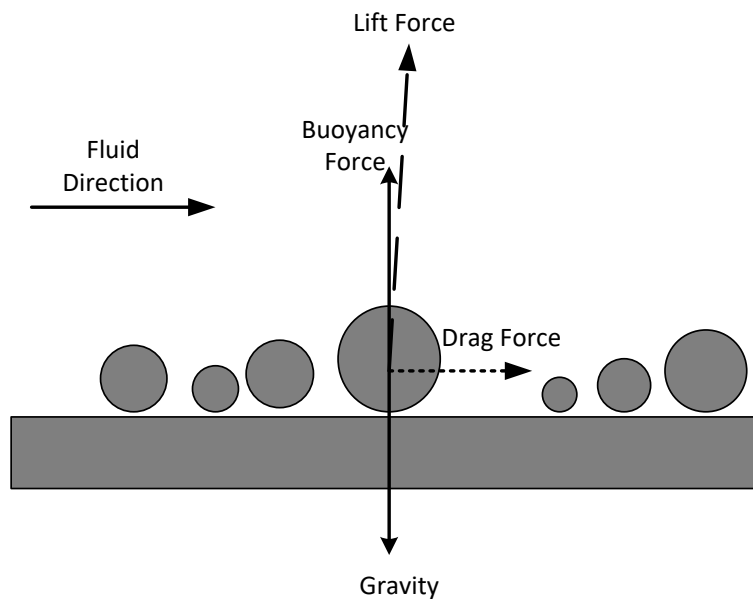


Figure 2-4: Forces acting on a sand particle in a flow (Chanson,1999)

- **Force due to gravity F_G**

The body force of a particle in a suspension due to gravitational acceleration is the solid particle volume and density, as expressed in equation 2-12:

$$F_G = \rho_P g V_P \quad (2-12)$$

where ρ_P is the particle density and V_P is the volume of a single particle in a fluid.

- **Force due to buoyancy F_B**

Buoyancy force on a particle in a fluid acts in the opposite direction to gravity force. When a solid particle is submerged in a fluid, it experiences buoyancy effect (Archimedes law). Buoyancy effect reduces the weight of the particle in a carrying fluid. The particle's submerged weight is due to the buoyancy and gravitational effects on the solid particle immersed in the fluid. Buoyancy force is expressed as equation 2-13:

:

$$F_B = \rho_L g V_P \quad (2-13)$$

where ρ_L is the liquid density and V_P is the volume of a single particle.

- **Drag Force F_D**

Drag force is the resistive force acting on the particle when moving through a fluid. A submerged particle in a fluid experiences drag when the surrounding fluid moves relative to a solid particle. The fluid in which the particle is submerged delivers additional force onto the particle. The drag force acts in the direction of the relative velocity between the fluid and the solid particle. Drag force is denoted by equation 2-14:

$$F_D = \frac{1}{2} \rho_L C_D u_p^2 A_b \quad (2-14)$$

where C_D is the co-efficient for drag, while A_b is the particle area projected in the direction of motion and u_p represents the velocity of the particle relative to the velocity of the fluid.

- **Lift force F_L :**

The lift force is the force that opposes the settling force on the particle. It occurs because a grain is in the zone of steepest velocity gradient and the velocity at the base of the grain is considerably less than that at the top. In accordance with Bernoulli's principle (which specifies an inverse relationship between velocity and pressure), there is an upward declining pressure gradient which tends to lift the grain off the bed.

$$F_L = \frac{1}{2} \rho_L C_K u_p^2 A_b \quad (2-15)$$

where C_K is the lift co-efficient and u_p represents the velocity of the particle.

2.8.2 Particle Settling Velocity

The velocity at which particles settle down according to the force of gravity in the fluid at rest is called *particle settling velocity*. Different particles behave differently when settling and their behaviour can be classified into three regimes or settling conditions (laws) based on the particles' Reynolds numbers. The particle Reynolds number is denoted as equation 2-16:

$$Re_p = \left(\frac{d_p \rho_L u_p}{\mu_L} \right) \quad (2-16)$$

where d_p is the particle diameter and u_p the particle velocity.

The three regimes or settling conditions (laws) based on particle Reynolds numbers are denoted as equations 2-17, 2-18 and 2-19. Particle settling velocity depends on several factors: viscous drag, effect of gravity and the forces acting on the particle.

Stoke's Law:

For $Re_p < 1$

$$u_t = \frac{gd_p^2(\rho_P - \rho_L)}{18\mu_L} \quad (2-17)$$

where u_t is the particle settling velocity.

Intermediate's Law:

$$1 < Re_p < 10000$$

$$u_t = \left[\frac{2g}{27} \left(\frac{\rho_P - \rho_L}{\rho_L} \right) \right]^{5/7} \frac{\rho_L^{3/7} d_P^{8/9}}{\mu_L^{3/7}} \quad (2-18)$$

Newton's Law:

$$Re_p > 1000$$

$$u_t = 1.73 \sqrt{d_P g \left(\frac{\rho_P - \rho_L}{\rho_L} \right)} \quad (2-19)$$

2.9 Factors Affecting Sand Transportation

In order to accurately predict sand transportation in multiphase flow, some important factors must be taken into consideration:

1. Sand properties in single phase liquid and multiphase flows (such as sand particle size, sand particle shape, particle size distribution and density).
2. The properties of the fluid in which the sand is transported. This can be termed as *medium property*: fluid viscosity and fluid density.
3. Fluid flow rate (average velocities of both the liquid and gas in which the particle is transported).
4. Pipeline properties (orientation): length, diameter, inclination.
5. Sand concentration.

2.9.1 Sand Concentration

According to Durand (1953) and Yan (2010), energy consumed per unit mass of solids transported at certain flow conditions depends on sand concentration.

Several studies had been made of the transportation of solid in water to determine and explain the sand concentration effect on sand transportation in pipes (Durand and Condolios 1952; Yan, 2010). Sand concentration increase tends to result in higher energy consumption in transporting sand particles from one point to another and also tends to increase the frictional pressure loss. The sand concentration effect on the MTC is an interesting subject in the petroleum industry. Very few models consider the effect of concentration of solids in the multiphase flow system (gas-liquid). For the purpose of this study, 50lb/1000bbl to 500lb/1000bbl were used and can be classified as low sand concentration. Stevenson and Thorpe. (1999) explained that the concentration of sand encountered in the oil and gas industry is between 5lb/1000bbl and 50lb/1000bbl volume fraction. However, at the shutdown or during maintenance, sand concentration could increase to the range of 200lb/1000bbl to 500lb/1000bbl. Experimental work from Najmi et al. (2014) confirms that increase in the concentration for the same particle size tend to increase the critical velocity or minimum transport velocity of the particle size.

2.9.2 Particle Size or Diameter

Sand particle size is one of the important parameters that tend to influence the MTC of sand transport in both single phase (liquid) and multiphase (gas-liquid). Solid particle size has a significant impact on the transport velocity; critical or minimum transport velocity increased steeply with an increase in solid particle size or diameter up to 600 microns, in research carried out by Durand and Condolios (1952). Further increases in solid particle diameter tend to increase critical velocity for 0.02 solid v/v gradually. However, the critical velocity between 0.05 and 0.15 solid v/v tends to decrease slightly and then flattens as the solid particle increases. Data regarding the effect of sand particle size or particle diameter on sand transport at MTC in multiphase flow are limited in the literature. An investigation into sand particle transport by Angelsen et al. (1989) in a stratified flow for 100, 200 and 400 microns' particle diameter in a 4-inch pipe showed that more energy is required to transport larger diameter sand particles than to transport small particles in a stratified flow regime. The research carried

out by Thomas (1962) and Stevenson et al. (2001) on particle size effects in a viscous sub-layer explained that some particles are larger than the viscous sub-layer while some are smaller. The investigation from these authors showed that more energy is needed to transit particles smaller than viscous sub-layer height while little or less energy is required to transport larger particles above the laminar sub-layer height. Furthermore, research carried out by Najmi et al. (2014) also established that an increase in particle size or diameter tends to increase the minimum transport velocity of sand or particles in multiphase flow (stratified flow).

2.9.3 Viscosity of Fluid

One of the parameters or factors affecting particle transport in single phase (liquid) and multiphase (gas-liquid) flow is the carrier fluid's viscosity. This parameter, among others, is most conflicting among authors. The literature review of the viscosity effect on particles shows that studies related to the viscosity effect of carrier fluids on particle transport in both multiphase and single phase flows are limited, have not been well studied and there are conflicting reports. Some of the studies report that an increase in the viscosity of the carrier fluid tends to increase the minimum transport velocities while some report opposite effect.

Yan (2010) reported that the sand minimum transport velocity increased as the carrier fluid viscosity increases (water, oil 7 and 20cP) at turbulent flow. However, at laminar flow, when the viscosity is higher than 105cP, the minimum transport velocity decreases as the carrier fluid viscosity increases. Yan (2010) explained that shear force acting on the particles from the liquid increases and high viscous fluid tends to decrease the settling velocity of sand particles. Furthermore, Yalin and Karahan (1979) reported that carrier fluid viscosity tends to increase MTC.

In multiphase flow, Oudeman (1993) investigated the effect of carrier fluid viscosity on particle transport and the changes in viscosity up to 7cP. He reported that the difference in sand transport in pure water and viscosified water is limited; he related this small difference to the fact that the viscosified water has less power to erode the sand bed, despite the fact that it can transport the particles

easily when they are in suspension. Najmi et al. (2015) investigated particle transport in a liquid carrier of viscosity 3cP and 10cP and concluded that critical sand transport velocity increases with increasing carrier fluid viscosity. He also explained that at constant liquid flow rate or velocity, higher gas flow rate or velocities are needed to transport sand particles.

2.9.4 Pipeline Orientation

Angelsen et al. (1989), Danielson (2007), and Shook and Roco (1991) all concluded that minimum transport velocity of particles increases slightly (of the order of 10%) for inclined (uphill) flows at angles beneath +15 degrees in particle-water (slurry) systems; however, Yan's (2010) experimental investigation showed no clear difference between horizontal and inclined orientations. He explained that this could be as a result of the sand concentration investigated in his experimental work. He established that the sand concentration used in his work was very low compared to the previous work being carried out on slurry systems. Yan's (2010) investigation also showed that in sand-water flow, there is little effect observed in sand transport in 2-inch and 4-inch pipes of the same pipe orientation. He explained that in sand-air-water flow, the sand transport behaviours in a slug body were the same as those encountered in horizontal flow; however, backward movement of sand particles were observed within the liquid film until particles were transported by another slug body.

2.10 Sand Transport Models in Pipelines

Sand transportation in horizontal pipes has four main regimes which are dependent on the fluid flow rate in near horizontal or horizontal pipelines. Figure 2-5 indicates liquid-sand flow regimes in horizontal pipes. Sand transportation models in the pipes are classified into two in this study: (1) Sand transport models in single phase liquid and (2) Sand transport models in air-liquid. The former are summarised in Table 2-6, the latter in Table 2-5.

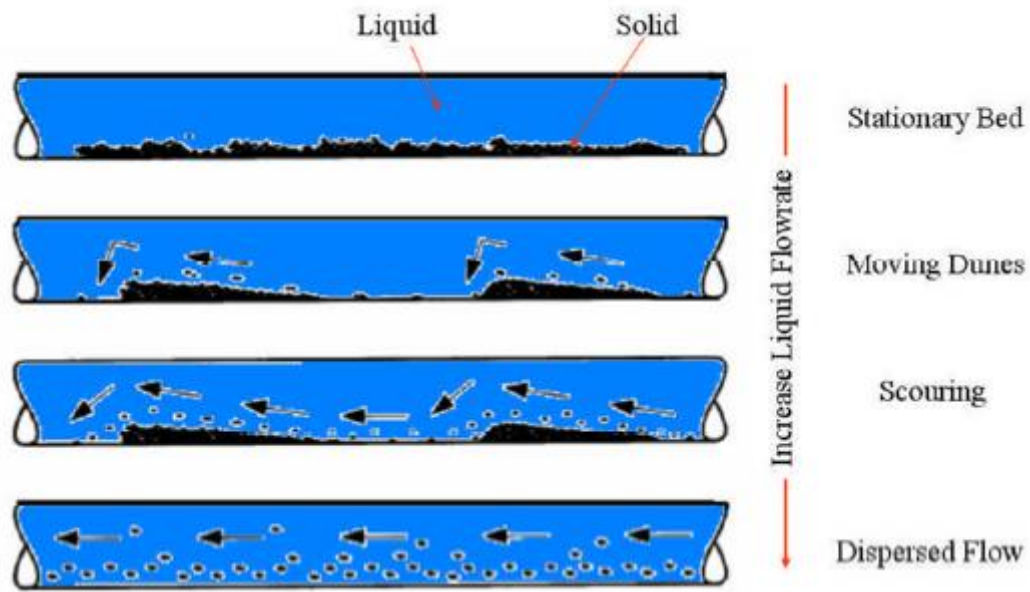


Figure 2-5: Liquid-sand flow regimes in horizontal pipe (Crowe 2006)

2.10.1 Stationary Bed

Stationary sand beds form when the liquid velocities transporting sand in horizontal pipelines are at their lowest. A stationary bed of sand is a stable bed when there is no movement of sand particles on the pipe bottom. Further decreases in the velocity of the fluid will cause a stable sand bed to reach a stable bed height.

2.10.2 Moving Dune

Further increases in the flow rate of the fluid will cause the stable stationary bed to break up into sand dunes with the particles of sand rolling from behind the dunes to the front of them.

2.10.3 Scouring

As the velocity of the fluid further increases, most of the sand particles will be rolled along the surface of the dunes and also transported as scouring

2.10.4 Dispersed

At very high flow velocity, sand particles become dispersed in liquid phases in the pipelines.

2.11 Definitions of Sand Transport Velocities

The prediction of minimum transport velocities for sand in oil and gas pipelines is very important in the design and operation of oil and gas pipelines prone to sand production. This is because deposition of sand in pipelines will wreak havoc on the entire production system, therefore requiring the operating companies to spend a huge amount of money to rectify any damages caused by sand deposition. In the literature, many correlations are available to estimate hydraulic slurry MTC (velocity). These correlations were developed based on the different definitions of minimum fluid velocity needed to prevent the formation of beds, and differences in the mechanisms of solid particle transport. For these reasons, different definitions have been proposed by different authors in the literature to explain the velocity needed for the transportation of solid particles in pipelines. Some of these transport velocities are defined below.

2.12 Saltation Velocity

This is the minimum fluid velocity needed to keep solid particles moving after being picked up and not coming to rest (Gomes and Mesquita, 2014).

2.13 Pick-Up Velocity

This is the fluid velocity needed to set solid particles moving which are formerly at rest. (Hayden et al., 2003).

2.14 Incipient Motion Velocity

This is the velocity needed in transporting a single solid particle at the bottom of the pipe, formerly at rest (Chanson, 1999).

2.15 Suspending Velocity

This is the minimum fluid velocity at which all solid particles are lifted and remain suspended in moving fluid.

2.16 Deposit Velocity

This is the velocity at which the solid particles initially suspended in the fluid settle at the bottom of the pipe.

2.17 Critical Velocity

This is the lowest fluid velocity that separates out the transformation from the solid particles settling at the bottom of the pipeline to the solid particles that are fully in suspension (Oroskar and Turian, 1980).

2.18 Minimum Transport Velocity or Minimum Transport Condition (MTC)

This is the mean stream velocity needed to avert the gradual gathering of a layer of stationary or sliding particles on the bottom of the horizontal pipe (Thomas, 1962).

2.19 Sand Transport in Liquid Flow System

2.19.1 Thomas (1962)

Thomas (1962) described minimum transport velocity as the “mean stream velocity needed or required to prevent the gathering of a stationary layer of particles or sliding particles on the bottom of the horizontal pipe”. *Terminal settling velocity* is the velocity that a particle has in the state of equilibrium. In this state, the sum of the force of gravity, buoyancy force and drag force are equal to zero. According to Thomas (1962), the minimum transport velocity is always enough to avert a longitudinal concentration gradient, which means particles congregate into islands or slowly sliding mounds at the bottom of the pipeline. Thomas (1962) takes into consideration the ratio of the terminal velocity to friction velocity (u_t/u_0^*), the thickness of the laminar sub-layer, and buffer layer with turbulent core, to be

the vital factors that affect the vertical distribution of suspending particles or solids in a fluid (liquid) flow stream.

He generated a particle characteristic map which was based on friction velocity, terminal velocity law region, buffer layer, turbulent core, particle Reynolds number and laminar sub-layer. The map co-ordinates are the ratio of the terminal velocity to friction velocity (u_t/u_0^*), and Reynolds number in terms of friction velocity. The ratio of the terminal velocity to friction velocity connotes the settling tendency of particles to the fluctuation of the turbulent core. These provide the force that maintains particles as suspension, while the particle Reynolds number in terms of friction velocity represents pipe wall vicinity fluctuation. A value of 0.2 was considered to determine if solids will be conveyed as a suspension or as a concentrated layer moving through the lower portion of the pipe. If (u_t/u_0^*), <0.2, the particulate phase will be conveyed in the suspension, while if (u_t/u_0^*), >0.2, the particulate phase will be conveyed in a layer at the bottom of the pipe.

Flow regime I in Figure 2-6 represents particles that are less than the height of the laminar sub-layer, in suspension, and which settle according to Stoke's law. This flow regime was investigated by experiments with particle concentration that varied from 0.01 to 0.17 (solid volume fraction), and particle diameters between 60 microns and 78 microns. A correlation was developed based on flow regime I (Equation 2-20):

$$u_0^* = \left\{ 100u_t \left(\frac{\nu}{d_p} \right)^{2.71} \right\}^{0.269} \quad (2-20)$$

where d_p is particle diameter, u_0^* is friction velocity, ν is kinematics viscosity and u_t is particle settling velocity.

Flow regime II in Figure 2-6 represents solid particles that are transported predominantly at the bottom of the pipe:

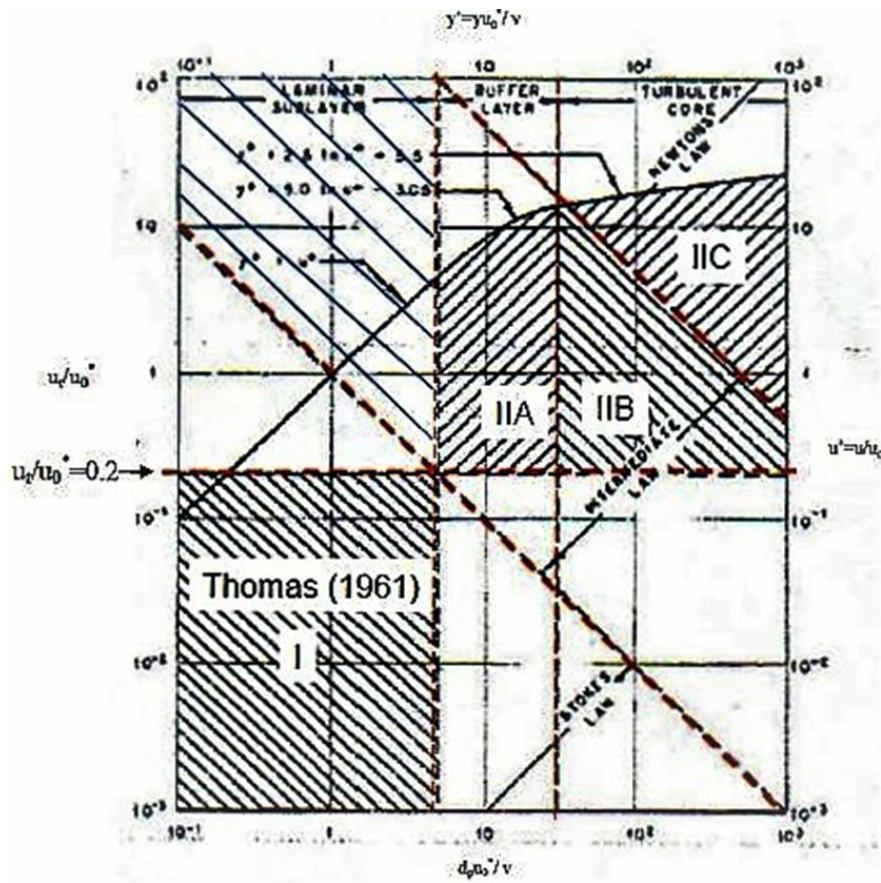


Figure 2-6: Classification of particle flow regimes (Thomas 1962)

IIA: These are particles that settle according to the Law of Intermediate, and they are less than the height of the buffer layer, but greater than the laminar sub-layer.

IIB: These are particles which are larger than the thickness of the buffer zone and settle according to the Law of Intermediate.

IIC: These are particles which settle according to Newton's Law and are larger than the thickness of the buffer layer.

The correlation developed for Flow Regime II by Thomas (1962) based on dimensional analysis and correlation from previous works is shown as equation (2-21):

$$u_0^* = \left\{ 0.204 u_t \left(\frac{\nu}{d_p} \right) \left(\frac{\nu}{D} \right)^{-0.6} \left[\frac{\rho_p - \rho_L}{\rho_L} \right]^{-0.23} \right\}^{0.714} \quad (2-21)$$

where D is the pipe diameter, ρ_p is particle density and ρ_L liquid density.

Thomas (1962) also proposed a correlation for the concentration correction. This was based on the data obtained from the experimental work on a 1-inch test facility and other data. He discovered that the friction velocity at MTCs under infinite dilution and concentration dependence is proportional to the square root of volume fraction for all the concentrated liquid-solid suspensions.

$$u_c^* = u_0^* \left[1 + 1.2 \left(\frac{u_t}{u_0^*} \right)^{0.33} \sqrt{V_f} \right] \quad (2-22)$$

where V_f represents solid fraction and u_c^* is the friction velocity (m/s) for a certain sand concentration

2.19.2 Oroskar and Turian (1980)

Oroskar and Turian (1980) described minimum transport velocity as the minimum fluid velocity that demarcates the transformation of the solid particles that settle at the bottom of the pipeline from the solid particles that are fully in suspension. *Force balance* and *turbulence theory* were used to develop a critical velocity model that accounted for solid particle suspension in slurry.

$$\frac{V_c}{\sqrt{g d_p (s-1)}} = \left[5 C_v (1 - C_v)^{2n-1} \left(\frac{D}{d_p} \right) \left(\frac{\frac{D \rho_L \sqrt{g d_p (s-1)}}{\mu}}{ED} \right)^{\frac{1}{8}} \right]^{\frac{8}{15}} \quad (2-23)$$

Equation (2-23) was further modified by Oroskar and Turian (1980) by regression analysis based on 357 experimental data points. The modified equation becomes equation (2-24):

$$\frac{V_c}{\sqrt{g d_p (s-1)}} = 1.85 C_v^{0.1536} \left((1 - C_v)^{0.3564} \left(\frac{D}{d_p} \right)^{-0.378} \frac{D \rho_L \sqrt{g d_p (s-1)}}{\mu_L} \right) ED^{0.30} \quad (2-24)$$

where s is the ratio of solid to liquid density, C_v concentration volume,

$$ED = \frac{2}{\sqrt{\pi}} \left[\frac{2}{\pi} \gamma e^{-4\gamma^2/\pi} + \int_{\gamma}^{\infty} e^{-4\gamma'^2/\pi} \delta\gamma' \right] = \text{fraction of eddies having velocities}$$
 greater than settling velocity and $\gamma = \frac{\text{hinder-settling velocity}}{\text{critical velocity}}$

The ED proposed in equation (2-24) was found to be close to unity (> 0.95).

2.19.3 Davies (1987)

A theoretical equation based on turbulence theory for critical velocity (V_c) was developed by Davies (1987). According to him, critical velocity is the velocity needed to put particles in suspension in horizontal pipe flow. Davies' (1987) correlation, equation 2-25, is similar to Durand and Condolios (1952) correlation. Davies (1987) calculated the force of sedimentation and the eddy fluctuation force. In his theory, he proposed that the force of sedimentation was equal to the eddy fluctuation force when all the particles are in suspension by eddies in the flow.

$$\frac{\pi}{6} d_p^3 \Delta \rho_G (1 - C_v)^n = \rho_L (V')^2 \left(\frac{\pi d_p^2}{4} \right) \quad (2-25)$$

where n depends on Reynolds number Re and V' eddy fluctuation velocity.

The eddy fluctuation velocity (V'), equation 2-26 (Davies, 1987), needed to suspend particles in the fluid was derived from equation 2-25 (Davies, 1987).

$$V' = 0.82 (1 - C_v)^{\frac{n}{2}} d_p^{\frac{1}{2}} \left[\frac{\Delta \rho_G}{\rho_L} \right]^{\frac{1}{2}} \quad (2-26)$$

In order to relate eddy fluctuation velocity to critical velocity, Davies (1987) calculated eddy fluctuation velocity in terms of eddy length and power dissipated per unit mass of the fluid (P_d). He assumed that eddies which were equal to the particle sizes can dissipate energy that will suspend the particles in the fluid while eddies that are smaller than the size particles will not be able to suspend the particles that are larger than them. Larger eddies do not exist close to the bottom of the pipe where some particles are suspended.

$$(V')^3 = P_d d_p \quad (2-27)$$

$$P_d = \frac{2fV_c^3}{D} \quad (2-28)$$

where P_d is the power dissipated per unit mass of the fluid and f is the Fanning friction factor $\left(\frac{0.079}{Re^{\frac{1}{4}}}\right)$

$$V' = (0.16)^{\frac{1}{3}} v^{\frac{1}{12}} V_c^{0.92} d_p^{\frac{1}{3}} D^{-0.42} \quad (2-29)$$

Merging equations (2-25) and (2-29) with the turbulence correction factor by Davies $\left(\frac{1}{1+3.64C_v}\right)$ gives the critical velocity required to suspend particles in fluid equation 2-30 (Davies, 1987).

$$V_c = 1.08(1 + 3.64C_v)^{1.09}(1 - C_v)^{0.55n_v-0.09} d_p^{0.18} \left[\frac{2g\Delta\rho}{\rho_L}\right]^{0.54} D^{0.46} \quad (2-30)$$

2.19.4 Gillies et al (1997)

The Meyer-Peter and Müller (1948), correlation was extended by Gillies et al. (1997). This correlation models solid transport in single phase liquids, but can apply to the transport of solids in multiphase flow systems. The model resembles that of Oudeman's model, as the equations used are comparable

$$\varphi_s = \frac{Q_s}{\left(\frac{\rho_p}{\rho_L}\right) \sqrt{d^3 g \left(\frac{\rho_p}{\rho_L} - 1\right)}} \quad (2-31)$$

$$\varphi_l = \frac{\rho_L g d_p \left(\frac{\rho_s}{\rho_L} - 1\right)}{\tau} \quad (2-32)$$

$$\varphi_s = \left[\frac{4}{\varphi_l} - 0.188 \right]^{1.5} \quad (2-33)$$

where Q_s is the volumetric flow rate per bed width.

Gillies et al. (1997) developed a correlation in two phase flow by relating the interfacial stress used by the Meyer-Peter equation to pressure gradient in order to generate flow regimes.

The pressure gradient is expressed as equation 2-34:

$$\frac{-dP}{dz} = \frac{\tau_w + \tau_i S_i}{A} \quad (2-34)$$

where w denotes the width of the sand bed, S_i is the pipe perimeter, τ_i is the interfacial stress, and A denotes the cross-sectional area of the pipe.

They also generated a correlation for the calculation of the viscosity of the mixture as equation 2-35:

$$\frac{\mu_m}{\mu} = 1 + 2.5C_v + 10.0C_v^2 + 0.00273 \exp(16.6C_v) \quad (2-35)$$

where C_v represents mean *in situ* solids volume fraction, μ_m = viscosity of flow mixture, μ = viscosity of carrier fluid.

Experimental data of three-phase flow (sand/air/liquids) for which a stationary deposit was present in horizontal pipelines with a 2-inch diameter were used to develop this model. The liquids employed in performing these experiments were water (Density = 998 kg/m³ and Viscosity = 1.0cP) and oil (Density = 872 kg/m³ and Viscosity = 78cP). The liquid superficial velocity ranged from 0 to 1.2 m/s. Sand particle size ranged from 10 to 200 microns and GVF between 0 and 0.8 were used. The axial pressure gradient and delivered concentration were measured in terms, or as a function, of mean velocity and *in situ* concentration.

Gillies et al. (1997) concluded that the injection of gas had little influence on the ability of solid transportation at low liquid superficial velocity when the flow was laminar. However, turbulent flow enhanced solids' transport. They also concluded that the correlation from Lockhart-Martinelli provides reasonable estimates of the axial pressure gradient in the turbulent liquid flow regime at GVF below 0.5 on sand transport in air-liquid and sand transport in liquid only respectively.

2.20 Sand Transport in Liquid-Gas Flow System

2.20.1 Piete Oudeman (1993) Correlation

Oudeman carried out several experiments of sand transport in two phase flow (air/water). In the experiments, three methods were used to check the transportation and deposition of injected sand particles into two phase flow (air-water): *visual observation*, *sampling* and *acoustic detection*. Furthermore, he was able to come up with a correlation by defining two dimensionless parameters:

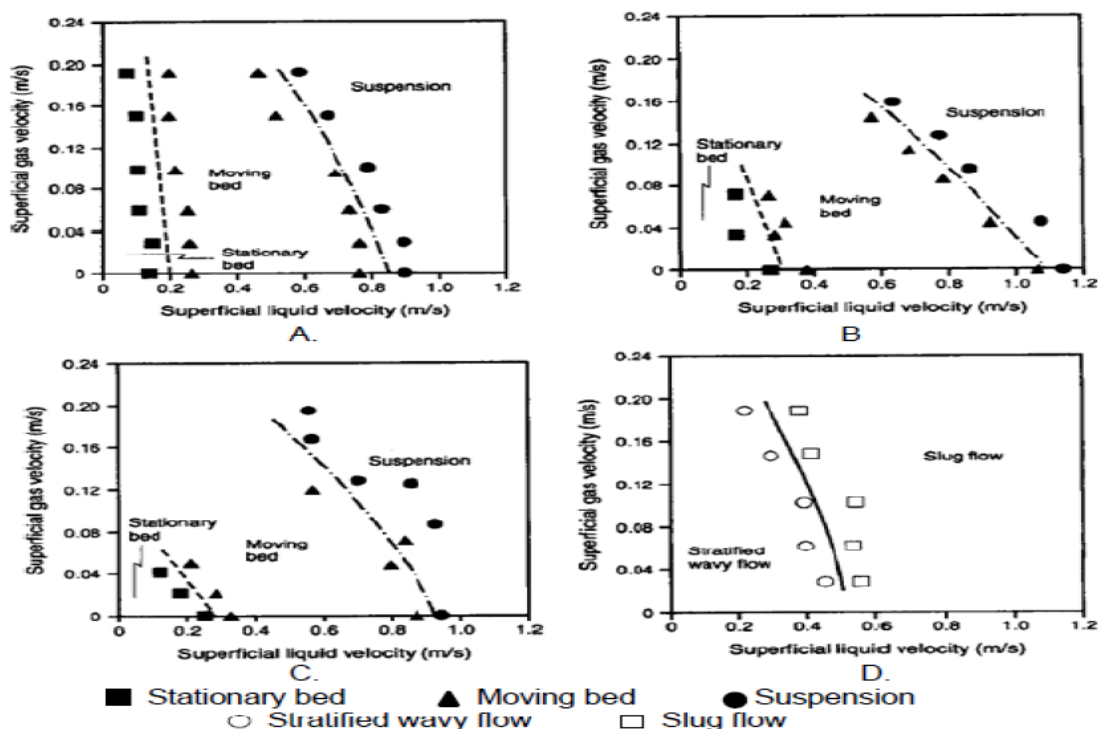


Figure 2-7 Oudeman's sand flow regime

(1) Fluid flow rate and (2) Sand transport rate. Experiments were conducted in such a way that he started with a stationary bed and moved to other sand transport regimes or modes by increasing gas and liquid velocities. Through his observation, he classified sand transportation in two- phase flow (air-water) into three modes and regimes:

(1) Stationary bed, which occurred at the lowest liquid velocity and the injected sand was found to have no movement at the bottom of the pipe at this mode or regime.

(2) Moving bed, which occurred at some established critical velocity, which can be as a result of pipe diameter, sand grain size, viscosity, and liquid and solid density. At this regime or mode, sand grains will start to travel originally as dunes and at a greater velocity the sand grains tend to travel as a sand streak.

(3) Suspension: In suspension, particles will be entrained in the fluid above the sand bed with an increase in the velocity and at some critical velocity, the whole sand bed disappears with no sand grain found at the bottom of the pipe.

Oudeman conducted experiments in 0.07m internal diameter test section and used 150 microns (0.15mm) to 300 microns (0.30mm) and 690 microns (0.69mm) particle sizes to determine the clustering effect of smaller particle sizes with gas volume fractions of 0% to 20%, and liquid velocities between 0.1 and 0.2m/s. In order to monitor the effect of viscosity, water was viscosified with carboxymethyl cellulose EHV to 7cP. No concentration of sand was mentioned in the experiment and also the effect of surface tension was determined by adding surfactant.

The following conclusions were drawn from the experiment through observations:

(1) The velocity at the transition of a moving bed to a suspended region occurred at higher value (superficial velocity), when compared with the transiting velocity of the stratified wavy flow to slug flow which occurred at lower superficial velocity. This shows that the sand transport mode is not influenced directly by the gas/liquid flow regime.

(2) The disparity between sand transported in viscosified water and pure water is limited. This originates from the fact that viscosified water having an increased sand carrying capacity, is less able to sweep away or erode the sand bed.

(3) In the transition of the stationary bed to moving bed, gas fraction has little influence. This is normally occurring in the stratified wavy regime, where the slip between the gas and liquid phases is so great that the real liquid velocity hardly increases by the presence of the gas phase.

(4) In the transition of a moving bed to suspension, the fraction of the gas has a moderate influence.

Oudemans correlated sand transport rate φ_{sa} (dimensionless) with liquid flow rate φ_{Li} (dimensionless) successfully.

$$\varphi_{sa} = \frac{Q_d}{\sqrt{d_p^3 g \left(\frac{\text{Solid density}}{\text{Liquid density}} - 1 \right)}} \quad (2-36)$$

$$\varphi_{Li} = \frac{U_b^2}{gd_p \left(\frac{\text{Solid density}}{\text{Liquid density}} - 1 \right)} \quad (2-37)$$

Q_d is the grain transport rate, this is in grain volume per second per metre of sand bed, d_p , represents particle size, g represents acceleration due to gravity, and U_b is the drag velocity at the sand bed.

2.20.2 Stevenson et al (2000, 2002)

Stevenson et al. (2000, 2002) investigated an isolated particle in different flow patterns (intermittent and stratified flow) of multiphase flow; this represents the low particle loading. In 1996, Stevenson and Preston stated that sand hold-up in specific oil and gas flow-lines must be less than 0.01v/v. Therefore, it is important

to consider the behaviour of an isolated particle, i.e., very low solids concentration rather than moving beds of sand.

Stevenson and Thorpe 2002 studied particle transport in smooth stratified flow regimes. Their experiments were performed in 0.04m and 0.07m pipes at an angle of inclination of 1° and 2° to the horizontal. The velocity of the particles was investigated by tracking particles at random over a distance of 5.72m with a stop watch. This was done by checking particles' transit time between the start point and finish point, which is marked at the end of the pipe. A particle which is spotted by an observer at random is followed from the upstream of the pipe to the downstream of the pipe. The particle sizes studied in these experiments were of sizes 150 microns to 1180 microns. The effect of viscosity was also investigated, which ranges from 1cP to 4.8cP. Table 2-1 shows the properties of particles used in the experiment.

Table 2-1: Stevenson and Thorpe (2002) experimental particle properties

Material	Sieve Diameter (Micron)	Density (kgm⁻³)	Circularity
Coarse Sand	1000-1800	2540	0.883
Medium Sand	425-600	2540	0.913
Fine Sand	150-300	2540	0.91
Olivine	707-841	3300	0.871
Lead Shot	1000-1800	11200	0.92

Stevenson and Thorpe 2002 also developed a correlation to predict threshold velocity (critical velocity) of particles in smooth stratified regimes

$$w_c = 3.43d^{-0.034}V_L^{0.34}[g(s-1)D_f]^{0.33} \quad (2-38)$$

The following were observed during the experiment:

- Average velocity of liquid stratum is linearly proportional to particle velocity.
- Large particles transit quicker than small particles.

- Particle velocity decreases with increase in liquid viscosity. This is because as the liquid viscosity increases, particles tend to submerge deeper into the viscous sub-layers, which tends to reduce the velocity of the particles.
- The proposed correlation under-predicts the velocity of the lead shot. This is due to the rounded shape of the lead shot which enhanced the mobility compared to the angular shape of olivine and sand particles.

2.20.3 King and Hill (2001)

Minimum transport pressure drop model was developed by King et al. (2001). This model is an extension of the Thomas (1962) model for the prediction of MTCs in two phase flow (air-water). King et al. (2001) derived a relationship relating the friction velocity to the pressure gradient based on the principle of whether the particle diameter is larger or smaller than the thickness of the viscous sub-layer. Thomas (1962) derived equations for the friction velocity of particle diameters smaller or greater than the laminar or viscous sub-layer thickness. These equations are classified as *upper* and *lower* models.

The equation for friction velocity for particles smaller than the laminar sub-layer at infinite dilution (i.e., a single particle), for Thomas Lower model, is stated as equation (2-39).

Lower Model

$$u_0^* = \left\{ \{100u_t \left(\frac{\nu}{d_p}\right)^{2.71}\}^{0.269} \right\} \quad (2-39)$$

where d_p is particle diameter, u_0^* is friction velocity, ν is kinematics viscosity and u_t is particle settling velocity.

The equation for the friction velocity of the particles larger or greater than the laminar sub-layer, classified as the upper model, is given in equation (2-40):

Upper Model

$$u_0^* = \left\{ 0.204 u_t \left(\frac{V}{d_p} \right) \left(\frac{V}{D} \right)^{-0.6} \left[\frac{\rho_p - \rho_L}{\rho_L} \right]^{-0.23} \right\}^{0.714} \quad (2-40)$$

where D represents the pipe diameter, ρ_p is the particle density and ρ_L denotes liquid density.

Associated friction pressure drop at MTC was calculated from the friction velocity by King et al. (2001) in the fluid, instead of minimum transport velocity. The friction pressure drop equation is stated as equation (2-41). Friction Pressure Gradient Equation for Minimum Transport Condition:

$$\frac{\Delta P}{\Delta X_{MTC}} = \frac{4\rho_L (u_c^*)^2}{D} \quad (2-41)$$

Pressure gradient at MTC unit is (Pam^{-1}).

If the actual pressure gradient is greater than the pressure gradient at the MTC, the particles will be transported.

2.20.4 Danielson (2007)

Danielson (2007) developed a correlation for critical solid-liquid velocity based on the data obtained from the experiment. He reported that the minimum transport velocity in solid/liquid flow had no angle of dependence on the range of angles investigated. Favourable results were obtained for both sand bed height and measured pressure drop. This model was based on the assumptions that there is no slip velocity between liquid and sand, which is constant over a wide range of velocities, and also that the surface roughness is augmented by particle diameter. The model is given as equation 2-42:

$$V_c = K v^{-\frac{1}{9}} d_p^{\frac{1}{9}} (gD(s-1))^{5/9} \quad (2-42)$$

where V_c is critical carrying velocity and s is the ratio of the particle to the density of the fluid carrier.

Danielson's (2007) experiments were conducted by using the following materials and conditions: Pipe diameter: 0.069m, maximum pipe inclination: -1.35° to

+4.0°, total loop length: 215m, test section length:15m, liquid phases: Exxsol D80 and water, sand diameter: 280 and 550 microns, gas phases: air, nitrogen, SF₆, superficial water velocity: 0.01-2m/s oil superficial velocity: 0.01-2m/s, gas superficial velocity: 0.01-8m/s and maximum pressure: 8bar .

A sand slurry feeder was used to inject sand into a pipeline of 15m test section. Exxsol D80 and water were used as the carrier liquid, while the gas phase is air.

The following conclusions were drawn by Danielson (2007):

- The model for critical solid-carrying velocity V_c matches the results obtained from the experiment and can be used for prediction of the bed height based on the assumption that the slip velocity between the sand and carrier fluid is kept at V_c for all liquid rates.
- Gas rate had no impact on the slip velocity between the carrier liquid and the sand.
- The OLGA 2000 code was used in order to estimate the liquid velocity and an estimation of sand hold-up, by modelling sand as a pseudo-phase with a slip velocity equal to V_c . There was a good match to data that were obtained for both liquid/solid and gas/liquid/solid experiments using this method.

2.20.5 Soepyan et al (2013)

Soepyan et al. (2013) developed methodologies to improve threshold velocity prediction accuracy for solid transport for a specific operating condition by using a multi-steps approach. In order to test the performance of the methodology, 164 experimental data points were used as the operating condition while the velocity prediction, calculated by using the three highest ranked fine-tuned models, was compared against experimental velocity. The following multi-steps methodologies were proposed by Soepyan et al. (2013): (1) Data clustering component, (2) Model parameter fine-tuning, and (3) Model screening and protocol.

- **Data Clustering Component**

In the data clustering component, each operating condition was selected based on the experimental database most similar to them. This also uses three distance functions: (a) Volumetric concentration $d_{\text{conc},i}$ (b) Pipe inclination angle distance $d_{\text{angle},i}$ and (c) Euclidean distance d_i . The *volumetric concentration distance* ensures that only experimental data for flows which are at low particle concentration are included in the reduced experimental data base. *Pipe inclination angle distance* was quantified to ascertain that the experimental data bases for horizontal flow only were collected, while *Euclidean distance* was calculated in order to collect the experimental data that were closest to the operating condition.

Equations (2-43) and (2-44) were used to calculate the volumetric concentration and pipe inclination angle for each datum point:

$$d_{\text{conc},i} = / \bar{c}_i - \bar{c}_0 / \quad (2-43)$$

$$d_{\text{angle},i} = / \bar{\theta}_i - \bar{T}_0 / \quad (2-44)$$

where c_i is the concentration of datum point i , c_0 represents the operating condition at datum point i , θ_i denotes the pipe inclination angle at datum point i , and T_0 connotes the operating condition at datum point i .

The normalized values for both pipe inclination and volumetric concentration were calculated using equation (2-45):

$$\bar{x} = \frac{/x_i - \min(/x_0, \dots, /x_{N_{\text{data}}}/)/}{\max(/x_0, \dots, /x_{N_{\text{data}}}/) - \min(/x_0, \dots, /x_{N_{\text{data}}}/)} \quad (2-45)$$

where $i = 0, \dots, N_{\text{data}}$, x_i is the value of the independent variable of datum point i : the particle diameter d_p , hydraulic diameter, fluid viscosity etc., x_i represents normalized value for the independent variable.

- **Mode Parameter Fine-tuning Module**

This improves the accuracy of the model by using selected experimental data to adjust the parameters of the model. Equation 2-46 (Soepyan et al., 2013) was used to fine-tune. This is called *optimisation formulation*. The importance of this is to minimise the error sum of the square (E_{SSj}) of the model.

$$E_{SSj} = \sum_{i=1}^{n_{data}} (V_{calc,i,j} - V_{exp})^2 \quad (2-46)$$

$$V_{calc,j} = f(x_{m,i}, K_{lj}) \quad (2-47)$$

$$1 \leq l \leq K_j \quad (2-48)$$

$$1 \leq i \leq n_{data} \quad 1 \leq l \leq K_j \quad (2-49)$$

where j represents the indices for model parameters, n denotes the indices for independent variables, the l th parameter of model j is K_{lj} , n_{data} is the number of data points in the reduced data base, $V_{calc,i,j}$ is the velocity prediction of model j for datum point i , V_{exp} is the experimental velocity for datum point i , K_j connotes number of parameters in model j , and $x_{m,i}$ is the value of the m_{th} independent variable of datum point i . The non-negative of equation 2-46 (Soepyan et al., 2013) represents the prevention of inversion of dimensionless groups.

- **Model Screening and Ranking Protocol**

These methodologies rank the accuracy of the models for selected experimental data. Model screening protocol uses statistical analysis to annul any overestimated or underestimated models for the prediction of the threshold velocity of experimental data points in the reduced database, while model ranking

protocol ranks based on the velocity prediction accuracy of the remaining model. Modified adjusted $-R^2(R_{\text{mod,adj},j}^2)$ for each model j and slope m_j , of the best fitting line between the predicted velocity calculated by model j against experimental velocity and the intercept of the line set as the origin are the statistics used for model screening analysis. In order to calculate the modified adjusted R^2 statistics, equations 2-50 and 2-51 were used:

$$R_{\text{mod,adj}}^2 = 1 - \left(\frac{E_{\text{SS}j}}{T_{\text{SS,mod}}} \right) \left(\frac{n_{\text{data}} - 1}{n_{\text{data}} - n_{\text{indep}j} - 1} \right) \quad (2-50)$$

$$T_{\text{SS,mod}} = \sum_{i=1}^{n_{\text{data}}} V_{\text{exp},i}^2 \quad (2-51)$$

where $T_{\text{SS,mod}}$ is the modified total sum of square and $V_{\text{exp},i}$ is the experimental velocity datum point i .

According to Soepyan et al. (2013), the accuracy of the velocity predictions suggested by using the proposed methodologies were compared against Oroskar and Turian (1980) correlation and Mantz (1977) correlation. Based on the critical analyses and observations, the above suggested methodologies were far better and advantageous for velocity prediction when compared with Oroskar and Turian (1980) and Mantz (1977) correlations

2.20.6 Ibarra et al (2014)

Ibarra et al. (2014) investigated sand transport in stratified flow (air-water). The experimental work was carried out in a 4-inch diameter transparent horizontal test loop. Water and air were used as the fluid, while glass beads were used as the solid particle. The experimental test matrix is shown in Table 2-2:

Table 2-2 Experimental matrix

Variables	Range	Unit
Temperature	18-25	°c
Pipe inner diameter	0.0962	<i>m</i>
Sand volume fraction	0.0008-0.0048	<i>v/v</i>
Liquid superficial velocity	0.10-0.14	<i>ms</i> ⁻¹
Gas superficial velocity	5-11	<i>ms</i> ⁻¹
Particle diameter	211-297	<i>μm</i>
Slurry injection velocity	0.95	<i>ms</i> ⁻¹

Ibarra et al. (2014) classified sand flow regimes into three, in stratified flow. They are as follows:

Suspension: At higher mixture fluid velocity, particles are dispersed.

Moving bed: This occurs at lower fluid velocities. Particles tend to move as a sand bed and in this sand regime, the bed layer attains maximum packing concentration.

Dunes and Stationary bed: When the fluid flow rate is completely low, the moving particles come to rest and the bed size increases because of the deposition of sand particles from the upstream.

The MTC in this paper was defined as the transition between the stationary bed and the moving bed. The Oroskar and Turian (1980) model is extended to develop a new predictive model for sand minimum deposition velocity while the Chisholm (1967) liquid hold-up model was modified for the calculation of liquid hold-up and the liquid hold-up can then be used to calculate the actual liquid velocity at which sand is deposited.

$$\sqrt{\frac{V_{M,C}}{gd_p(\rho_p/\rho_{L-1})}} = 1.3277 \left(\frac{V_{sl}}{V_{M,C}} \right)^{-0.285} (1 - C_v)^{-35.490} \left(\frac{d_p}{D} \right)^{-0.378} N_{Re,c}^{0.09} \quad (2-52)$$

$$H_L = 1 - (1 - X^{0.8})^{-0.378} \quad (2-53)$$

Equation 2-53 was modified to 2-54

$$H_L = 1 - (1 - X^{1.06})^{-0.573} \quad (2-54)$$

2.20.7 Najmi et al (2014)

Najmi et al. (2014) investigated particle transport in low liquid loading with gas flow rate. They studied the effects of: particle shape, particle concentration, particle size and pipe size. In their experiment, however, the effect of viscosity was not studied. Najmi et al. (2014) conducted experiments by using two pipe diameters of 0.05m and 0.1m. The irregular and regular particles used in the investigation ranged from 20 microns to 350 microns with volume concentrations of 0.01% and 0.1%. The liquid used in the experiment is water. Table 2-3 shows the particle properties investigated in their experimental works:

Table 2-3: Najmi et al experimental particles properties

Particle	Nominal Diameter (Microns)	Density	Shape
Silica Sand	300	2650	Irregular
Silica Sand	150	2650	Semi-Round
Silica Sand	20	2650	Irregular
Glass Bead	350	2480	Round
Glass Bead	150	2480	Round
Glass Bead	73	2480	Round

According to them, the data obtained in the 0.05m pipe diameter were not within the low liquid loading because of the pumping capacity; however, the loading was still low. *Low liquid loading* can be defined as the ratio of volumetric liquid flow rate to volumetric gas flow rate at standard conditions. In the oil and gas industry, if the ratio is less than $1100 \frac{\text{m}^3}{\text{MMSm}^3}$, this is classified as low liquid loading. They determined the liquid flow rate for the experiments by measuring the time taken for specific volume loss from the tank, which was performed three times to ensure accuracy. The superficial velocities were calculated by using the average of those three measurements.

Fan et al.'s (2007) model was used to calculate the liquid hold-up in order to determine the actual sand deposition liquid velocity. According to Najmi et al. (2014), Fan et al.'s (2007) model was chosen because it was developed mainly for low liquid loading flow conditions.

Najmi et al. (2014) concluded the following:

1. It was discovered that critical velocity tends to increase with an increase in particle concentration and also the actual velocity of liquid slightly decreases with an increase in gas flow rate for both the 0.1% and 0.01% concentrations tested.
2. As the particle size increases, the critical actual liquid deposition or transport velocity increases, and also the difference in critical velocity between 20 microns and 150 microns of silica sand is larger than the difference between 150 microns and 300-micron silica sand. This means the difference in particle size increases the higher the critical actual liquid deposition or transport velocity.
3. The critical velocities for irregular shaped particles (sand) are higher when compared with the same concentration and particle size of spherically shaped particles (such as glass beads). According to Najmi et al. (2014), the small difference may be as a result of the irregularly shaped (sand) having a greater friction effect with the wall of the pipe while the regularly shaped particles (glass beads) have a tendency to roll faster.
4. Considering the pipe effect on critical velocity of particles, it was found that the critical velocity of particles in the 0.1m pipe diameter is higher than the critical velocity in the 0.05m pipe diameter. The differences in the results can be due to parameters such as liquid velocity and turbulence intensity, liquid hold-up and characteristics such as liquid film.

2.20.8 Dabirian et al (2015)

Dabirian et al. (2015) investigated sand transport in stratified wavy flow. A comprehensive analysis was undertaken in classifying different sand flow regimes that exist in stratified wavy flow. Furthermore, the effect of concentration and particle size on particle MTCs (velocity) were investigated. Dabirian et al. (2015) classified sand flow regime in stratified flow (multiphase flowline) into six different flow regimes: (1) Dispersed flow regime (2) Dilute solids on the wall (3) Solids concentrated on the wall (4) Moving dunes (5) Stationary dunes and (6) Stationary bed.

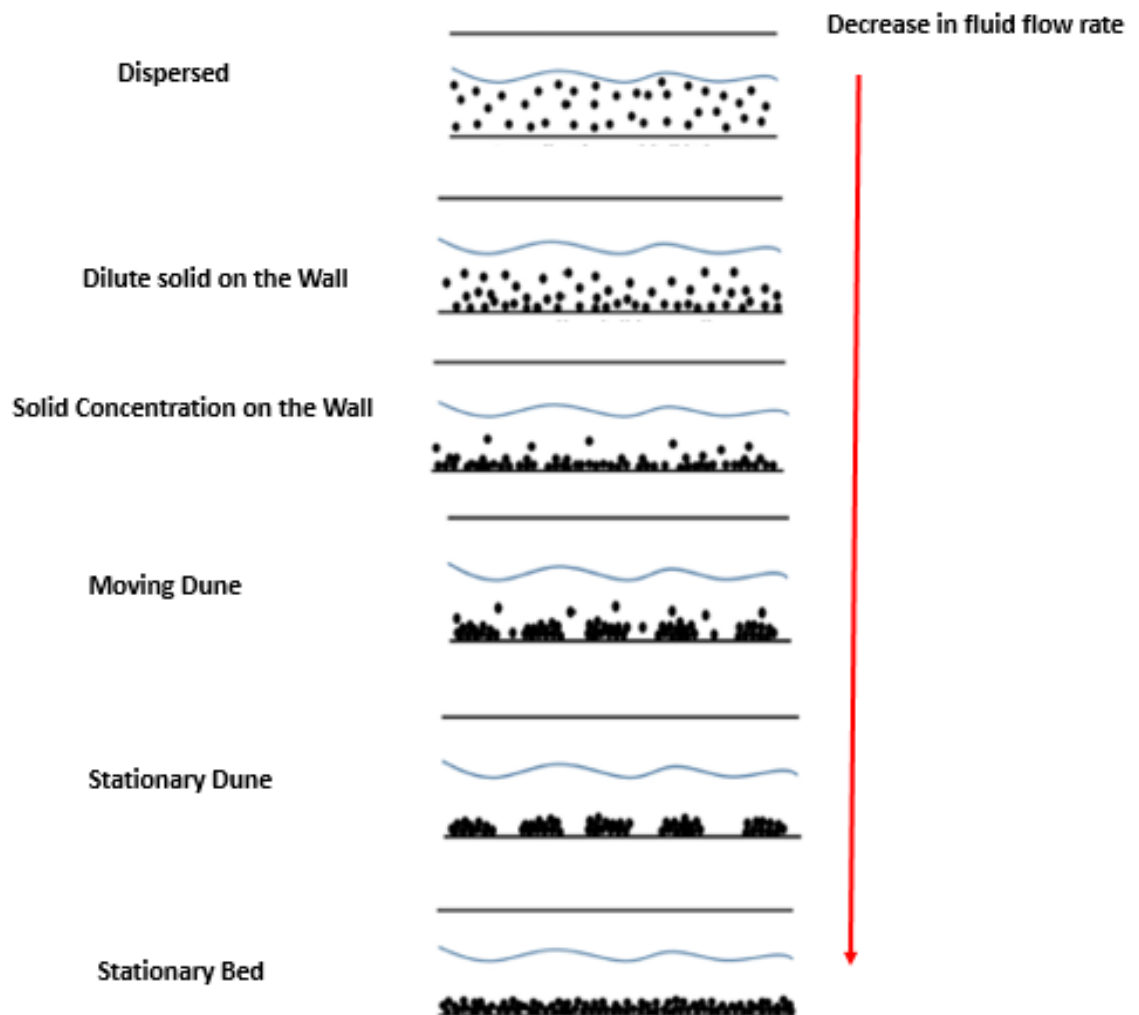


Figure 2-8: Sand flow regime in stratified flow (Dabirian et al, 2015)

- **Fully dispersed solid**

Fully dispersed solid occurs when particles are suspended at a high flow rate. The particles are fully suspended in the liquid phase having no contact with the bottom of the pipe.

- **Dilute solids on the wall**

In this sand flow regime, some of the particles that are transported will be dragged to the bottom of the pipe line and also roll. This is as a result of the effect of the moderate flow rate. In this sand flow regime, particle interaction ceases to exist.

- **Solids concentrated on the wall**

Solids concentrated on the wall occurs when the mixture flow rate in which the particles are transported decreases further. As a result of this decrease in the mixture flow rate, the particles tend to be more concentrated on the wall of the pipe. Particle interaction does exist in this type of sand flow regime and particles are also transported by pushing one another rather than rolling within the pipe.

- **Moving dunes**

Moving dunes exist when the waves create turbulence at the gas-liquid interface which tends to scatter the surface of the streak or moving bed and causes the streak or moving bed to break down into moving dunes at the bottom of the pipe. This sand flow regime occurs as a result of the slower mixture flow rate

- **Stationary dune**

Stationary dune occurs as a result of low mixture flow rates. The moving dunes stop moving. This sand flow regime is seen when a 2-D wave occurs at the gas-liquid interface.

- **Stationary bed**

In this sand flow regime, particles are deposited and remain at rest at the bottom of the pipeline.

The experimental work was investigated in a 4-inch polyvinyl pipe. Liquid hold-up, liquid velocity and pressure drop were measured. Water was used as the liquid phase, while air served as the gas phase. The solid particles used in this experimental work are glass beads with an average density of 2475 kg/m^3 . The diameter of the glass beads ranges from 45 microns to 600 microns. Table 2-4 depicts the test matrix:

Table 2-4: Experimental test matrix

Variables	Range	Units
Pipe inner diameter	0.096012	m
Particle density	2475	kgm^{-3}
Particle diameter	45-90,250 and 600	μm
Sand concentration	100-10000	ppm
Liquid superficial velocity	2.5 to 14	ms^{-1}
Gas superficial velocity	0.12	ms^{-1}

Dabirian et al. (2015) concluded the following:

- The minimum transport velocity increases with increased particle diameter.
- The minimum transport velocity also increases with increased particle concentration.

Table 2-5: Experimental research on solid-air-liquid flow

Reference	Pipe Diameter (m)	Particle Diameter (micron)	Sand particle range	Liquid and liquid Viscosity (cp)	Fluid phase	Particle Type	Correlation	C _v
Oudemans (1993)	0.07	150, 300 and 690		Water & viscosified water)	Sand in air/water 2-phases	Sand	$\varphi_{sa} = \frac{S}{\sqrt{d^3 g \left(\frac{\text{Solid density}}{\text{Liquid density}} - 1 \right)}}$ $\varphi_{Li} = \frac{U_b^2}{gd \left(\frac{\text{Solid density}}{\text{Liquid density}} - 1 \right)}$	/
King et al (2000)	0.0152	1,3,150,300		Water & Carboxy-Methyl cellulose	Sand in Air/water	Sand	$\frac{\Delta P}{\Delta X_{MTC}} = \frac{4\rho_{L(U_o)^2}}{g_c D}$	0.00005v/v
Danielson (2007)	0.069	280, 550		Exxsol D80 & water) 1	2-phases	Sand	$V_c = K v^{-\frac{1}{9}} d_p^{\frac{1}{9}} (gD(s-1))^{5/9}$	0.0002v/v
Yan et al (2010)	0.054	200,750	200-750	Water	Sand in Water and Air/water 2-phases	Sand	/	0.00005 v/v, 0.0002 v/v, 0.0005 v/v
Stevenson (2001 And 2002)		1010 and 512	512-1010	Water and Rheovis CR2	2-phases	Sand & Lead	$\frac{v_p}{U_l} = 0.95 \left[1 + \frac{U_{sg}}{U_{sl}} \right] - \left[1.38 \frac{U_{sg}}{U_{sl}} + 0.88 \sqrt{Fr_f} \right] * [N_{Re(f)} \sqrt{Fr_f} \left(\frac{d}{D} \right)^{1.5}]^{-0.180}$ $w_c = 3.43 d^{-0.034} v^{0.34} [g(s-1)D_f]^{0.33}$	

Table 2-6: Experimental research on solid-liquid flow

Reference	Pipe Diameter (m)	Particle Diameter (micron)	Correlation	Particle Type	C _v
Thomas (1962)		190~3800	$u_0^* = \left\{ 100u_t \left(\frac{v}{d_p} \right)^{2.71} \right\}^{0.269}$ $u_0^* = \left\{ 0.204u_t \left(\frac{v}{d_p} \right) \left(\frac{v}{D} \right)^{-0.6} \left[\frac{\rho_p - \rho_L}{\rho_L} \right]^{-0.23} \right\}^{0.714}$ $u_c^* = u_0^* \left[1 + 1.2 \left(\frac{u_t}{u_0^*} \right)^{0.33} \sqrt{V_f} \right]$		
Davies (1987)	Obtained from turbulent theory and other's data $V_c = 1.08(1 + 3.64C_v)^{1.09}(1 - C_v)^{0.55}n_v^{-0.09}d_p^{0.18} \left[\frac{2g\Delta\rho}{\rho_L} \right]^{0.54} D^{0.46}$				
Oraskar and Turian (1980)	$\frac{V_c}{\sqrt{gd_p(s-1)}} = 1.85C_v^{0.1536} \left((1 - C_v)^{0.3564} \left(\frac{D}{d_p} \right)^{-0.378} \frac{D\rho_L\sqrt{gd_p(s-1)}}{\mu_L} \right) ED^{0.30}$ <p>Obtained from turbulent theory and other's data v/v of 0.1~0.50</p>				

2.21 Pressure Drop and Liquid Holdup

2.21.1 Beggs and Brill (1973) Model

The semi-empirical unified model was developed by Beggs and Brill (1973). Beggs and Brill studied the effects of pipe inclination on the liquid hold-up and pressure loss in multiphase flow (gas-liquid flow). Steady-state energy balance was used to develop a model and simplified equations were generated with two independent variables (two-phase friction factor and liquid hold-up). The investigation showed that pipe inclinations have a strong effect on liquid hold-up. This may be due to the interaction of gravity with viscosity on the liquid phase. Froude number and input liquid content were the two variables used to generate equations for hold-up prediction. These two variables were plotted and the intersection area gives the flow regime map for a horizontal pipe. The prediction of the flow pattern map is as follows:

$$\begin{array}{ll} Fr < L_1 & \text{Stratified flow or Annular Flow} \\ L_1 < Fr < L_2 & \text{Intermittent} \\ Fr > L_1 > L_2 & \text{Distributed Flow} \end{array} \quad (2-55)$$

where,

$$\begin{aligned} L_1 &= \exp(-4.62 - 3.757T - 0.481T^2 - 0.0207T^3) \\ L_2 &= \exp(1.061 - 4.602T - 1.609T^2 - 0.179T^3 + 0.635 \times 10^{-3}T^5) \\ Fr &= \frac{V_m^2}{gd} \quad Fr = \ln(\lambda) \quad \lambda = \frac{V_m^2}{dg} \end{aligned} \quad (2-56)$$

Fr and λ are Froude numbers, and input liquid content V_{sg} , V_{sl} , and V_m are superficial velocities for gas, liquid and mixture, respectively.

Liquid hold-up in varied pipe inclinations can be calculated as:

$$H_L(\theta) = H_L(0) \left\{ 1 + C \left(\sin(1.8\theta) - \frac{1}{3} \sin^3(1.8\theta) \right) \right\} \quad (2-57)$$

where θ is the pipe inclination angle. The above equation is valid when $H_L(0) > \lambda$ and $1 \geq H_L(\theta) \geq 0$. Horizontal liquid hold-up, $H_L(0)$, is calculated in Table 2-7.

Table 2-7: Beggs and Brill (1973) liquid holdup

Horizontal Flow Pattern	Horizontal Holdup	C +	C –
Stratified or annular	$\frac{0.98\lambda^{0.4868}}{Fr^{0.0868}}$	$(1 - \lambda) \ln \frac{0.011N_{lu}^{3.539}}{\lambda^{3.768}Fr^{1.614}}$	$(1 - \lambda) \ln \frac{4.7N_{lu}^{3.539}}{\lambda^{0.3692}Fr^{0.5056}}$
Intermittent	$\frac{0.845\lambda^{0.5351}}{Fr^{0.0173}}$	$(1 - \lambda) \ln \frac{2.96\lambda^{0.305}N_{lu}^{0.0978}}{Fr^{0.4473}}$	Same as stratified or annular
Dispersed	$\frac{1.065\lambda^{0.5824}}{Fr^{0.0609}}$	0	Same as stratified or annular

N_{lu} is the liquid velocity number with an expression of $V_{sl}(\rho_l/\sigma g)^{0.25}$. Another parameter used to solve the pressure gradient equation is the two-phase friction factor, which is normalized with a no-slip friction factor obtained from single phase flow correlation. It is given as equation 2-58 (Beggs and Brill, 1973):

$$\frac{f_{tp}}{f_{ns}} = e^s \quad (2-58)$$

Pressure gradient is calculated based on the energy balance for the flowing fluids between two points. Given a steady-state mechanical energy balance, the total pressure shown in equation 2-59 (Beggs and Brill, 1973) is assumed to be the sum of the pressure drops due to gravity elevation, acceleration and friction loss:

$$-\frac{dp}{dz} = \left(\frac{\delta p}{\delta z}\right)_{el} + \left(\frac{\delta p}{\delta z}\right)_{acc} + \left(\frac{\delta p}{\delta z}\right)_f \quad (2-59)$$

The friction pressure is given in equation 2-60:

$$\left(\frac{\delta p}{\delta z}\right)_f = \frac{f_{tp} G_m V_m}{2Dg} \quad (2-60)$$

where G_m is the mixture mass flux rate, f_{tp} is the two-phase friction factor and V_m is the mixture superficial velocity.

The pressure loss due to the acceleration is usually related to kinetic energy and negligible for simplification in most cases; it is denoted as equation 2-61:

$$\left(\frac{\delta p}{\delta z}\right)_{acc} = -\frac{\rho_m V_m}{g} \frac{G_g}{\rho_G^2} \frac{d\rho_G}{dz} \quad (2-61)$$

where

$$\rho_m = [\rho_L H_L + \rho_G (1 - H_L)] \quad (2-62)$$

ρ_m is the *in situ* mixture density and G_g is the gas mass flux rate.

Similarly, pressure gradient due to elevation change is given as:

$$\left(\frac{\delta p}{\delta z}\right)_{el} = \rho_m g \sin\theta \quad (2-63)$$

It is found that these equations are applicable to any pipe inclinations. In a horizontal pipe when acceleration pressure is neglected, the pressure gradient is calculated only by the frictional loss with a two-phase friction factor.

The Beggs and Brill (1973) model is widely used in the petroleum industry. The model is simple, explicit and easy to be applied. In this model, as the flow conditions approach all liquid or gas, the hold-up and friction factor degenerate to single phase flow (condition). The validation of the model was through the large data bank obtained from accurate measurements. However, the extrapolation to other flow conditions needs to be tested because the correlations were generated using air and water phases and only two pipe diameters (1 and 1.5-inch).

2.21.2 Taitel and Dukler (1976) Model

Taitel and Dukler (1976) studied the physics of flow transition in multiphase flow (gas and liquid flow) and flow transition predictions were proposed based on a mechanistic model for different flow conditions. The mechanistic model is suitable and applicable for steady state flow and also Newtonian flow in slightly inclined pipes, i.e. $\pm 10^\circ$ and a horizontal pipe (0°). The algebraic equation form or

dimensionless map was used to present the transition mechanisms for each boundary condition. In order to validate this model for large diameter pipes and viscous liquid, more studies need to be carried out because the model has only been tested with data from small diameter pipes.

Analysis of stratified flow was undertaken using the model, by which an equilibrium liquid height is estimated. The momentum balance analysis on each fluid phase is as follows:

$$-A_L \left(\frac{dp}{dx} \right) - \tau_{WL} S_L + \tau_i S_i - \rho_L A_L g \sin \theta = 0 \quad (2-64)$$

$$-A_G \left(\frac{dp}{dx} \right) - \tau_{WG} S_G - \tau_i S_i - \rho_G A_G g \sin \theta = 0 \quad (2-65)$$

Eliminating pressure gradient from the left hand side of the equation, the combination of the momentum equation becomes equation 2-66

$$\tau_{WG} \left(\frac{S_G}{A_G} \right) - \tau_{WL} S_L + \tau_i S_i \left(\frac{1}{A_L} + \frac{1}{A_G} \right) - (\rho_L - \rho_G) g \sin \theta = 0 \quad (2-66)$$

where A_L and A_G are the liquid and gas cross-sectional areas and D is the pipe diameter. S_G and S_L are the gas and liquid perimeter in the pipe. It is shown that equation 2-66 is an implicit equation for liquid height h_L , in the pipe. The equation merges all the forces that act on the gas and liquid phase and also determines the height of the liquid phase in stratified flow. Shear stresses for gas-wall (τ_{WG}), liquid-wall (τ_{WL}) with liquid-gas, (τ_i) were determined in a conventional manner

$$\tau_{WL} = f_L \frac{\rho_L V_L^2}{2}, \quad \tau_{WG} = f_G \frac{\rho_G V_G^2}{2}, \quad \tau_i = f_i \frac{(V_G - V_L)^2}{2} \quad (2-67)$$

The interfacial, liquid and gas friction factors can be estimated as follows:

$$f_L = C_L (Re_L)^{-n}, \quad f_G = C_G (Re_G)^{-m}, \quad f_i = f_G \quad (2-68)$$

where $C_L = C_G = 16$ and $m = n = 1$ for laminar flow; $C_L = C_G = 0.046$ and $m = n = 0.2$ for turbulent flow. V_L , V_G are liquid and gas velocities. The model assumed a smooth interface ($f_i = f_G$) with small interface velocity ($V_i \ll V_G$). Non-

dimension parameters were adopted by Taitel and Dukler (1976) to seek the final solution for the liquid height h_L .

They are expressed as:

$$\tilde{h} = \frac{h_L}{D} \quad S_{L,G} = \frac{S_{L,G}}{D}, \quad \tilde{D}_{L,G} = \frac{D_{L,G}}{D}, \quad \tilde{A}_{L,G} = \frac{A_{L,G}}{D^2}, \quad \tilde{V}_{L,G} = \frac{V_{L,G}}{V_{sl,sg}} \quad (2-69)$$

The geometry parameters are:

$$\tilde{A}_L = 0.25 \left[\pi - \cos^{-1}(2\tilde{h}_L - 1) + (2\tilde{h}_L - 1) \sqrt{1 - (\tilde{h}_L - 1)^2} \right] \quad (2-70)$$

$$\tilde{A}_G = 0.25 \left[\pi - \cos^{-1}(2\tilde{h}_L - 1) + (2\tilde{h}_L - 1) \sqrt{1 - (\tilde{h}_L - 1)^2} \right] \quad (2-71)$$

$$\tilde{s}_L = \pi - \cos^{-1}(2\tilde{h}_L - 1), \quad \tilde{s}_G = \pi - \cos^{-1}(2\tilde{h}_L - 1), \quad \tilde{s}_i = \sqrt{1 - (2\tilde{h}_L - 1)^2} \quad (2-72)$$

Dimensionless parameters (X) from the Lockhart and Martinelli parameter and (Y), which indicates inclinations, emerge from the analysis. When these two parameters were substituted into the combined momentum equation, the final expression becomes equation:

$$X^2 \left[(\tilde{V}_L \tilde{D}_L)^{-n} \tilde{V}_L^2 \frac{\tilde{s}_L}{A_L} \right] - \left[(\tilde{V}_G \tilde{D}_G)^m \tilde{V}_G^2 \left(\frac{\tilde{s}_G}{A_G} + \frac{\tilde{s}_L}{\tilde{A}_L} + \frac{\tilde{s}_i}{A_L} \right) \right] - 4Y = 0 \quad (2-73)$$

$$Y = \frac{(\rho_L - \rho_G)g \sin \theta}{\left(\frac{dP}{dz} \right)_{GS}} \quad X^2 = \frac{\left(\frac{dP}{dz} \right)_{LS}}{\left(\frac{dP}{dz} \right)_{GS}} \quad (2-74)$$

where the LS and GS subscripts represent the single liquid and gas phases. Each $X - Y$ pair are equivalent to a particular value of $\frac{h_L}{D}$ for flow conditions of inclinations and pipe diameters, fluid properties, flow rates and so on, at stratified

flow. As soon as the liquid height is determined, stratified flow momentum equations can be obtained. When the gas or liquid flow rate changes, flow patterns tend to change and this leads to transition between stratified, wavy-stratified, slug and annular.

- Transition from stratified to non-stratified flow:

The instability of stratified flow in gas and liquid flows was investigated by Taitel and Dukler (1976) by the application of a simplified Kelvin-Helmholtz theory. At the inlet of the pipe, stratified flow was first observed; however, this becomes unstable as the wave is developed at the interface between the liquid and gas. This is due to the increase in gas flow rate. The wave continued to grow because the pressure in the gas phase over the wave decreased and a suction force is induced as a result of Bernoulli effects. The Kelvin-Helmholtz theory imparts stability for waves with infinitesimal amplitudes formed at the smooth interface. A simplified equation is developed and introduced with dimensionless parameters by Taitel and Dukler (1976):

$$Fr^2 = \left[\frac{1}{(1-\tilde{h}_L)^2} \frac{\tilde{V}_G^2 \frac{d\tilde{A}_L}{d\tilde{h}_L}}{\tilde{A}_G} \right] \geq 1 \quad (2-75)$$

$$Fr = \sqrt{\frac{\rho_L}{\rho_G}} \frac{V_{sg}}{\sqrt{Dg \cos \theta}} \quad (2-76)$$

$$\frac{d\tilde{A}_L}{d\tilde{h}_L} = \sqrt{1 - (2\tilde{h}_L - 1)^2} \quad (2-77)$$

- Transition from stratified to wavy-stratified flow:

The transition of stratified flow to wavy-stratified flow exists when gas superficial velocity is sufficient to create waves at the interface, though this is still lower than the gas velocity needed to cause the transition to non-stratified flow. Taitel and Dukler (1976) developed an expression based on the Jeffrey theory:

$$V_G \geq \left[\frac{4v_L (\rho_L - \rho_G) \cos \theta}{s \rho_G V_L} \right] \quad (2-78)$$

where, s is a sheltering coefficient which has a value of 0.01 used in the model. v_L is the liquid kinematic viscosity.

- Transition from annular to intermittent flow:

Slug flow comes into existence when the liquid height rises, such that the waves grow rapidly and form a blockage of flow. At a high gas velocity, the insufficient liquid that flows to maintain the liquid bridge is swept up around the inner pipe wall. This formed an annulus with appreciable gas entrainment. Taitel and Dukler (1976) suggested that the flow that develops in intermittent or annular only depends on the liquid level in the stratified equilibrium flow. Therefore, an expression for the transition above in which annular flow occurs is proposed:

$$\frac{h_L}{D} = 0.5 \quad (2-79)$$

The choice of constant value as a transition from intermittent to annular flow can be explained by the fact that as the wave with finite amplitude begins to grow, due to suction over the wave crest, the film adjacent to the wave supplies liquid and at this point a depression or trough will be formed. This will cause the wave to be sinusoid. Whenever the peak of the wave reaches the top, before the trough bridges the bottom of the pipe, slugs will occur as the passage of the gas is blocked. This occurs when the level of the wave comes above the centreline. However, if the liquid level comes below the centreline, which is the inverse, the formation of slugs will be averted.

- Transition from dispersed to intermittent:

This transition exists as a result of the high liquid flow rate with low gas flow rate. The occurrence of high liquid flow rate causes the gas pocket to be shattered into dispersed bubbles which are mixed with the liquid phase. This transition that took place came into existence as a result of turbulent fluctuations which are strong enough to overcome the forces of buoyancy and this tends to keep the gas at the

top of the pipe. The proposed expression by Taitel and Dukler (1976) is shown in equation 2-80:

$$V_L \geq \left[\frac{4A_G}{S_i} \frac{g \cos \theta}{f_L} \left(1 - \frac{\rho_G}{\rho_L} \right) \right]^{0.5} \quad (2-80)$$

2.21.3 Xiao et al. (1990) Model

Xiao et al. (1990) identified three major flow regimes' transition and were able to develop models that will predict pressure gradient and liquid hold-up for stratified flow (smooth and wavy), intermittent flow and annular flow. The proposed models were validated by a large data bank from both laboratory and field. Each of the models was also compared with other existing models and their performance with these other existing models is good, especially in the intermittent flow.

- Stratified flow model:

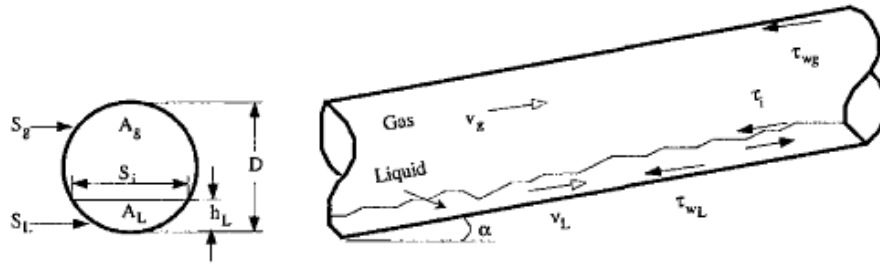


Figure 2-9: Stratified flow model (Xiao et al 1990)

The steady state one-dimensional two-fluid model approach is adopted to develop the model for stratified flow. Xiao et al. (1990) used forces balance and mass balance from each phase at the inlet and outlet of the control volume, which are considered in momentum and continuity equations. Pressure gradient is obtained by eliminating the interfacial shear stress:

$$-\left(\frac{dp}{dx}\right) = \left(\frac{\tau_{WL}S_L + \tau_{WG}S_G}{A}\right) + \left(\frac{A_L}{A}\rho_L + \frac{A_G}{A}\rho_G\right)g \sin \theta = 0 \quad (2-81)$$

where the shear stress at the gas wall, liquid wall and interface is evaluated as equation 2-82:

$$\tau_{WL} = f_L \frac{\rho_L v_L^2}{2}, \quad \tau_{WG} = f_G \frac{\rho_G v_G^2}{2}, \quad \tau_i = f_i \frac{\rho_G v_G^2}{2} \quad (2-82)$$

Xiao et al.'s (1990) work was based on the assumption that pressure gradient and velocity of both gas and liquid phases were the same, and also liquid phase hydrostatic gradient and surface tension. f_L and f_G represent liquid-wall and gas-wall friction factors respectively and f_i denotes the friction factor at the gas and liquid interfaces. Geometry relationship is used to derive the liquid hold-up and once the liquid height is determined, the liquid hold-up can be obtained as:

$$H_L = \frac{\theta - \sin\theta}{2\pi}$$

$$\theta = 2\cos^{-1}\left(1 - 2\frac{h_L}{D}\right) \quad (2-83)$$

- Intermittent flow model:

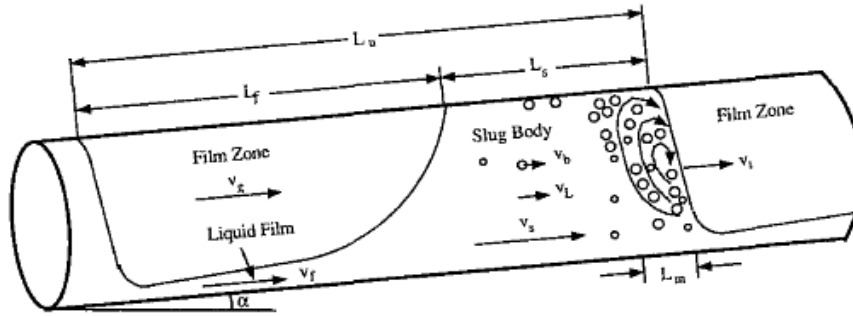


Figure 2-10: Intermittent flow model (Xiao et al. 1990)

The intermittent flow regime constitutes either a plug or slug region that fills the entire cross-sectional area of the pipe, which is separated by a gas pocket region that flows over the liquid film. The gas and liquid phase continuity equations in the entire slug unit are estimated, where an equilibrium liquid height is assumed. The momentum equations are built for the slug film region. The slug unit pressure gradient can be determined as follows:

$$\left(-\frac{dp}{dx}\right)_u = \rho_u g \sin\theta + \frac{1}{L_u} \left[\left(\frac{\tau_s \pi D}{A} L_s \right) + \left(\frac{\tau_f S_f + \tau_G S_G}{A} L_f \right) \right] \quad (2-84)$$

$$\rho_u = H_u \rho_L + (1 - H_u) \rho_G \quad \rho_s = H_s \rho_L + (1 - H_s) \rho_G \quad (2-85)$$

$$\tau_f = f_L \frac{\rho_L V_f / V_f}{2}, \quad \tau_s = f_s \frac{\rho_s V_s / V_s}{2}, \quad \tau_i = f_i \frac{\rho_G (V_G - V_f) / V_G - V_f}{2} \quad (2-86)$$

$$\tau_G = f_G \frac{\rho_G V_G / V_G}{2}$$

where, ρ_u and ρ_s denote the density of the slug unit and slug body and also τ_s, τ_f, τ_G and τ_i denote shear stresses at the slug body, film region, gas core and liquid-gas interface at the film region. f_s, f_L, f_G and f_i are the friction factors, respectively. The prediction of the pressure gradient is dependent on the slug characteristics, such as translational velocity, V_t , dispersed bubble velocity in the slug body, V_b , liquid hold-up in the slug body, H_L and slug length, L_s . The average liquid hold-up of slug unit H_u is defined in equation (2-87) once the closure equation and continuity equation are solved.

$$H_u = \frac{V_t H_s + V_b (1 - H_s) - V_{sg}}{V_t} \quad (2-87)$$

- Annular flow model:

In the annular flow model, just like stratified flow, the two-fluid model is being extended to a fully developed steady-state annular flow in the pipeline. The liquid film in the horizontal pipe is not circumferentially uniform. The liquid film of annular flow in the horizontal pipes is usually thinner at the top when compared with the bottom. This is quite different from what is encountered in vertical pipes. Xiao et al. (1990) proposed that an average of film thickness and gas core can be treated as a homogeneous fluid and also assumed that the gas core has the same velocity as the liquid film.

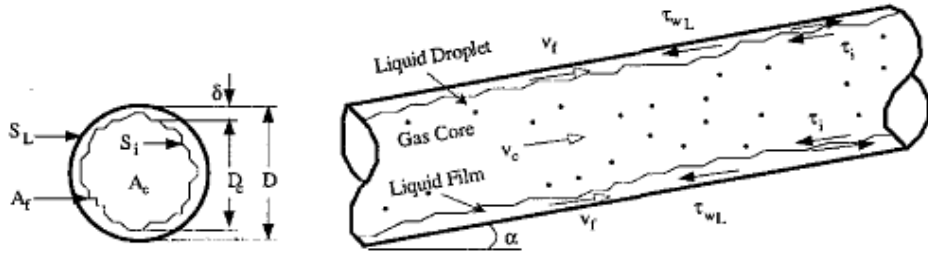


Figure 2-11: Annular flow model (Xiao *et al.* 1990)

The liquid holdup in the gas core, H_C can be expressed as:

$$H_C = \frac{V_{sl}FE}{V_{sg} + V_{sl}FE} \quad (2-88)$$

where FE is the liquid entrainment fraction and the liquid holdup is given as:

$$H_L = 1 - (1 - 2\widetilde{h_{F,a}})^2 \frac{V_{sg}}{V_{sg} + V_{sl}FE} \quad (2-89)$$

where $\widetilde{h_{F,a}}$ is the dimensionless average film thickness. The elimination of interfacial shear stress results in a combined momentum equation:

$$\tau_{wf} \frac{S_f}{A_f} - \tau_i S_i \left(\frac{1}{A_f} - \frac{1}{A_c} \right) + (\rho_L - \rho_c) g \sin \theta = 0 \quad (2-90)$$

where, A_f and A_c are actual areas for liquid film and gas core respectively. The pressure gradient is obtained as follows:

$$-\frac{dp}{dx} = \frac{\tau_{wf} S_f}{A} - \tau_i S_i + \left(\frac{A_f}{A} \rho_L - \frac{A_c}{A} \rho_c \right) g \sin \theta = 0 \quad (2-91)$$

then the shear stresses are defined:

$$\tau_{wf} = f_L \frac{\rho_L V_{f,v}^2}{2}, \quad \tau_i = f_i \frac{\rho_c (V_{G,c} - V_{f,v})^2}{2} \quad (2-92)$$

where, ρ_c represents the density of the core flow, which is given as $H_c \rho_c + (1 - H_c) \rho_G$. The liquid film velocity, $V_{f,v}$ and gas core velocity, $V_{G,c}$ can be obtained from the overall liquid volumetric flow rate balance:

$$V_{f,v} = \frac{V_{sl}(1-FE)}{4\overline{h_{F,a}}(1-\overline{h_{F,a}})} \quad V_{G,c} = \frac{V_{sg}+V_{sl}FE}{(1-2\overline{h_{F,a}})^2} \quad (2-93)$$

So that this model can be completed, there is a need for correlations for the interfacial friction factor and the liquid entrainment fraction.

2.21.4 Fan et al (2007)

Fan et al. (2007) developed a mechanistic two-fluid model with closure relationship to predict the pressure gradient and liquid hold-up for stratified flow in a multiphase flow pipeline. The proposed closure relationships developed by Fan et al. (2007) to predict pressure gradient and liquid hold-up are interfacial-friction factor, liquid-wall friction factor and wetted-wall friction factor. To develop these closure relationships, experiments were conducted from two different sets of facilities: (1) Small-scale facility, which has an internal diameter of 51mm and (2) Large scale facility with a pipe internal diameter of 150mm.

In the large diameter scale facility, the superficial gas velocities used in the experiment were varied from 5 to 25m/s while those of the liquid superficial velocity were varied from 0.00025 to 0.03m/s. Furthermore, the superficial liquid and gas velocities for the small scale facility were varied from 0.005m/s to 0.05m/s and 7.5m/s to 21m/s respectively. The pipe inclination angle was also put into consideration, which varied from -2° to 2°. In Fan et al.'s (2007) experimental work, compressed air was used as the gas phase while water was used as the liquid phase.

Fan et al. (2007) assumed in their model that gas and liquid phases flow separately within the pipe (stratified flow). The two- fluid model is shown in Figure 2-12.

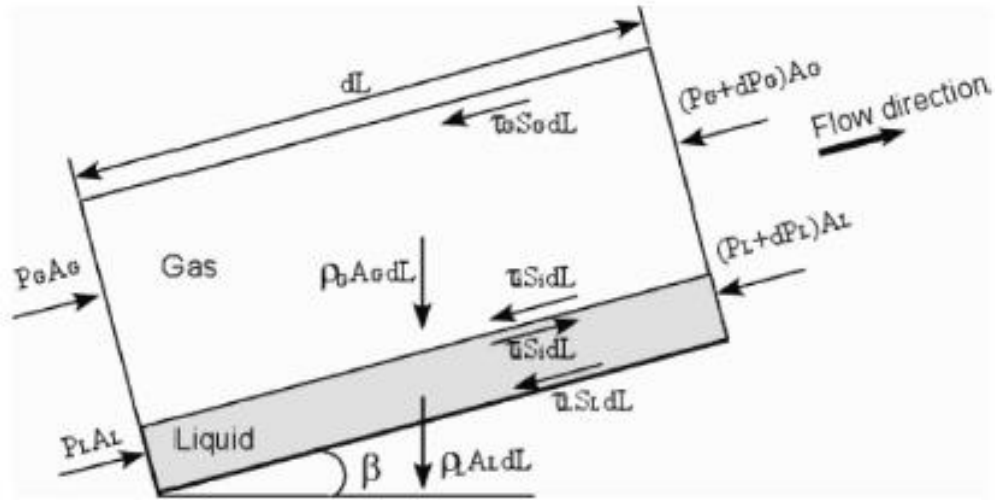


Figure 2-12: Force analysis of stratified flow (Fan et al, 2007)

The model (1D) constitutes the momentum balance equation for both gas and liquid phases. They also assumed that the pressure gradient across the pipe, phase-wall shear stress and normal full pipe velocity for liquid and gas momentum equations are constant.

The liquid-phase momentum is expressed as

$$-A_L \left(\frac{dp}{dx} \right) - \tau_{WL} S_L + \tau_i S_i - \rho_L A_L g \sin \theta = 0 \quad (2-94)$$

Gas-phase momentum equation:

$$-A_G \left(\frac{dp}{dx} \right) - \tau_{WG} S_G - \tau_i S_i - \rho_G A_G g \sin \theta = 0 \quad (2-95)$$

It is also assumed that the pressure gradient in the gas phase is equal to that in liquid phase equations and becomes:

:

$$\tau_{WG}S_GA_L - \tau_{WL}S_GA_G + \tau_i S_i A_P - A_L A_G (\rho_L - \rho_G) g \sin \theta = 0 \quad (2-96)$$

The shear stresses can be expressed as follows:

$$\tau_{WL} = f_L \frac{\rho_L V_L^2}{2}, \quad \tau_{WG} = f_G \frac{\rho_G V_G^2}{2}, \quad \tau_i = f_i \frac{\rho_G (V_G - V_i)^2}{2} \quad (2-97)$$

where A_L and A_G are the liquid and gas cross-sectional areas, τ_{WL} the liquid-wall shear stress, τ_{WG} the gas-wall shear, τ_i the interfacial stress and f_L , f_G and f_i , are the liquid-wall friction factor, gas-wall friction factor and interfacial friction factor respectively.

The phase average velocities can be expressed as follows:

$$V_L = \frac{V_{sl}}{H_L} \quad (2-98)$$

$$V_G = V_{sg} (1 - H_L) \quad (2-99)$$

where V_L and V_G are actual liquid and actual gas velocities.

The *wetted wall fraction* is defined as the fraction of the pipe perimeter wetted by the liquid phase. The closure relationship for the wetted-wall fraction was solved based on the assumption of double circle and gravity-centre shift.

$$\vartheta = \left[\frac{\theta_0}{\pi} + C_1 F_r^{0.68} \left(\frac{V_{sg}}{V_{sg,c}} \right) \right] \left(\frac{\sigma_w}{\sigma_L} \right)^{0.15} \quad (2-100)$$

where ϑ is wetted-wall fraction.

$$\theta_0 = \pi H_L + \left(\frac{3\pi}{2} \right)^{0.33} [1 - 2H_L + H_L^{0.33} - (1 - H_L)^{0.33}] \quad (2-101)$$

$$F_r = \rho_L V_L^2 (\Delta \rho D g \cos \theta) \quad (2-102)$$

$$V_{sg,c} = 5 \left(\frac{1.24}{\rho_L} \right)^{0.5} \quad (2-103)$$

When the wetted-wall fraction is calculated, the liquid and gas-phase wetted perimeters can be calculated using equations 2-104 and 2-105:

$$S_L = \pi D \vartheta \quad (2-104)$$

$$S_G = \pi D (1 - \vartheta) \quad (2-105)$$

where S_L and S_G are the liquid and gas-phase wetted wall perimeters.

The gas wall friction factor was also developed by using a hydraulic diameter model, and the gas wall friction factor can be expressed as follows:

$$f_G = \frac{16}{Re_G} \quad for \quad Re_G \leq 2000 \quad (2-106)$$

$$f_G = 0.046 Re_G^{-0.2} \quad for \quad Re_G \geq 2000 \quad (2-107)$$

The liquid wall friction factor was also developed by integrating velocity profile for turbulent and laminar flow.

The liquid wall friction factor for turbulent can be expressed as:

$$f_L = 0.0709 Re_L^{-0.2666} \text{ for } 1000 \leq Re_L \leq 25000 \quad (2-108)$$

For laminar flow:

$$f_L = \frac{8}{Re_L} \text{ for } Re_L \leq 1000 \quad (2-109)$$

The Reynolds number is defined as:

$$Re_L = \frac{\rho_L V_L h_F}{\mu_L} \quad (2-110)$$

where h_L is the liquid thickness or hold-up.

Fan et al (2007) also proposed a correlation for the interfacial friction factor:

$$f_i = f_G \left[1 + 21 \left(\frac{h_{F,a}}{D} \right)^{0.72} \left(\frac{V_{sg}}{V_{sg,c}} \right)^{0.8} \right] \quad (2-111)$$

where

$$h_{F,a} = \frac{2A_L}{s_L + s_i} \quad (2-112)$$

2.22 Classification of Wave Structures in Stratified Flow

2.22.1 Stratified Wave Structure

The understanding of the wave structure in a stratified flow regime helps to improve the closure in mechanistic models. In a fully developed stratified flow regime, the widely used models are based on the assumption of a sharp gas-liquid interface. The models assume that above the interface of local volume fraction is zero and below the interface is unity. This assumption is applied to the stratified flow regime with a less chaotic wavy interface structure and smooth stratified flow regime; however, this assumption may not be valid for severe entrainment (Hu et al., 2014).

Hu et al. (2014) conducted several experiments under different flow conditions, and different gas-liquid interfacial structures were observed in stratified wavy flow. The experimental work by Hu et al. (2014) classified stratified wavy flow into different flow wave patterns which are described below:

- **Stratified wavy with small amplitude capillary-gravity wave on the interface**

This wave pattern is characterised by many small amplitude waves on the interface, which occur with a wide range of lengths and velocities. It has a low Reynolds number and mostly occurs with turbulent liquid or gas in horizontal conduit. This structure is depicted in Figure 2-13.

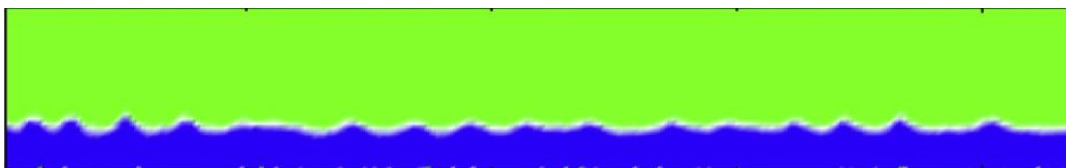


Figure 2-13: Structure of stratified wavy with small amplitude capillary-gravity wave on the interface (Hu et al., 2014).

- **Roll wave with no-breaking front**

The wave structure is mostly found in the inclined (upward) flow but can also occur in horizontal pipe flow at a low mixture velocity. It is characterised by long

wavelength waves transiting in an axial direction. This structure is shown in Figure 2-14. Owing to the low travelling speed of the wave crest, the front of the wave maintains a regular shape while the liquid ahead is picked up and then shed at the tail. Gas entrainment does not occur in this flow structure due to the non-breaking of the front of the wave structure.

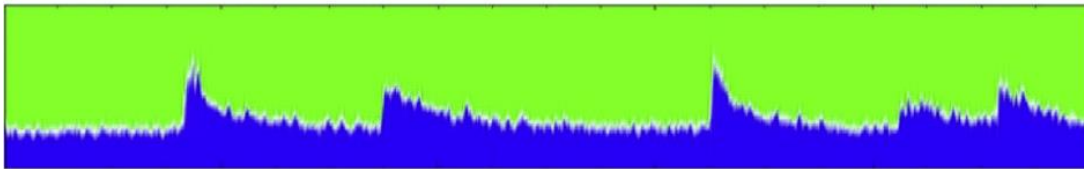


Figure 2-14: Structure of a roll wave with a no-breaking front (Hu et al., 2014)

- **Roll wave with a breaking front**

This type of wave structure is commonly found in an inclined (upward) flow. The roll wave with breaking fronts is characterised by high gas or liquid velocities. The large travelling velocity in the wave front causes the hydraulic shock to occur in-between the crest of the wave and the liquid layer downstream, which then leads into a breaking front. Gas entrainment and gassy wave fronts occur as a result of the breaking front. The gas bubbles entrain steadily to the gas-liquid surface and tend to merge with the gas. The structure of a roll wave with a breaking point is shown in Figure 2-15.

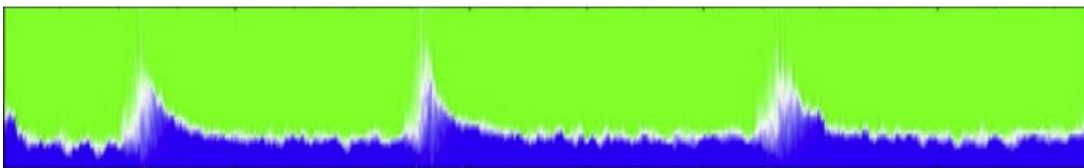


Figure 2-15: Structure of a roll wave with a breaking front (Hu et al., 2014).

- **Irregular large amplitude waves with insignificant entrainment**

The wave structure occurs in a stratified wavy flow in the horizontal dominated flow at a slow or moderate gas velocity and very high liquid velocity. This structure is of non-linear waves which are characterised by irregularity in shapes with a wide range of velocities and wavelengths; the waves from the structure constantly

collide and coalesce with one another. The structure of irregular large amplitude waves with insignificant entrainment is shown in Figure 2-16.

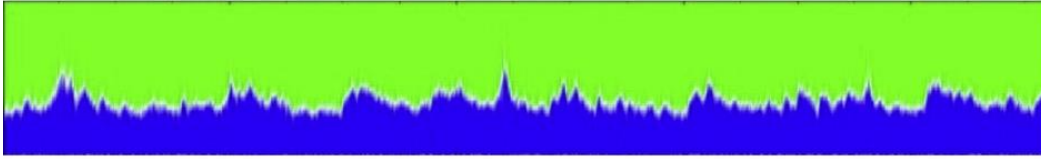


Figure 2-16: Structure of irregular large amplitude waves with insignificant entrainment (Hu et al., 2014).

- **Irregular waves with severe entrainment occurring on the interface**

The wave pattern or structure occurs in friction dominated flows at a very high gas velocity. The gas bubbles in the liquid layer in this flow structure are trapped in the intense interfacial turbulence, which tends to splash the droplets of liquid into the gas core. The structure or pattern of the wave is more driven by the interfacial shear stress; it is more pronounced in gravity dominated flow than in the flow inclination of pipes. The process of the strong entrainment of this flow allows a transition region between the layer dominated by the liquid and the layer dominated by the gas. This process is different from the flows that are characterised by a sharp gas to liquid interface. The structure of irregular waves with severe entrainment occurring on the interface is depicted in Figure 2-17.

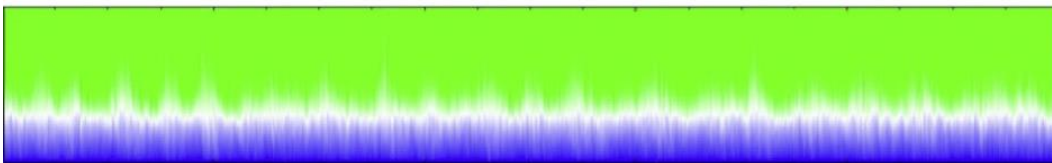


Figure 2-17: Structure of irregular waves with severe entrainment occurring on the interface (Hu et al., 2014).

- **Thin liquid layer at the bottom of the pipe with chaotic and highly aerated interface**

The structure mostly occurs in a flow with very high gas velocity and low liquid velocity. The liquid layer will become thin that turbulent gas can make holes in the liquid layer. The liquid layer exhibits foamy structure due to high aeration as

it spreads up the sides of the pipe. The liquid may also exhibit curved interface with layer of gas. Figure 2-18 depicts the structure of Thin liquid layer at the bottom of the pipe with highly aerated interface.

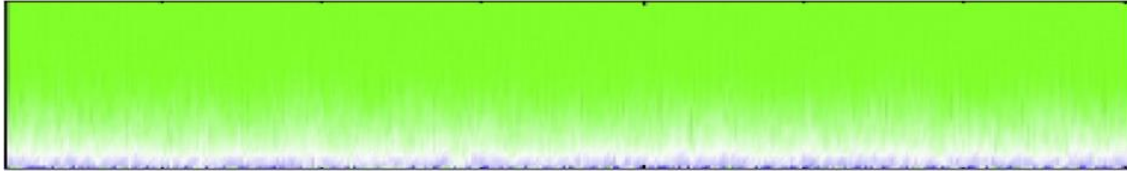


Figure 2-18: Thin liquid layer at the bottom of the pipe with highly aerated interface (Hu et al., 2014).

2.23 Frequency Domain Analysis

Power Spectral Density, abbreviated as PSD is one of the statistical tools used to measure signal's power intensity over a frequency domain. In other words, it indicates where frequencies variation is strong or weak. *Power Spectral Density* can be defined mathematically as the Fourier Transform of the autocorrelation sequence of the time series. In signal processing, Discrete Fourier Transform is commonly used for the analysis of frequencies present in a specific signal. In processing a signal, the time series of signal function is taken by the Fourier Transform and plotted on the frequency spectrum.

Signal representation in the frequency domain is called *frequency spectrum*. This is presented as a function onto a range of sinusoidal functions. This can be found from the result of a Fourier-related transform. A specific frequency spectrum constitutes phase information and amplitudes that describe the strength of a signal that lies in any given frequency band, without regard for the phase. The power spectral density graph is shown in Figure 2-19. This consists of *dominant frequency* and *harmonic frequency*. The dominant frequency has the highest peak and the harmonic frequency are the short peaks.

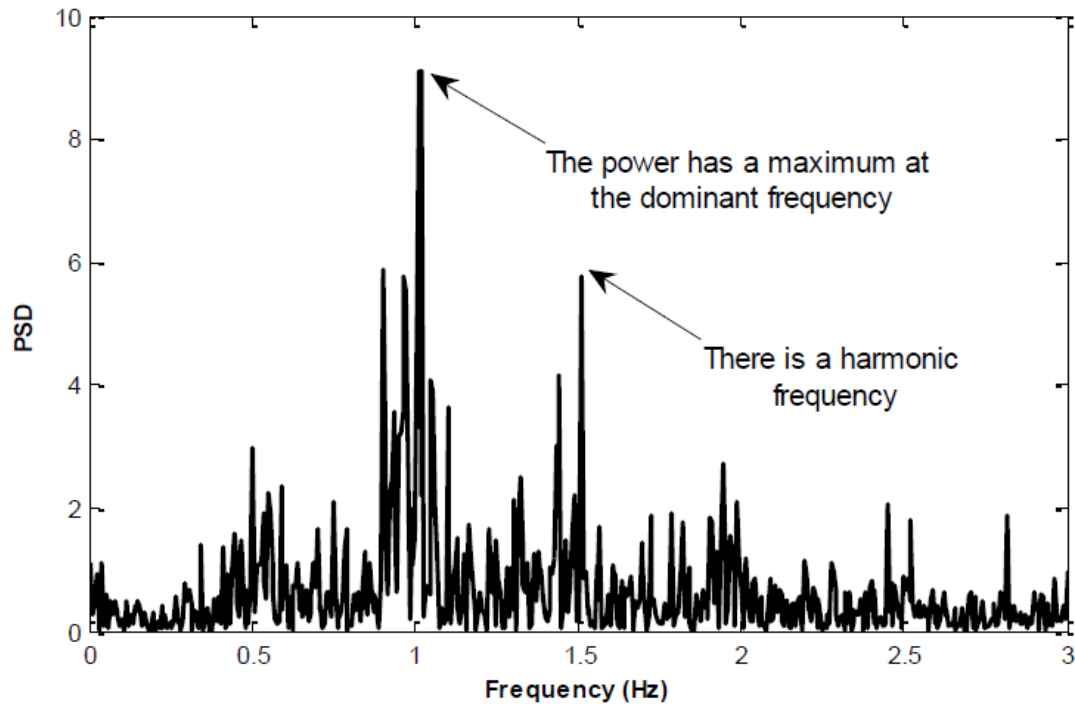


Figure 2-19: Power spectral density

2.24 Sand Monitor

In the oil and gas industry, sand monitors are classified into intrusive and non-intrusive. The intrusive sand sensor penetrates the wall of the pipe and its principle in detecting sand is by measuring the loss of element due to erosion. Non-intrusive sand monitors, such as acoustic, are mounted on the outer wall of the pipeline and its principle in detecting sand is by measuring the noise generated by the impact of sand on the wall of the pipe. In the laboratory, non-intrusive sensors such as acoustic are normally used to monitor sand in multiphase flow pipes. However, in this work, a sand sensor (similar to those employed to measure liquid film thickness) was used to monitor and detect sand movement in the pipe. Sand sensors (similar to those employed to measure liquid film thickness) are normally used in multiphase flow to measure the thickness of the film. Several authors, such as Collier and Hewitt (1967), Kang and Kim (1992), Koskie et al. (1989) and Lao and Yeung (2008), have used sand sensors to measure the thickness of a film. In addition, experimental investigation related to solid (sand) transport in multiphase flow in a pipe have shown that the sand

sensor has not been used for sand movement and detection within the pipe. Investigators such as Nasr-El-Din et al. (1987), Malin et al. (2007), and many more have used conductivity sensors to measure local concentrations of solid slurry in the pipe. None of these investigators has mentioned the use of sand sensors for sand detection and movement in a multiphase flow pipe.

2.25 Chapter Summary

This section summarises Chapter 2: solid-liquid flow regimes; solid-gas-liquid flow regimes; causes of sand production; single phase liquid flow; multiphase flow; sand transport in both single phase and multiphase; power spectral density; and sand sensor.

Solid being transported in a pipe (i.e. single phase or multiphase pipelines) can be classified into different flow regimes. The solid-liquid flow regimes were classified into: stationary bed; moving dunes; scouring; and dispersed (Crowe 2006). Also, Dabirian et al. (2015) classified solid-gas-liquid regimes (i.e. solid transport in stratified two-phase flow) into six different flow regimes: dispersed flow regime; dilute solids on the wall; solids concentrated on the wall; moving dunes; stationary dunes; and stationary bed.

Sand transportation in single-phase water flow has been studied for many years. However, studies on sand transport in stratified two-phase flow are limited and complex, and depend on a large number of parameters. The parameters include sand concentration, fluid viscosities, pipe orientation and sand particle size.

Based on the review of the literature, it has been discovered that investigation into the effects both of sand particle diameter and concentration on MTC are limited in stratified two-phase flow; these effects are so crucial for the design of wet gas pipelines. Furthermore, sand behaviour in stratified two-phase flow is not well understood and the data for sand transport in multiphase pipelines for different orientations were not adequate. Thus, more work needs to be done to improve understanding.

In the literature, the majority of the models available upgrade the existing solid-liquid correlations to multiphase systems. However, the application of these models only covers a certain range. Therefore, caution needs to be used in applying them outside their range. Furthermore, modelling of sand transport in multiphase flow is still at a fundamental stage, with few models bringing together state-of-the-art multiphase (gas-oil) hydrodynamic analysis with solid-liquid state-of-the-art models. For this reason, more research is required to be done in this area.

The review of the literature indicated that several researchers have used conductivity sand sensors to measure the thickness of a film in multiphase flow. However, none of these investigators has mentioned the use of sand sensors for sand monitoring and detection in a multiphase flow pipe. In addition, experimental investigation related to solid transport in multiphase flow in a pipe have shown that the sand sensor has not been used for sand movement and detection within the pipe.

3 EXPERIMENTAL SET UP

The aim of this research work is to investigate sand transport and its behaviour in single-phase liquid (water) and air-water flow systems (stratified flow) in a horizontal pipe. This chapter discusses the features of the constructed experimental facility used in this work. It also describes the various instrumentations, calibration, data acquisition and processing techniques employed to achieve the objectives.

The detailed design of the test facilities used in this study is described in section 3.1; this includes the supply system (air and water), conductivity ring, sand sensor and some measuring instruments. Finally, the details of the experimental procedure are also presented.

3.1 Test Section

The experiments were carried out on the 2-inch horizontal test facility in the Oil and Gas Engineering Centre Laboratory, Cranfield University. The whole experimental set-up is illustrated in Figure 3-1.

The illustrated schematic diagram consists of a horizontal pipe with an inner diameter of 0.0504m. The 2-inch test rig constitutes a loop length of 25m; 10.5m of that is PVC pipe that serves as the water supply inlet and the remainder is of a Perspex pipe material. Two conductivity based sand monitoring sensors (similar to those employed to measure liquid film thickness) were installed about 6m to the air and sand injection point along the horizontal pipe but 0.21m apart from each other. The second sand sensor was placed within the conductivity ring sensors. Pressure transducers were also put into the test section. The first pressure transducer was positioned at about 1.5m from the first sand sensor and about 4m from the sand and air injection points. Furthermore, the test section was equipped with 2-inch conductivity ring sensors to measure the liquid hold-up. Table 3-1 summarises the instrumentation used, their designations as shown in Figure 3-1, manufacturer and model, measuring range, and error.

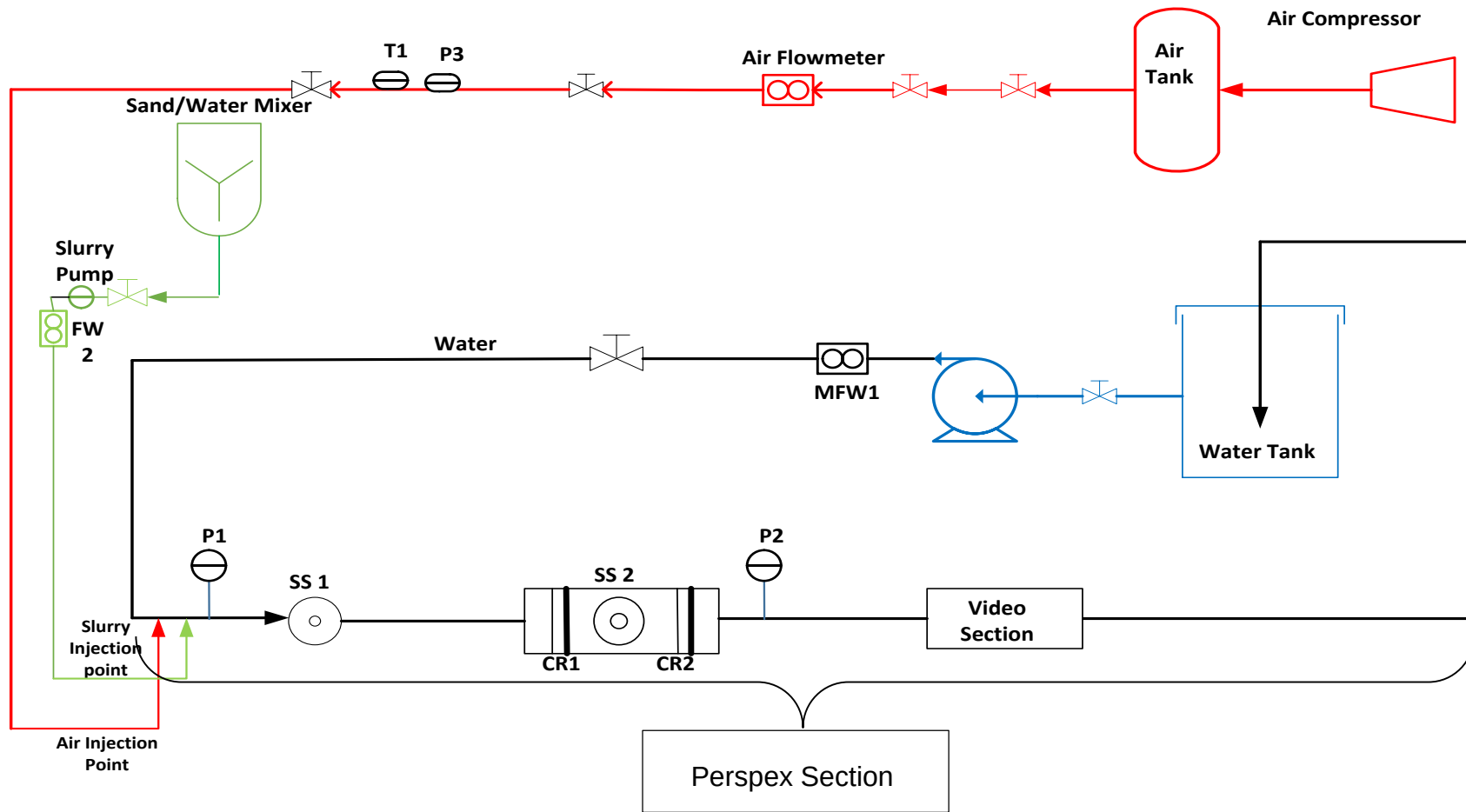


Figure 3-1: 2-inch sand transportation test facility

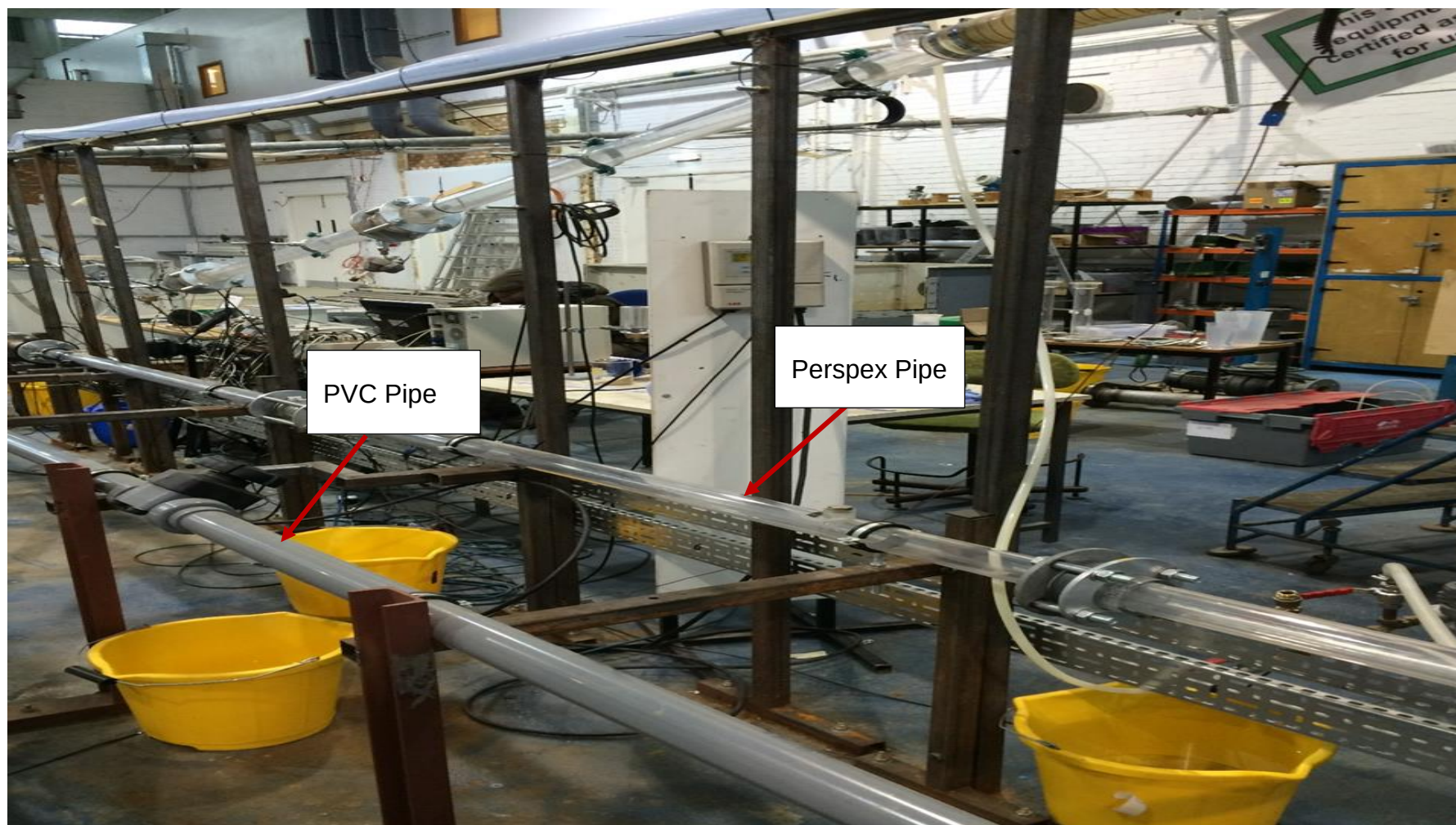
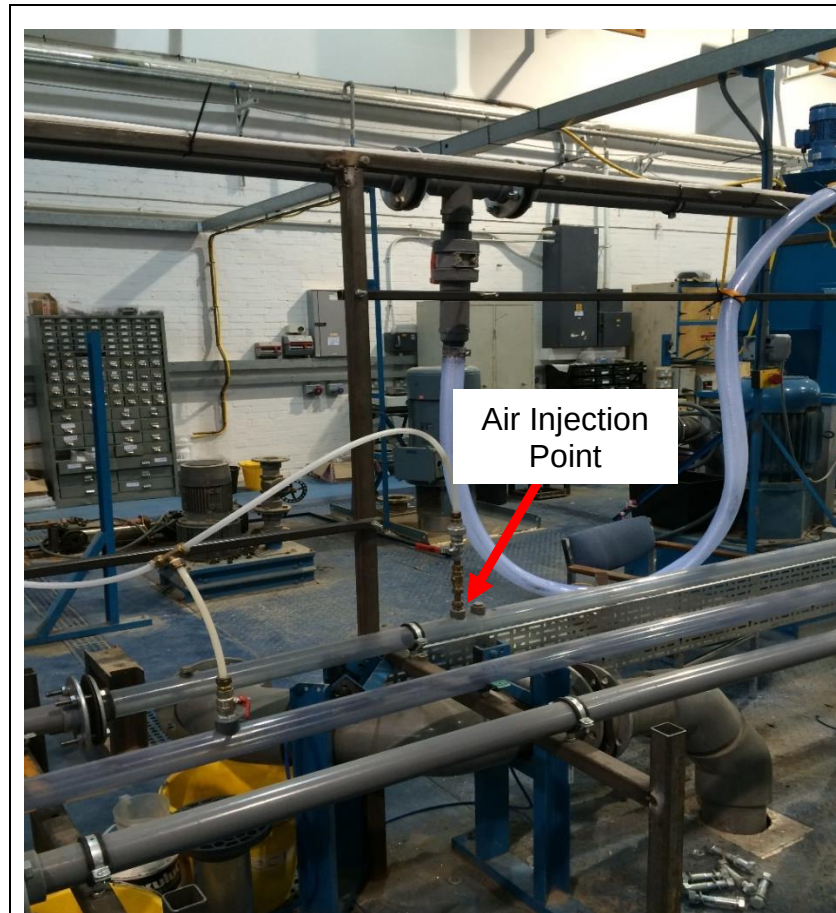
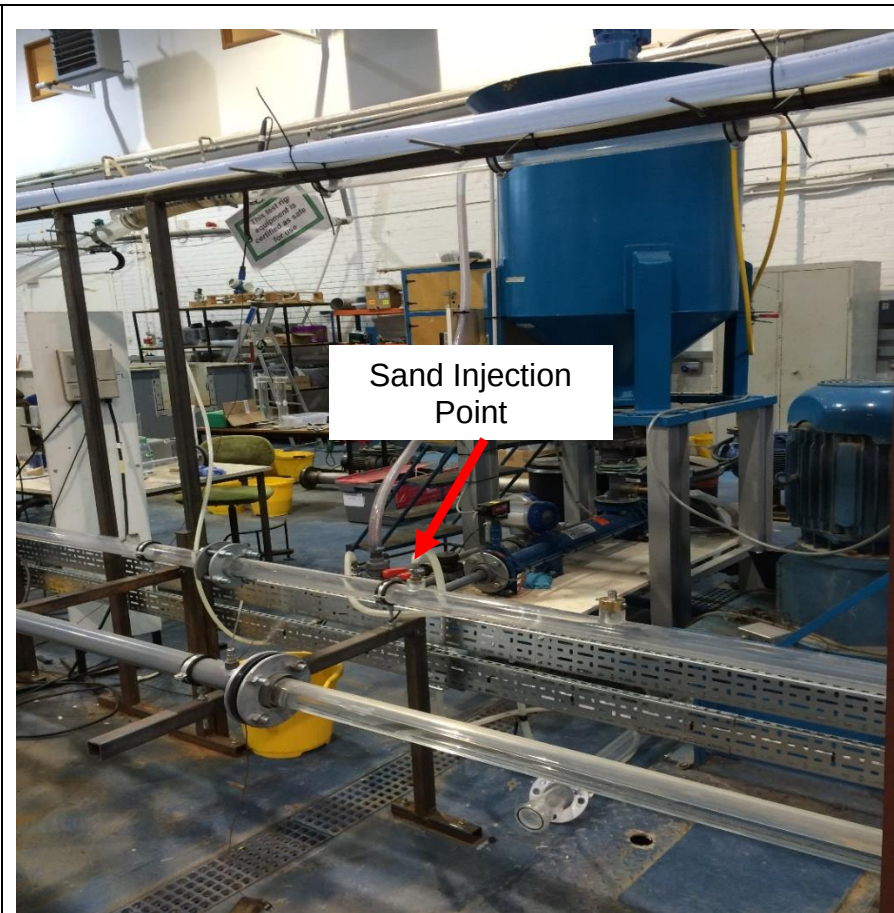


Figure 3-2: Snapshot of the 2-inch facility



a: Air Injection Point



b: Sand Injection Point

Figure 3-3: Snapshot of the air and sand injection point

Table 3-1: List of instruments

Abbreviations	Full Name	Description	Full Range	Error
P1	Pressure Transducer 1	Druck PMP 4070 (Pressure Measurement)	0 ~ 6 bar	±0.06%
P2	Pressure Transducer 1	Druck PMP 4070 (Pressure Measurement)	0 ~ 6 bar	±0.06%
CR1 and CR2	Conductivity Ring 1 and 2	Manufactured in Oil and Gas Engineering Centre Lab (Liquid Hold-up)	0 ~ 1	(±2.4%)*
SS1 and SS2	Sand Sensors 1 and 2	Manufactured in Oil and Gas Engineering Centre Lab (Sand detection and monitoring)	0~ 3.8mm	(±3.6%)*
Air Flowmeter	Proline t-mass 651 Thermal Flowmeter	Proline t-mass 65F Thermal Flowmeter Endress + Hauser (Gas Superficial Velocity)	0 ~ 70m ³ h ⁻¹	±0.15%
MFW1	Magnetic Flowmeter (Liquid)	ABB K280/0 AS (Liquid Superficial Velocity)	0 ~ 20 m ³ h ⁻¹	±0.8%
FW2	Magnetic Flowmeter (Sand + Water)	OPTIFLUX 2300C Krohne Magnetic Flowmeter	0 ~ 21 m ³ h ⁻¹	0.2%

* Determined through the repeat of three calibration tests.

3.1.1 Sand Injection System

The sand injection system is made up of a hopper, flowmeter and displacement pump. Sand in the hopper is mixed thoroughly with water before being injected into the test section through a 0.25-inch flexible pipe. A 1-inch OPTIFLUX 2300C Krohne magnetic flow meter was installed downstream of the injection pump. The sand-water mixture is supplied continuously into the horizontal pipe at each time of the experiment.

The diameter of the sand mixer is 0.8m and is equipped with a 0.2m diameter axial impeller. The outlet of the sand mixer is connected to a displacement pump. The sand injection point and sand hopper are shown in Figures 3-3b and 3-4 respectively.



Figure 3-4: Sand Hopper

3.1.2 Air Supply System

Compressed air was supplied by a compressor unit via a flexible pipe into the test section. The air compressor unit has the capacity to supply 400 m³/h into the test section. The supplied compressed air was metered using a 0.5-inch thermal flowmeter Endress + Hauser, Proline t-mass 65F which ranges from 0 to 70 m³/h. Air is injected into the horizontal test section via 0.5-inch flexible airline at the upstream. The air injection point is shown in Figure 3-3a. Pressure transducers and a thermocouple were installed along the test section at the exit where the flowmeter is positioned. The gas flowmeter was connected to the data acquisition system. The superficial gas velocities were controlled manually by different valves attached to the test section at the upstream.

3.1.3 Liquid Supply System

Municipal water was used as the carrier liquid in this study. Water was supplied from the tank through a centrifugal pump via PVC pipe into the main horizontal transparent test section. The system is *re-circulation*, whereby the water supplied will return to the tank and a continuous cycle is formed. The water tank from which water was supplied to the main horizontal test section is exposed to the atmosphere with the base attached to the floor. The centrifugal pump, with a capacity of 40 m³/h, discharged water from the tank to the test section and was connected 0.2m above the base of the tank to prevent the centrifugal pump from sucking up sand particles that settle at the bottom of the tank. The water tank has a capacity of 1.7m³. The tank is partitioned into two (return and suction chambers) and fitted with a baffle and sieve. The return chamber is the section that holds the water from flowing back into the water tank while the suction chamber is located at the bottom of the tank section and supplies water into the test section. The baffle prevents sand particles from being sucked up by the pump.

An electromagnetic flowmeter is used to measure the water flow rate. The model of the electromagnetic flowmeter is ABB K280/0 AS and it has a range of 0 to 20m³/h. Manual valves are used to adjust the flow rate within the system.

3.2 Instrumentation

In this section, the instrumentations used in this study are described in detail.

3.2.1 Flowmeters

The liquid (water) flow rate was measured downstream of the centrifugal pump by an electromagnetic flowmeter, model ABB K280/0 AS, with an accuracy of $\pm 0.8\%$. The serial port of the PC is connected to the flowmeter with serial communication protocol (RS232) so the flowmeter can communicate serially with the data acquisition system. The rate of gas flow into the test section was measured using a gas flowmeter manufactured by Endress+ Hauser (Proline t-mass flanged 65F). The mixture of sand-water flow rate was measured with a Krohne magnetic flowmeter OPTIFLUX 2300C, which was connected to the downstream of the sand injection pump located below the sand hopper. The sand injection pump is connected to the horizontal test section via a 0.25-inch flexible pipe; the function of the latter is to transport the sand-water mixture to the horizontal test section. The sand flowmeter has an accuracy of $\pm 0.2\%$.

3.2.2 Sand Sensor

Conductivity measurement between the electrodes has long been used to examine the liquid film thickness, hold-up and void fraction in multiphase flow research. In this study, it is considered that sand particles are non-conductive; they behave like air bubbles and affect the output of the sand sensor. Figure 3-5 depicts the design of the sand sensor used (i.e. similar to those employed to measure liquid film thickness).

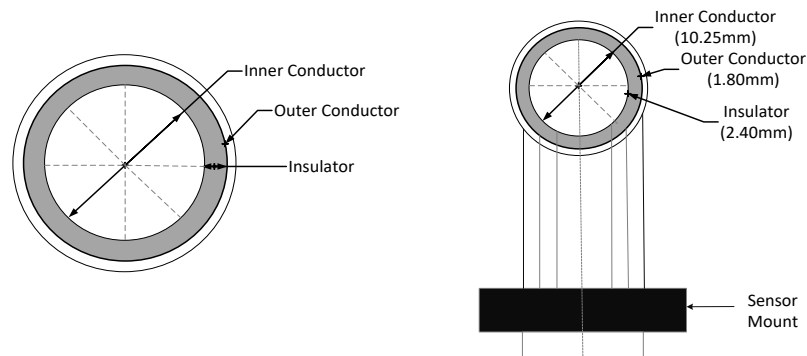


Figure 3-5: Design of the sand sensor

In this study, the sand sensor was used to monitor and detect sand movement based on the conductivity of sand relative to water. The sand sensor consists of two electrodes: a central circular plate electrode of 10.25mm diameter (Inner conductor) and the channel wall or an outer circular plate of 1.80mm (Outer conductor). The two circular plates are separated by a 2.40mm circular insulator. The operating principle of the sand sensor is based on the conductivity change caused by the presence of sand in water (conducting liquid). The sand sensor in water functions in such a way that when a potential difference is applied to the electrodes, current will flow from one electrode to the other. The quantity of current that flows between the inner and outer electrodes depends on the conductivity of the substance surrounding the field electrodes. When the sand sensor comes into contact with the mixture (sand and water), the current decreases, thereby causing a decrease in the output voltage of the sand sensor relative to water only. This allows sand movement to be detected by the sand sensor. The sand sensor has an accuracy of $\pm 3.6\%$.

3.2.3 Conductivity Ring

Liquid hold-up within the horizontal pipe was measured using a conductivity ring. The electrical conductance of a conducting liquid across the horizontal pipe diameter is determined by the contact electrodes, which are ring shaped. Electrical conductivity techniques have been one of the major and most common techniques for measuring liquid hold-up in multiphase flow. The conductive ring

sensor determines the relationship that exists between the electric impedance of a medium and its phase distribution across the pipe. A conductivity ring sensor operates in such a way that the measured electrical impedance across its electrode pair, submerged in a conducting liquid, becomes resistive when the frequency of the alternate current excitation signal is high. In this study, a conductivity ring sensor was used to measure the liquid hold-up across the horizontal pipe section.

The advantages of the impedance technique are as follows:

- Cheap and simple to construct
- The flow within the pipe cannot be interrupted because it is flush-mounted (non-intrusive)
- Recording of *in situ* liquid volume fraction is provided continuously

The calibration procedure for the conductivity ring sensors can be found in Appendix A.

3.2.3.1 Design & Construction Aspect of Conductivity Ring

In theory, the electrical conductivity of conductive liquid can be measured (immersed in flush-mounted sensors) by subjecting the conductive liquid to electrical excitation (A.C.) by applying a sufficiently high frequency signal between the electrodes of the sensor. The accuracy in the measurement of a multiphase flow system depends on the design and geometry of the conductivity sensor. Several investigators have designed and investigated different types of electrical conductivity sensor. Coney (1973) investigated the electrical conductivity of the wavy film thickness of water using flat electrodes. Merilo et al. (1977) investigated how conductive electrodes can generate a rotating field and Asali et al. (1985) were the first to use ring electrodes to measure the electrical conductivity of conductive liquid. However, the problem associated with all of these conductivity sensors is their inability to differentiate different flow patterns that exist in a two-phase flow system.

Andreussi et al. (1988) and Fossa (1998) reported that simple flush-mounted electrical conductivity sensors made of two-ring electrodes are effective for the measurement of average liquid hold-up under different flow conditions for the following reasons:

- Good repeatability of test on the ring sensors was ascertained on condition that the measured conductance must be normalized to a reference situation (i.e. when the conductance of the pipe is full of liquid). This will avoid having to monitor the electrical conductivity of the liquid during the operation.
- Ring sensors have more suitable applications in the evaluation of the average liquid hold- up or void fraction.

The liquid hold-up was measured by using the ring shaped design shown in Figure 3-6. The ring shaped electrical conductivity sensors were designed and constructed at the Oil and Gas Engineering Centre Laboratory, Cranfield University, to study continuous air-water flow in a horizontal pipeline.

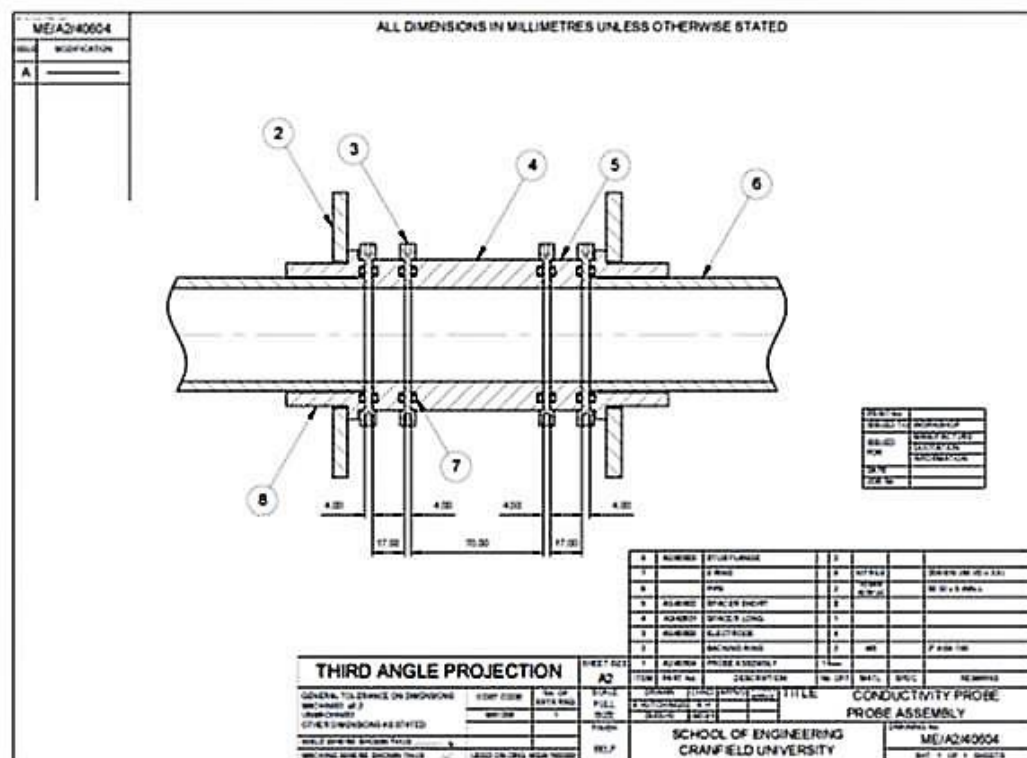


Figure 3-6: Conductivity ring design

Coney (1973) and Fossa (1998) investigated the effects of sensor geometry on the response of the measuring devices with reference to multiphase flows (stratified, bubble and annular flow). Based on their investigation, it was deduced that the response of the conductivity sensor is affected by the sensor geometry and also by the flow pattern. Accordingly, the mixture of electrical conductivity changed with the phase distribution at the same mean void fraction. To overcome this problem, the conductivity sensor was designed and constructed in such a way that it produces a response that will be relatively insensitive to the changes that occur between the uniformly dispersed bubble flow regime and the stratified regime (Fossa et al., 2003).

Fossa et al. (2003) suggested that the sensor geometry aspect ratios: (distance between a pair of ring / pipe internal diameters) < 0.4 and (thickness of the ring/ pipe internal diameter) < 0.08 .

Based on the recommendation and design guidelines by Fossa et al. (2003), the conductivity ring electrodes were constructed for this study, using the following configuration: the thickness of each ring is 4mm and the distance between a pair of rings is 17mm.

3.2.4 Pressure Transducers

Two single silicon diaphragm type pressure transducers, model PMP 4070 manufactured by Druck, were installed in the horizontal test section 2m apart. The first was installed upstream of the test section before the sand and conductivity ring sensors and the second after the sand and conductivity ring sensors at the downstream of the test section. In order to avoid interference of the two pressure transducers with the flow, they were flush-mounted. The pressure transducer measurement ranges from 0 to 6 bar (0-100psi) and the voltage of the output ranges from 0-5 volts (D.C.). The calibration curves of the two pressure transducers are depicted in Figures 3-7 and 3-8 respectively. Calibration procedures for pressure transducers are described in Appendix D.

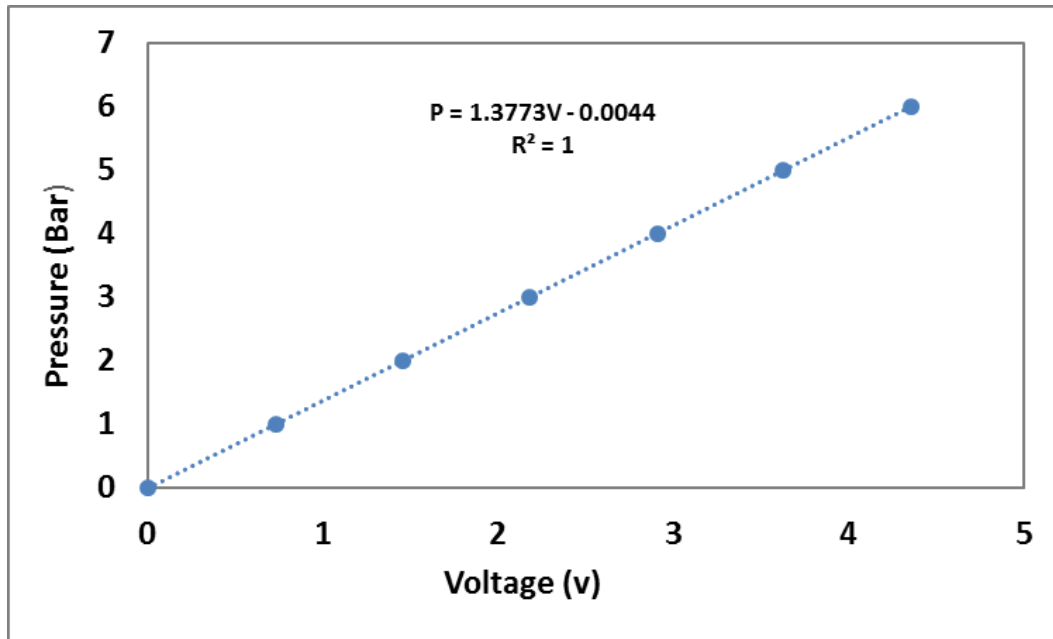


Figure 3-7: Calibration curve for pressure transducer at upstream of the test section

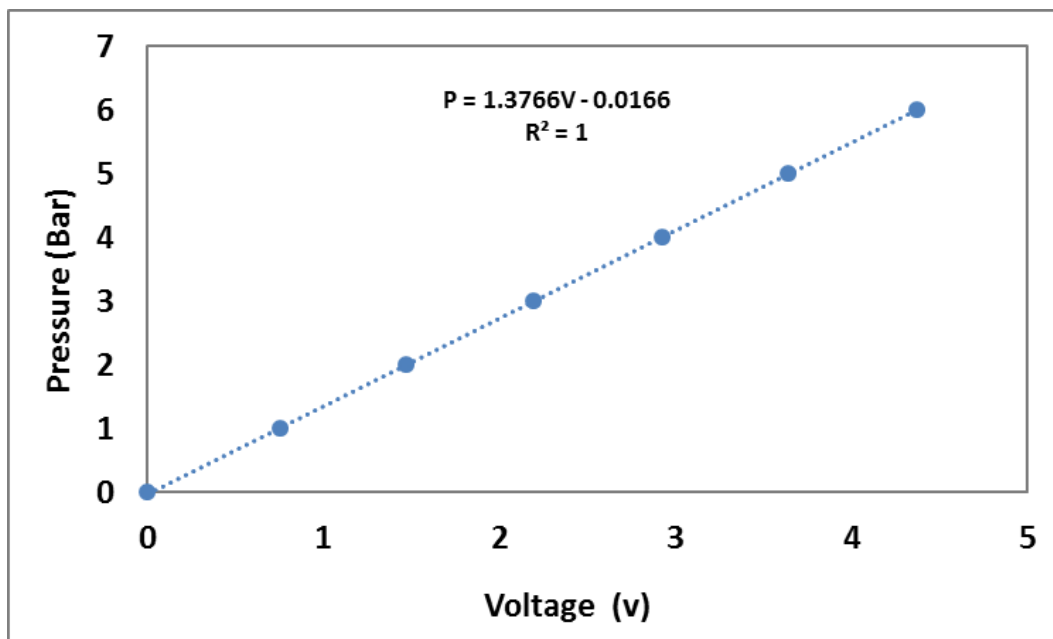


Figure 3-8: Calibration curve for pressure transducer at downstream of the test section

3.2.5 Data Acquisition

All the measurements from the instrumentation such as conductivity sand sensors, conductivity ring sensors, flowmeters, and pressure transducers were obtained with a data acquisition system PC of 12 channels. The 12-channel based data acquisition system constitutes a series of signal conditioning units. Signals are transferred from the conditioning unit through a 32-channel parallel port multiplexer into the PC after it has been processed and converted to digital signals. The real time data are gathered and displayed on the computer monitor through LabVIEW, when all the data from each instrumentation have been converted to engineering units.

3.2.5.1 Procedure for data recording

The LabVIEW was set up to record data, and monitor both liquid and gas superficial velocities. The scan rate was set to 1000Hz while the sampling rate was set to 200Hz for each experimental test. After all the parameters needed for each experimental test had been set up on the LabVIEW, files were named for each experiment carried out and recorded.

3.3 Experimental Programme Description

The experimental programmes are highlighted below. The experimental test matrix is shown in Table 3-2.

Table 3-2: Experimental test matrix

Variable	Range	Units
Liquid superficial velocity	0.06-0.35	ms^{-1}
Gas superficial velocity	3.0-6.7	ms^{-1}
Sand Concentration	5.30E-05-5.39E-04	lb/1000bbl
Particle size	212,500,800	μm
Inner pipe diameter	0.0504	m

1. Experimental tests were carried out for water-sand settling from suspension to moving dunes.
2. The air-water experimental test at given liquid superficial velocities was aimed to cover the wide range of stratified flow in the horizontal pipeline. The superficial liquid velocities were 0.06m/s, 0.07m/s, 0.08m/s and 0.09m/s. The superficial gas velocities ranged from 0.3m/s to 7m/s.
3. Sand-air-water experimental tests were carried out for settling tests within stratified flow regimes.

Different sand particle diameters were injected for different experimental tests from the sand hopper as a sand-liquid homogeneous mixture. Prior to the injection of sand particles into the test line, the sand-liquid composition was mixed thoroughly and injected into the horizontal test section via a 0.25-inch flexible pipe that connects the sand injection pump to the test section. A material balance model was used to calculate the quantity of sand injected into the test section. This is shown in Figure 3-9:

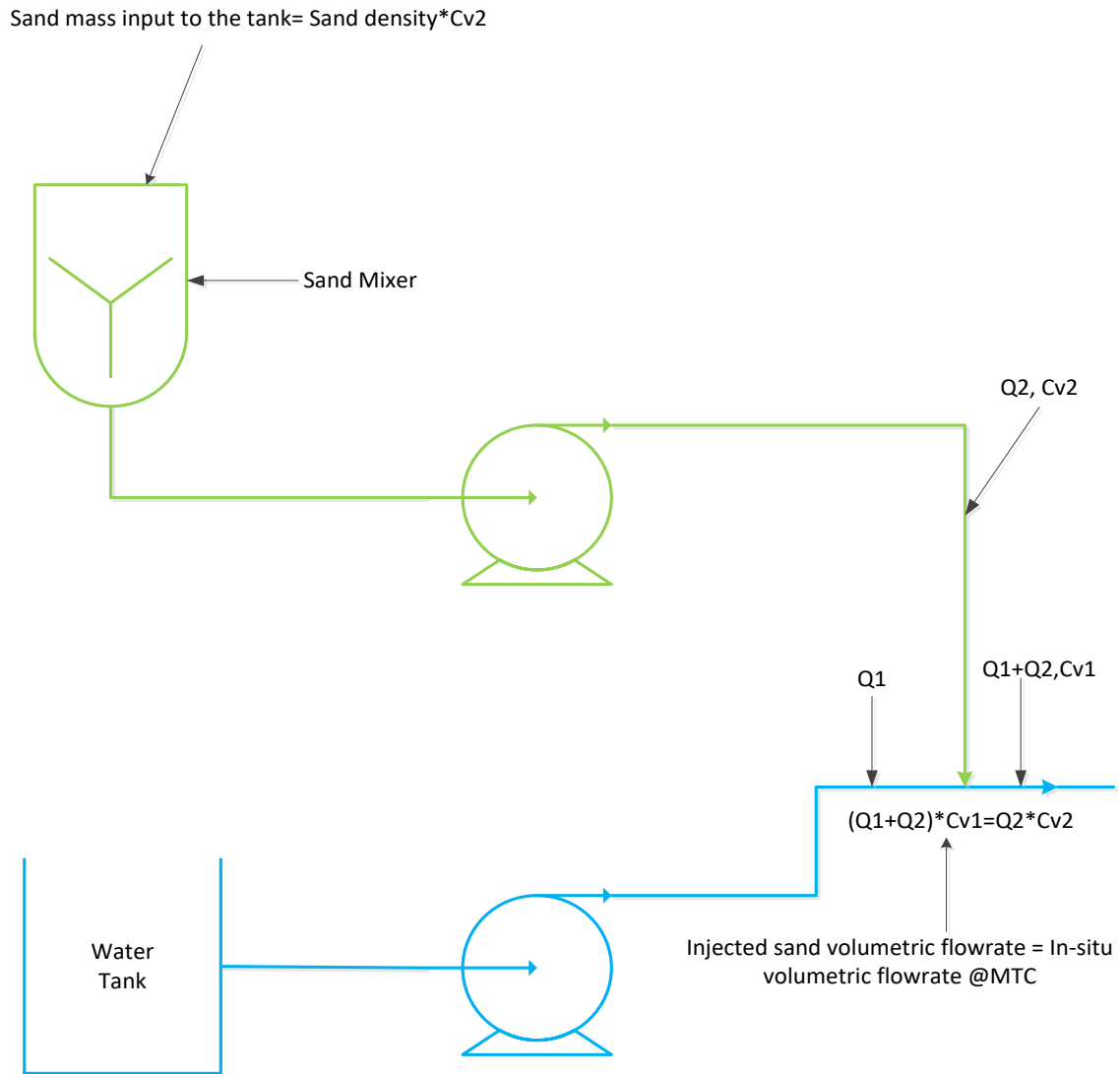


Figure 3-9: Design criterion to determine the *in situ* sand concentration in the pipeline

where:

- $Cv1$ represents *in situ* sand concentration or required sand concentration in the test section.
- $Cv2$ denotes the sand concentration when injecting a mixture of sand-water into the horizontal pipe. This concentration is achieved based on the different *in situ* sand concentrations ($Cv1$) required in the test section.
- $Q2$ represents a volumetric flow rate of sand-water from the sand hopper.
- $Q1$ denotes the calculated flow rate based on the given or required liquid flow rates at the test section.

3.3.1 Sand Properties Measurement

The sand used in this study was Congleton HST. Figures 3-10a, b and c depict average sand particle distribution for 212, 500 and 800 microns respectively. The porosities of these particles were determined through experiment. Table 3-3 lists the porosities of particles used in this study. The full description of how the porosities were determined can be found in Appendix B.

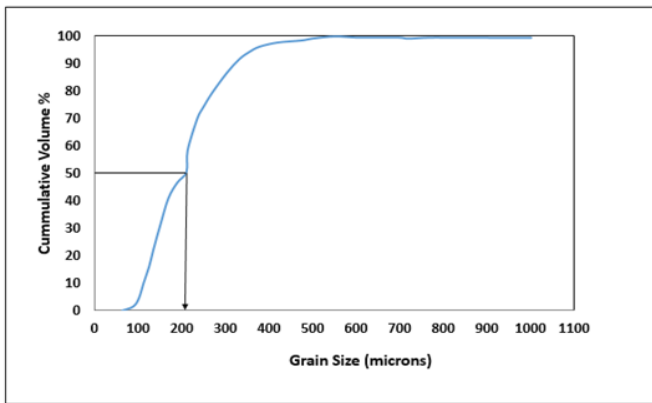
Table 3-3: Sand properties

Particle Diameter (microns)	Porosity %	Particle Density (kgm^{-3})
212	31.38	2650
500	30.69	2650
800	30.56	2650

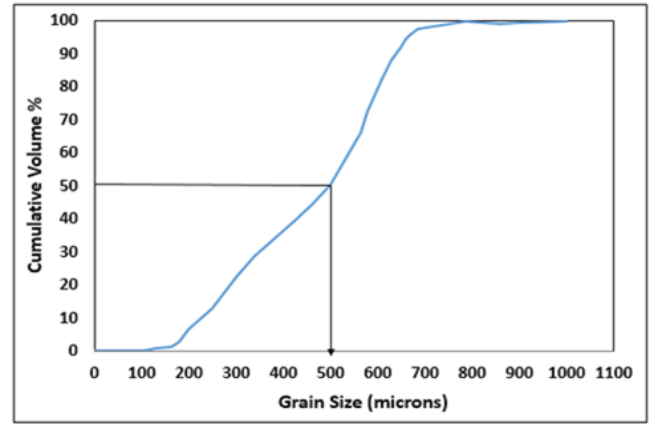
3.3.1.1 Procedure for sand sieving

The particle size distributions were obtained as follows: First, all the sieves were cleaned before use and each sieve was then weighed and recorded, including the bottom pan. The sieves were assembled in ascending order such that the last pan contained particles with the smallest microns. A dry sand sample that had been weighed was poured into the top sieve and covered with a cap.

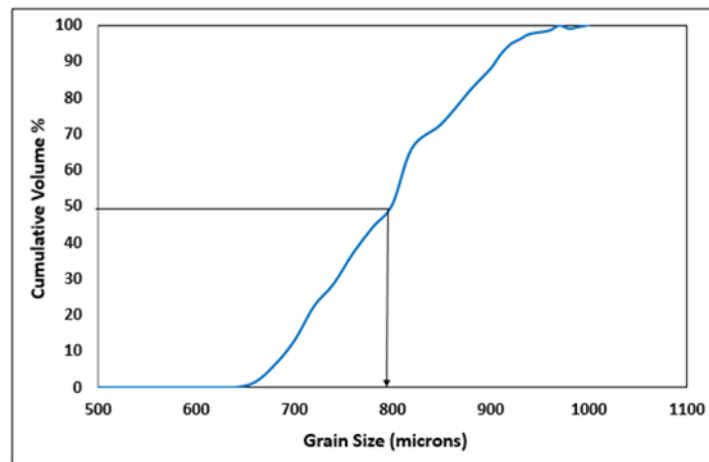
The sieve stack with the weighed dry sand sample was placed on a mechanical shaker for 35 minutes, after which the stack from the shaker was removed and each sieve with its retained content was weighed and recorded, including the bottom pan. The weight of each empty sieve was subtracted from the weight of sieve and its retained content to determine the mass of dry sand sample from each sieve. The percentage of dry sand on each sieve was calculated by dividing the weight of the retained dry sand on each sieve by the original sample mass. The cumulative percentage was determined and plotted against the grain size.



(a)



(b)



(c)

Figure 3-10: Sand particle distribution used in this study

3.4 Experimental Procedure

Test 1: Procedure for Sand-Water Settling Test

1. LabVIEW must be set to desired reading before the start of the experiment. This can be done by inputting the data needed on the LabVIEW display page and for gas and liquid superficial velocities, it is done by regulating the valves.
2. Make a preparation and weigh an accurate amount of sand that will result in the concentration of sand desired in the pipe.
3. The sand mixture is prepared in the sand hopper; this is executed by mixing the estimated sand with the known volume of water that will amount to the desired sand concentration within the horizontal test section for specific liquid superficial velocity.
4. Switch on the water Progressive Cavity Pump and set the superficial water velocity to the needed value by turning the line valve until the desired water superficial velocity is reached.
5. Introduce the sand-water mixture into the horizontal pipe under the homogeneous condition. This is done to obtain accuracy during the experiment.
6. Allow enough time for the desired water superficial velocity to stabilise and also for the sand-water mixture to reach the injection point of the horizontal pipe. Gradually decrease water velocity until the sand begins to settle before the LabVIEW is clicked on for recording purposes.
7. Ensure that the remaining sand within the flowline is flushed out after each experiment before conducting another experiment.
8. Repeat steps 1 to 7 for another experiment.

Test 2: Sand-Air-Water Multiphase Settling Test

The MTCs for sand are determined in air-water tests for different sand microns at different concentrations in the 2-inch test rig. In this experiment, water

superficial velocity is fixed for specific values and at these values, the gas flow rate is varied.

The procedure used to conduct the experiment is as follows:

1. A sand-water mixture of required concentration must be prepared in the sand mixing tank.
2. Control the water superficial velocity to a desired value by turning the valve within the line and introduce the air by opening the valve that controls it in the downstream.
3. Introduce sand into the horizontal pipeline from the sand hopper at a constant flow rate.
4. Decrease the gas flow rate at specific intervals for every fixed value of water superficial velocity.
5. Record and collect the data when the desired flow rate is achieved by using visual observation.
6. The remaining sand and air bubbles must be flushed out of the system before moving to the next experiment.
7. The next experiment is performed by changing the water superficial velocity to the next lower value.
8. The experiment must be repeated for another sand concentration

3.5 Cross Correlation

The average velocity measurement along the flow direction can be determined by the cross correlation of two sensor signals. Cross correlation is the standard method that measures the degree to which two signals relate to each other with respect to the displacement of time that exists between them. Identical signals tend towards unity when cross correlated. However, cross correlation for dissimilar signals will be closer to zero. Considering two different signals, $X(t)$

and $Y(t)$, then the cross correlation function $R_{xy}(\tau)$ can be defined as equation 3-1;

$$R_{xy}(\tau) = \lim_{N \rightarrow \infty} \frac{1}{N} \int_0^N X(t)Y(t + \tau)dt, \quad (3-1)$$

The cross correlation coefficient $C_{xy}(\tau)$ can be defined as equation 3-2;

$$C_{xy}(\tau) = \frac{R_{xy}(\tau)}{\sqrt{R_{xx}(0)R_{yy}(0)}} \quad (3-2)$$

where τ is the time delay between the two signals and it can be determined by searching for the time position of the maximum cross correlation coefficient.

The average flow velocity v can be calculated by equation 3-3;

$$V = \frac{L}{\tau} \quad (3-3)$$

where L is the distance between the centres of the two sensors.

3.6 Chapter Summary

In this chapter, experimental set-ups for sand-water and sand-air-water tests were described in detail. In addition, the design of the facilities used to investigate sand transport in single phase (Water) and multiphase (Air-water) were also discussed.

In section 3.1, water, air and sand-water mixture supply into the test section, as well as instrumentation specifications for air and water flow rate measurements, were discussed. In section 3.2, instrumentation used for measurement was discussed. This section also described the design aspects of the ring sensor, and the operating principle of ring and sand sensors. Furthermore, calibration curves for pressure transducers were presented with the data acquisition system used to obtain experimental data. Section 3.3 discussed the experimental programme of this study. It also discussed some of the techniques used to analyse data obtained from the experiments. The remaining sections discussed experimental procedures and cross correlation.

4 SAND-WATER RESULT, ANALYSIS AND DISCUSSION

4.1 Sand-Water Flow Regime Map

The sand-water settling tests were conducted to determine the different sand-water flow regimes and MTC. The liquid superficial velocity started from the highest to determine full suspension and gradually reduced to determine other sand-water flow regimes, such as streak, saltation and moving dunes. The reduction in the liquid superficial velocities caused all other sand-water flow regimes to occur. Figures 4-1, 4-2 and 4-3 depict sand-water flow regimes with MTC for 212, 500 and 800 microns respectively at concentration of 200lb and 500lb per 1000bbl.

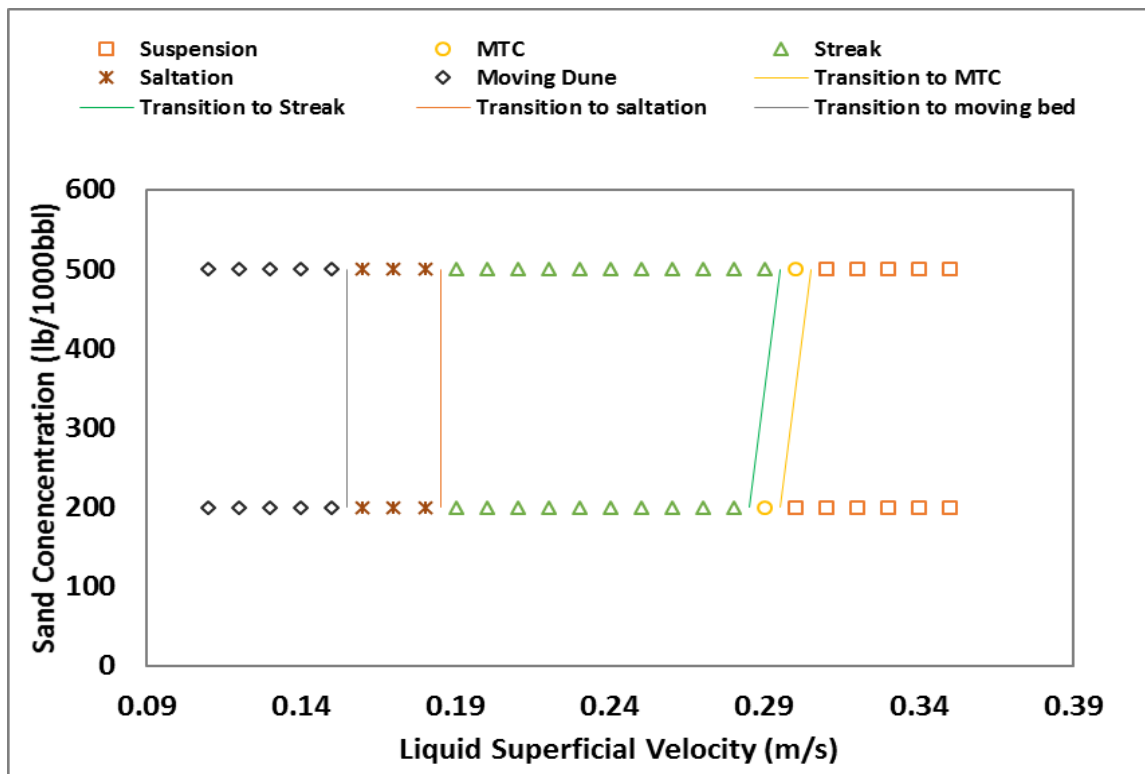


Figure 4-1: Sand-water flow pattern for 212 microns (200lb and 500lb per 1000bbl)

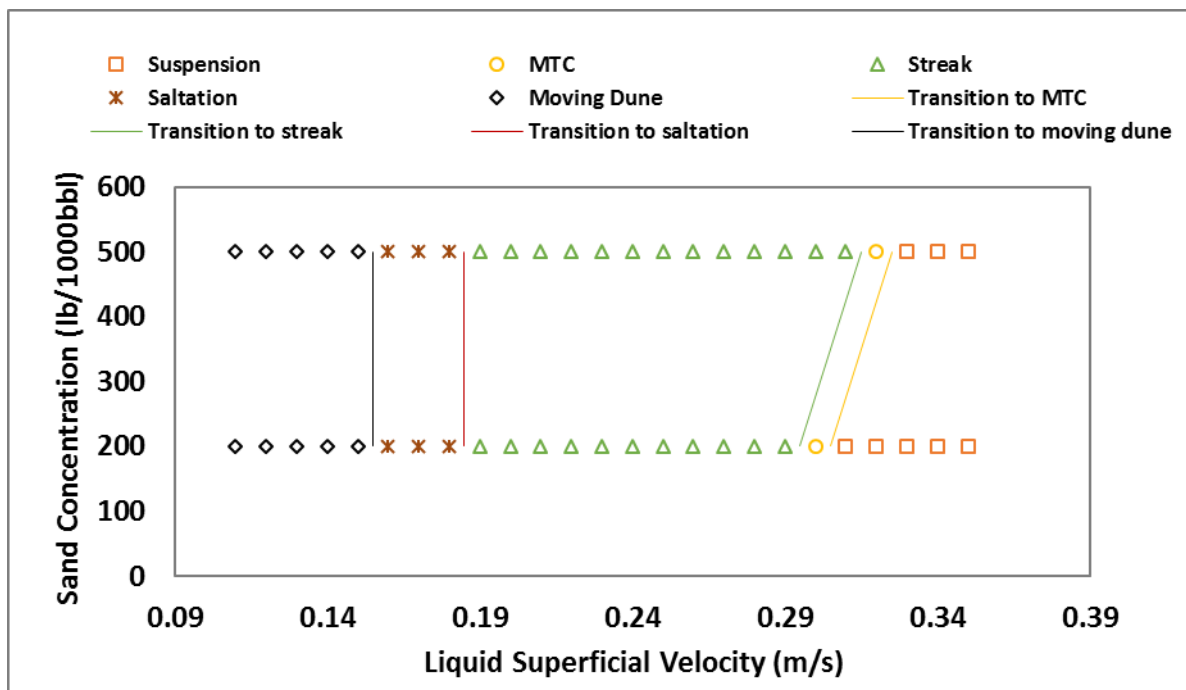


Figure 4-2: Sand-water flow patterns for 500 microns (200lb and 500lb per 1000bbl)

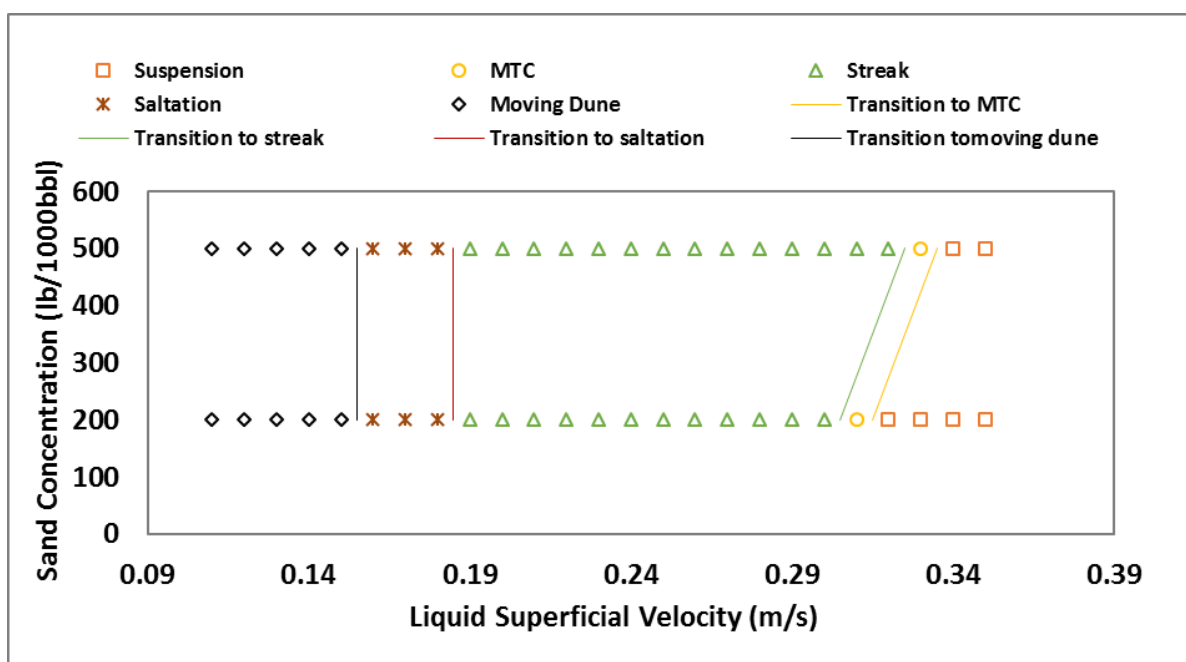


Figure 4-3: Sand-water flow patterns for 800 microns (200lb and 500lb per 1000bbl)

4.2 Sand Sensor with Respect to Sand-Water Flow Regime and Sand Characteristics in Pipelines

There are two methods that can be used to identify sand-water flow patterns and also to determine sand MTCs: (1) Sand-water settling method (2) Sand-water entrainment method. The *sand-water settling* method is when the liquid superficial velocities are gradually reducing from the higher velocity (suspension) to lower velocities in sequential order (when sand-water mixture is injected into the pipe) until the MTC and other sand-water flow patterns are observed. However, the *sand-water entrainment* method can be used to identify sand-water flow patterns and also to determine sand MTC. This is done by reducing liquid superficial velocity to the lowest when the sand-water mixture is injected into the horizontal pipe to form a sand bed along the pipe. The gradual increase of liquid superficial velocity in a sequential order helps to determine MTC and identify different sand-water flow patterns. This study employed the sand-water settling test to determine MTC and sand-water flow patterns.

Two conductivity sand sensors were installed downstream of the 2-inch horizontal pipe to monitor and understand sand-water flow behaviour during sand-water settling experiments. Data that were obtained from the conductivity sand sensor were studied and critically examined to determine the different sand-water flow patterns from the conductivity sand sensor signal. Furthermore, visual observation and several video clips were taken to analyse the sand-water flow regime in support of the sand sensor analysis. The signals obtained as time series from the conductivity sand sensors were analysed in such a way that the normalized voltage values from the sensor were plotted with the time. The raw voltage from the sand sensors for each sand-water flow pattern is normalized as follows:

$$Normalization = \frac{\text{Voltage of sand with water} - \text{Voltage of empty pipe}}{\text{Voltage of full pipe of water} - \text{Voltage of empty pipe}}$$

Each sand-water experiment was recorded from the conductivity sand sensor for 120 seconds. As a result of similarity in the behaviour of sand transport in water

flow for all concentrations and particle diameters tested, the normalized time series from the conductivity sand sensor signals of 212 microns sand particles diameter were considered for the identification of sand-water flow regimes (full suspension, streak, saltation, and moving dunes) for all particle diameters and sand concentrations.

4.2.1 Full suspension

When the liquid superficial velocity was reduced from 1m/s to 0.31m/s, all sand particles were still suspended but very close to the MTC. The snapshot and sand sensor signal for full suspension of sand particles with a size of 212 microns at a concentration of 500lb/1000bbl are shown in Figures 4-4 and 4-5 respectively. It can be observed from Figure 4-5 that the normalized voltage value is very close to 1.0 (unity) at this liquid superficial velocity. This implies that sand particles were not in contact with the conductivity sand sensor and also signifies that all the sand particles were suspended in the fluid (liquid).

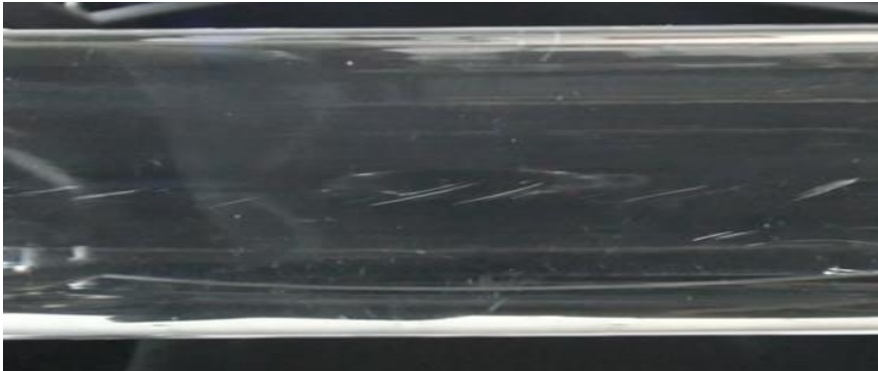


Figure 4-4: Snapshot of full suspension, (500lb/1000bbl, 212 microns $V_{sl}=0.31\text{m/s}$. Flow: left to right, View: Bottom)

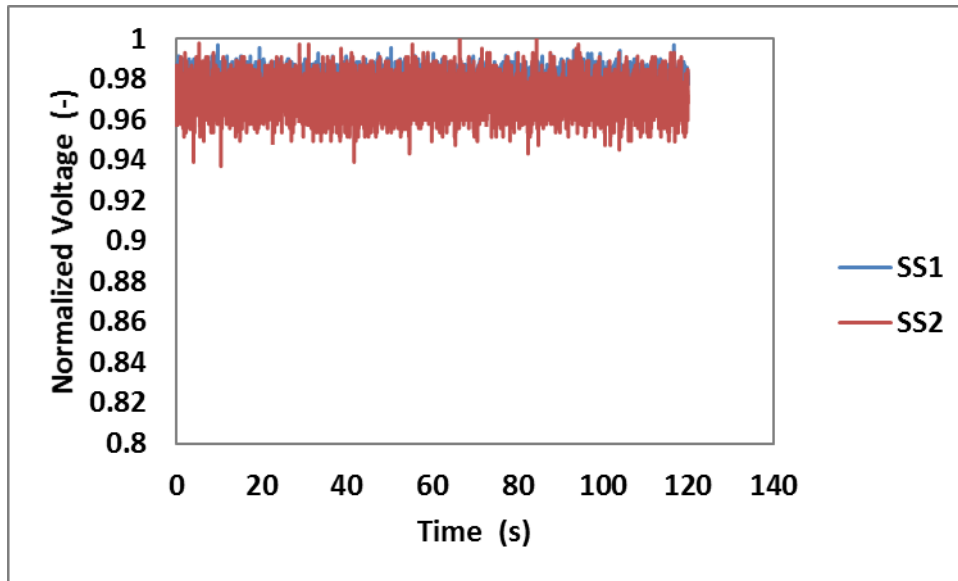


Figure 4-5: Signal of a full suspension from the sand sensor, (500lb/1000bbl, 212 microns $V_{sl}=0.31\text{m/s}$)

4.2.2 Streak

Further reduction of liquid superficial velocity from 0.31 to 0.20m/s caused sand streak to appear at the bottom of the pipe. The sand streak found moving at the bottom of the pipe at liquid superficial velocity 0.20m/s was dense. This flow is far below the MTC. Figures 4-6 and 4-7 depict the snapshot and sand sensor signal for the streak flow regime of sand particles' size of 212 microns at a concentration of 500lb/1000bbl, as the flow velocity was reduced to 0.20m/s. It can be observed from Figure 4-7 that the normalized voltage value is slightly less than the value of the full suspension flow regime. This indicates that sand was influencing the sand sensor output. Furthermore, Figure 4-7 shows a little dip at some points in the signal when sand particles were transported. The dip can be explained from Figure 4-6. The region marked with a red circle in Figure 4-6 shows that sand particles clump together in this region. The clumped sand particles cause a reduction in the conductivity between the electrodes of the sensor. This effect is due to the chaotic movement of the sand particles as they move in clumps and different speeds on the sand sensors.

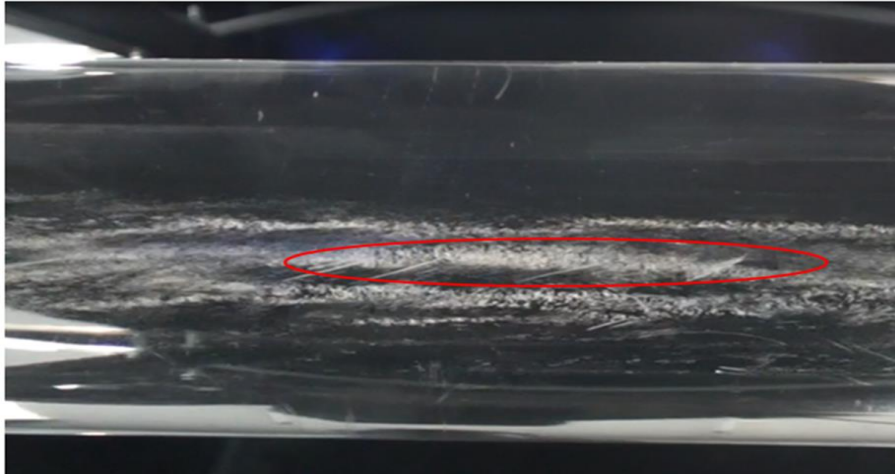


Figure 4-6: Snapshot of streak regime, (500lb/1000bbl, 212 microns, $V_{sl}=0.20\text{m/s}$. Flow: left to right, View: Bottom)

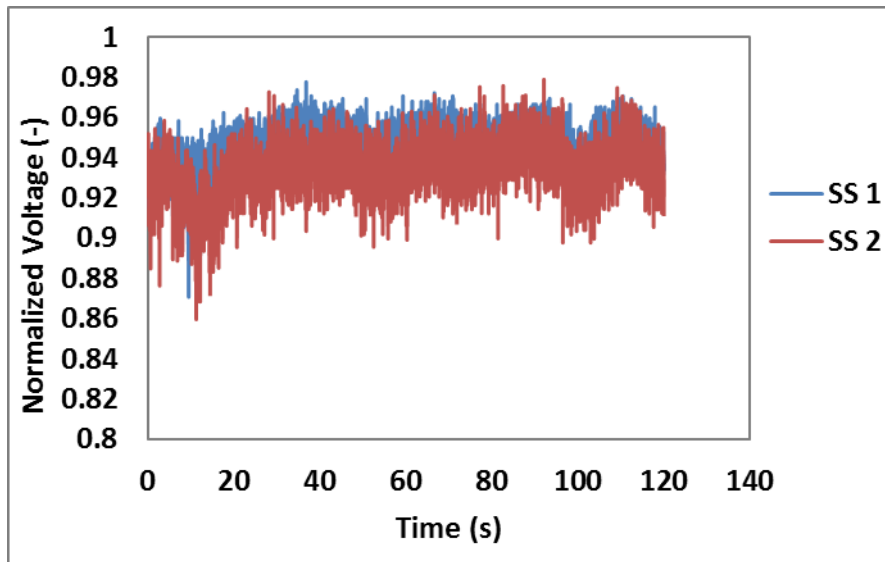


Figure 4-7: Signal of a streak from the sand sensor, (500lb/1000bbl, 212 microns $V_{sl}=0.20\text{m/s}$)

4.2.3 Saltation

When the liquid superficial velocity further reduced from 0.20m/s to 0.18m/s , a denser sand streak (saltation) was observed at the bottom of the pipe. Particles were seen bouncing from upstream to downstream with the sand streak moving slowly at the bottom of the pipe. Figures 4-8 and 4-9 represent the saltation flow regime of sand particles with a size of 212 microns at concentration of

500lb/1000bbl. The saltation flow regime shows a line of normalized time series that is more deviated from unity when compared with the normalized time series both from the suspension and streak flow regimes. This implies that more sand particles are moving at the bottom of the pipe. The movement of the sand particles at the bottom of the pipe was due to a further reduction in the liquid velocity. The velocity reduction causes the sand particles to come together. The saltation signal shown in Figure 4-9 behaves like a wave and exhibits crests and troughs. From Figure 4-8, it can be deduced that sand particles interact and concentrate more in the region marked with red circles (trough) when compared with the region outside the red circle (region with few, or a small amount of, sand particles). The trough in the signal occurs because of the large amount of sand particles which tend to cause a greater reduction in the conductivity between the electrodes of the sand sensors.

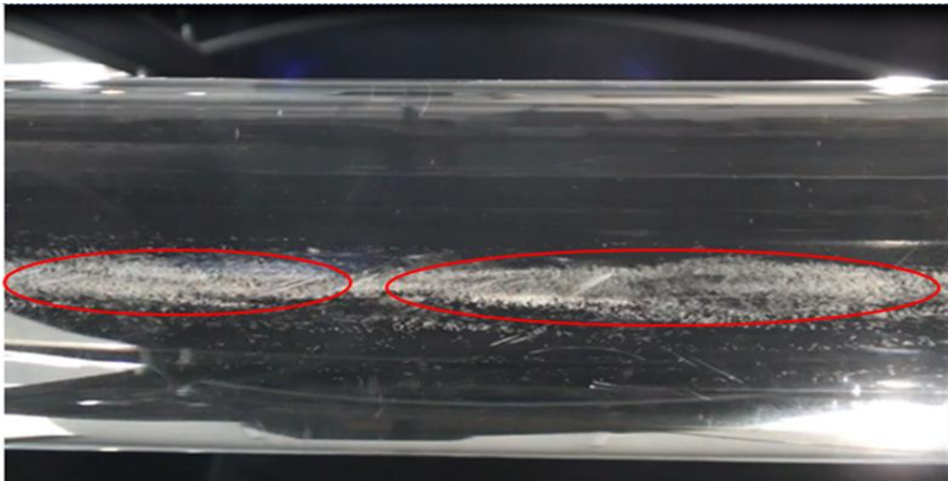


Figure 4-8: Snapshot of saltation regime, (500lb/1000bbl, 212 microns, $V_{sl}=0.18\text{m/s}$, Flow: left to right, View: Bottom)

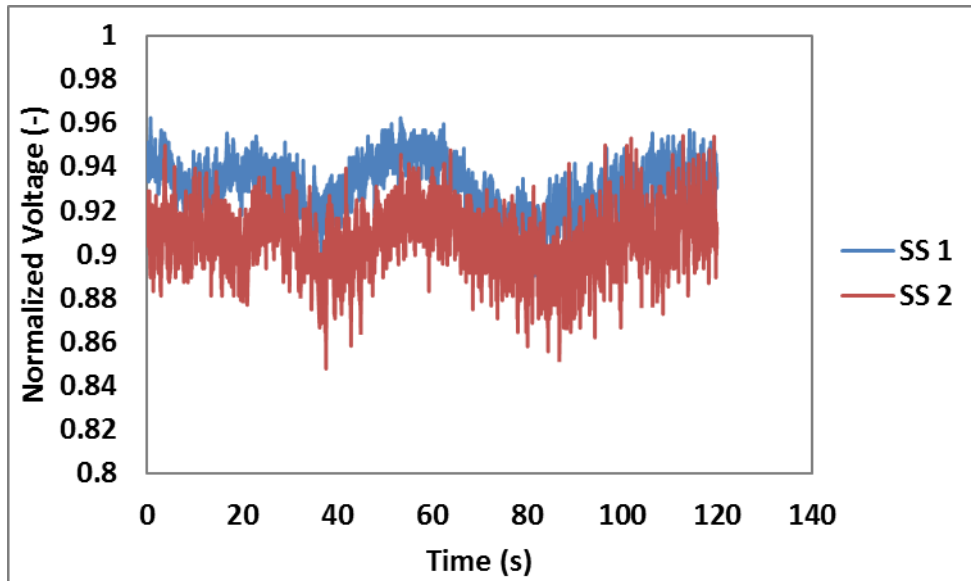


Figure 4-9: Signal of the saltation regime from the sand sensor, (500lb/1000bbl, 212 microns, $V_{sl}=0.18\text{m/s}$)

4.2.4 Moving Sand Dune

Moving dunes formed as soon as the flow velocity is reduced from 0.18m/s to 0.15m/s . The moving dunes are characterised by lumps of sand separated by few sand particles or water between them. They are very slow in movement when compared with saltation and streak. Figures 4-10 and 4-11 depict a moving dune flow regime of sand particles with a size of 212 microns at a concentration of 500lb/1000bbl. This flow regime shows line of normalized time trace that is farthest from one (unity), when compared with the normalized time series from suspension, streak and saltation flow regimes. This is because many sand particles are migrating as an island at the bottom of the pipe. The sand sensor resistivity effect is most pronounced with moving dunes when compared with other sand flow regimes (streak and saltation). This is because large amounts of sand particles form the dunes. Furthermore, it can be observed from Figure 4-10 that the dunes are separated with few sand particles and more water when compared with Figure 4-8 (Saltation). The space between the dunes tends to result in an increase in conductivity of the sand sensor due to the dominance of water in-between the moving dunes.

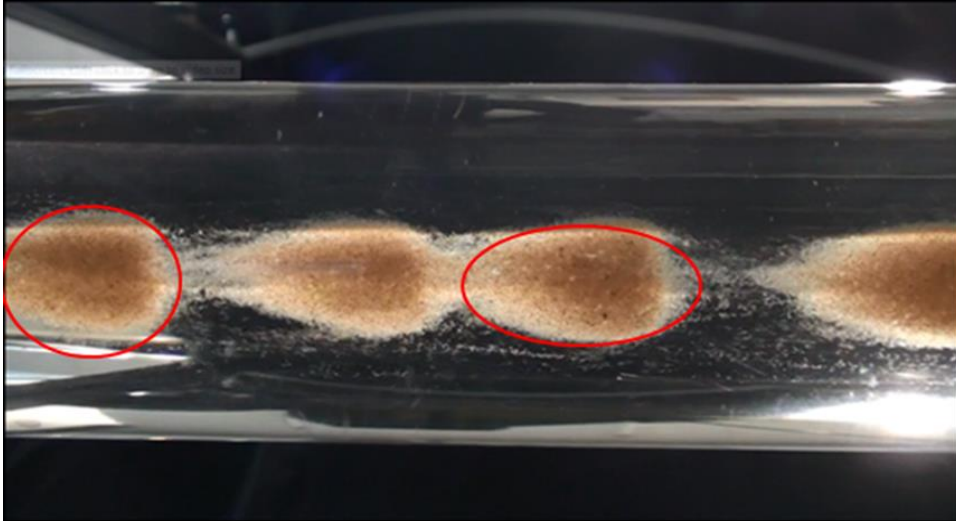


Figure 4-10: Snapshot of a moving sand dune regime, (500lb/1000bbl, 212 microns, $V_{sl}=0.15\text{m/s}$. Flow: left to right, View: Bottom)

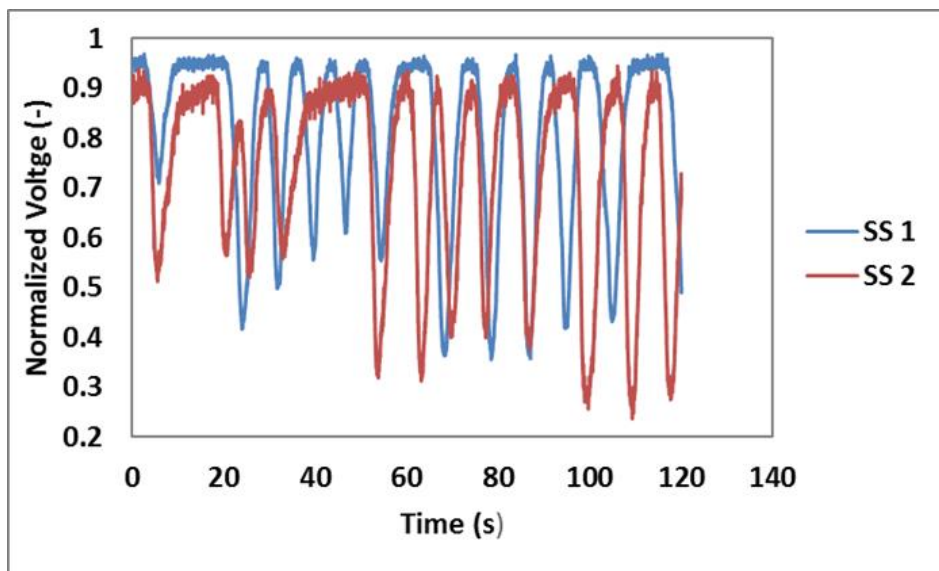
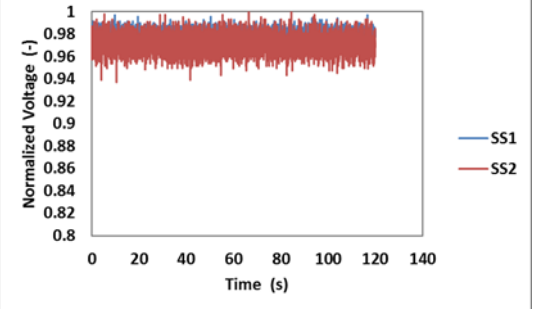
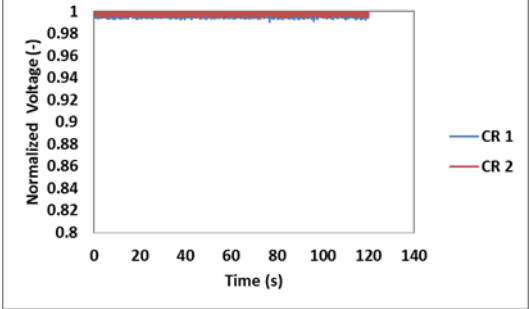
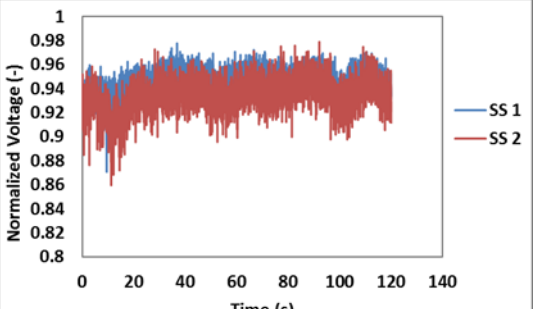
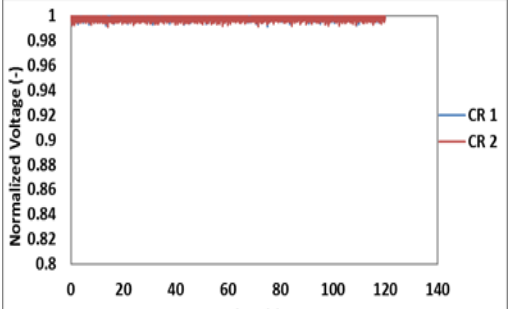
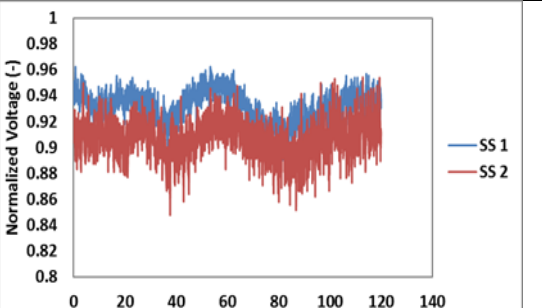
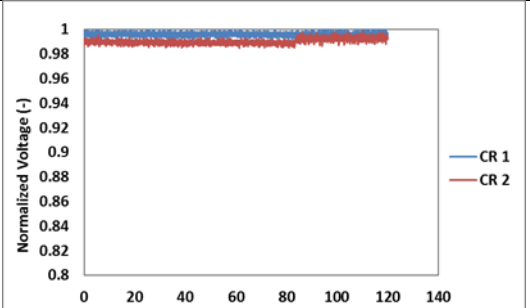
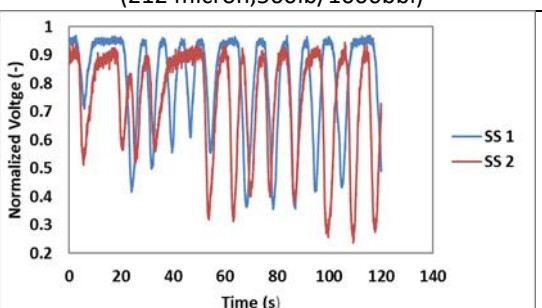
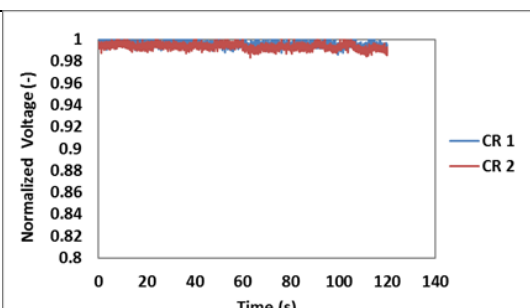


Figure 4-11 : Signal of a moving sand dune regime from the conductivity sand sensor, (500lb/1000bbl, 212 microns, $V_{sl}=0.15\text{m/s}$)

4.3 Comparison of Sand Sensor and Conductivity Ring Signals for a Sand-Water Flow Regimes

Different sand-water flow regime signals are shown in Table 4-1. A conductivity ring and sand sensors were used to identify different sand-water flow regimes. It can be seen from Table 4-1 that the conductivity ring sensors have less output response to the sand-water flow regime (suspension, streak and saltation). However, there is a greater response of conductivity ring to moving dune. The sand sensors responded better to the sand-water flow regimes when compared with the conductivity ring sensors. Conductivity ring sensors are less sensitive to a small amount of sand in water because its response is across the cross-sectional area while the concentric geometry of the sand sensor allows the measurement to be reasonably localized. Because ring sensors are less sensitive to a small amount of sand in water, the gas fraction or liquid hold-up measurement will not be affected in sand-air-water studies.

Table 4-1: Conductivity ring and sand sensor signals

Sand Sensor Signal	Conductivity Ring Signal
 <p data-bbox="363 658 671 712">Suspension Vsl 0.31m/s (212 micron,500lb/1000bbl)</p>	 <p data-bbox="938 658 1246 712">Suspension Vsl 0.31m/s (212 micron,500lb/1000bbl)</p>
 <p data-bbox="363 1061 671 1115">Streak Vsl 0.20m/s (212micron,500lb/1000bbl)</p>	 <p data-bbox="938 1061 1246 1115">Streak Vsl 0.20m/s (212 micron,500lb/1000bbl)</p>
 <p data-bbox="363 1460 671 1514">Saltation Vsl 0.18m/s (212 micron,500lb/1000bbl)</p>	 <p data-bbox="938 1460 1246 1514">Saltation Vsl 0.18m/s (212 micron,500lb/1000bbl)</p>
 <p data-bbox="363 1845 671 1899">Moving Dune Vsl 0.15m/s (212 micron,500lb/1000bbl)</p>	 <p data-bbox="938 1845 1246 1899">Moving Dune Vsl 0.15m/s (212 micron,500lb/1000bbl)</p>

4.4 Analysis of the Sand Sensor with Respect to Sand-Water Behaviour

4.4.1 Coefficient of Variation of the Sand Sensor

The coefficient of variation, standard deviation and mean normalized voltage for MTC and each sand-water flow regime for 212 microns (500lb per 1000bbl) are indicated in Table 4-2. The importance of this section is to apply the coefficient of variation to identify when sand will be transported as a suspension or moving dunes with the aid of the sand sensor

Table 4-2: Coefficient of variation and sand-water flow regime

Sand Sensor				
212 microns, 500lb/1000bbl				
Flow Regime	Vsl (ms⁻¹)	Mean Normalised Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation (%)
Suspension	0.31	0.98	±0.0023	0.24
MTC	0.30	0.97	±0.0033	0.34
Streak	0.20	0.94	±0.0087	0.93
Saltation	0.18	0.91	±0.0099	1.09
Moving Dune	0.15	0.77	±0.13	16.88

In Table 4-2 the coefficient of variation for suspension and MTC of 212 microns (500lb per 1000bbl) are 0.24 and 0.34% respectively and other sand-water flow regimes indicated higher coefficient of variation. This implies that suspension and MTC had less variability in their data points than other sand-water flow regimes. Thus, the data points for each of suspension and MTC are close. This is due to the fact that particles were not in contact with the sand sensor during suspension and fewer particles were in contact with the sand sensor at MTC. Therefore, the sand sensor response to the suspension and MTC has not fluctuated much. Streak and saltation (sand-water flow regime) have coefficients of variation of

0.93 and 1.09% respectively. The coefficient of variation of streak and saltation are greater and their data points are more dispersed, when compared with MTC and the suspension sand-water flow regime. This indicates that streak and saltation had higher variability because sand particles in a conducting liquid are more in contact with the sand sensor and chaotic in their movement. Finally, a moving dune which is transported as lumps has a coefficient of variation of 16.88%. The large coefficient of variation could be due to sand having being transported as lumps and the concentration measured by the sand sensor fluctuating wildly.

Sand particles will be transported as suspension in single phase water when the coefficient of variation is small and the data points from the sand sensor are close and consistent. However, they could be transported as a moving dune when the data points are far apart with a very high coefficient of variation.

Note: *Coefficient of variation* = $\left(\frac{\text{Standard deviation of normalised voltage}}{\text{Mean normalised voltage}} \right) * 100$

4.4.2 Frequency Domain Analysis

Figures 4-12 to 4-16 depict the PSD of the sand-water flow regime for 212 microns at 500lb per 1000bbl. Figure 4-12 shows that suspension is characterised with a spectrum of several peaks which spread from 0 to 5Hz with the dominant frequency at 0.8Hz. Figure 4-13 represents the PSD at MTC. The PSD for MTC constitutes several peaks of almost the same height which spread from 0 to 5Hz and the dominant frequency occurred at 0.1Hz. The streak flow regime PSD is depicted in Figure 4-14. The PSD of the streak flow pattern is characterised by several peaks from 0 to 5Hz with dominant frequency occurring at ~0.1Hz. The PSD of saltation is shown in Figure 4-15. The spectrum for saltation constitutes several peaks between 0 and 1.5 Hz and spectra almost disappear from 1.5 to 5Hz and the dominant frequency occurred at ~0.5Hz. The moving dune in Figure 4-16 has a pronounced frequency between 0 and 0.1Hz and there are no peaks from ~0.2 to 5Hz; the dominant frequency occurs at ~0.1Hz. By considering the PSD from the moving dune to suspension (i.e.

Figures 4-16 to 4-12), shows that as the liquid flowrate rate or liquid superficial velocity increases the sand particles transported over the sand sensor become less concentrated and the spectral peaks of the PSD spread out from the left to the right and their amplitudes increased from the moving dune to suspension. This implies that the energy needed to transport sand particles in a moving dune flow regime was lower than that of suspension. Thus, energy increases with increased flow rate.

In sand-water flow, sand is transported as a suspension when the PSD has its peaks spreading from 0 to 5Hz by analysing the sand sensor.

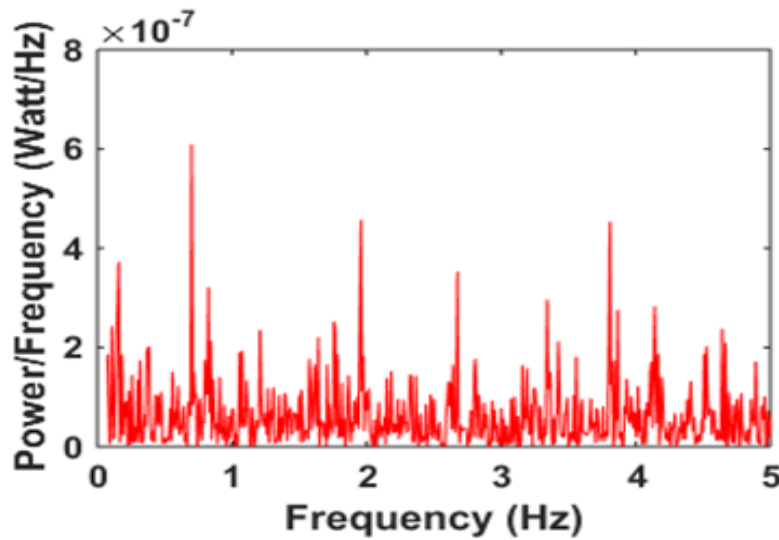


Figure 4-12: Power spectral density for sand-water flow regime (Suspension)

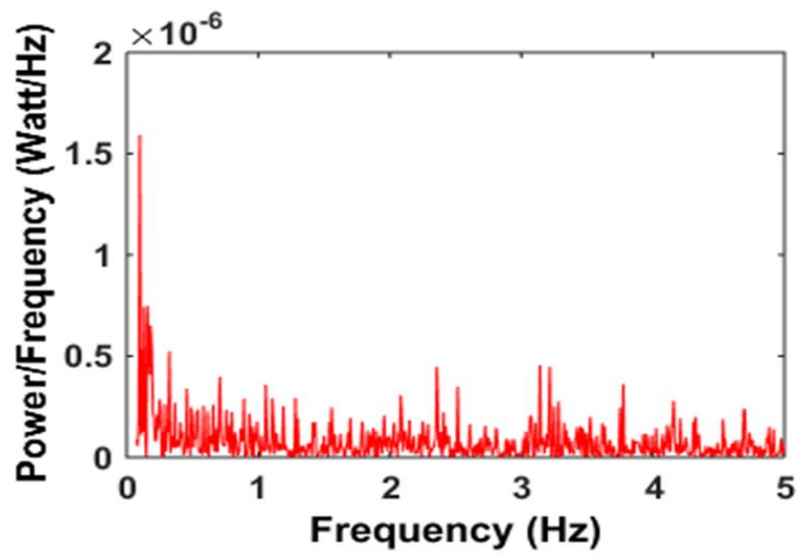


Figure 4-13: Power spectral density for sand-water flow regime (MTC)

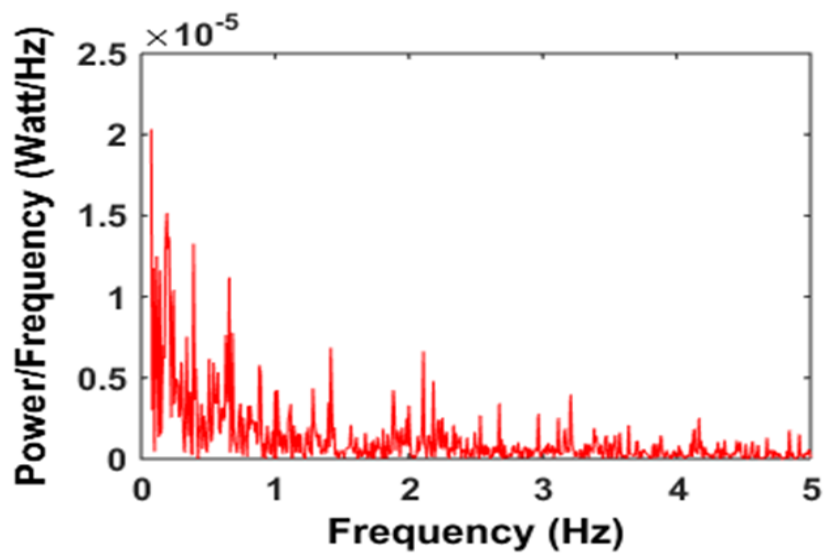


Figure 4-14: Power spectral density for sand-water flow regime (Streak)

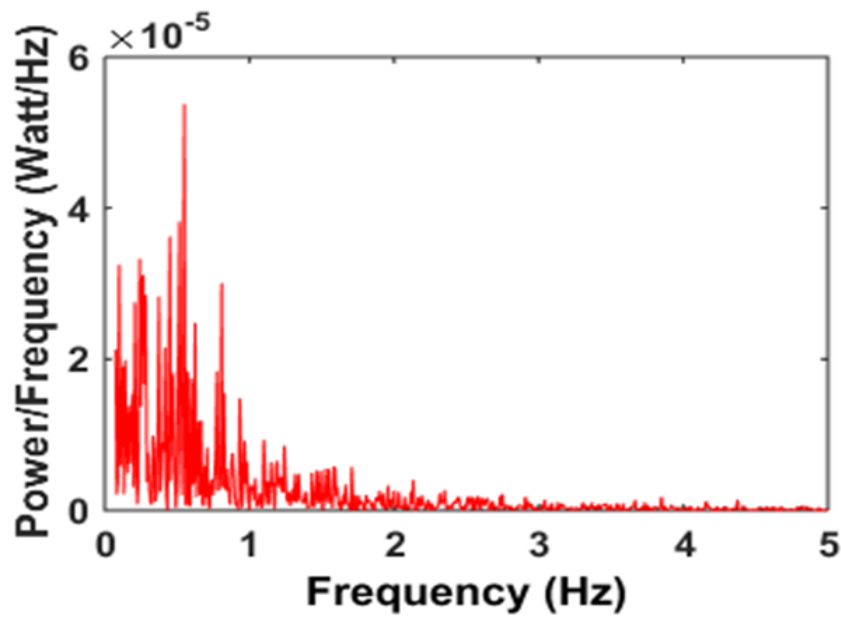


Figure 4-15: Power spectral density for sand-water flow regime (Saltation)

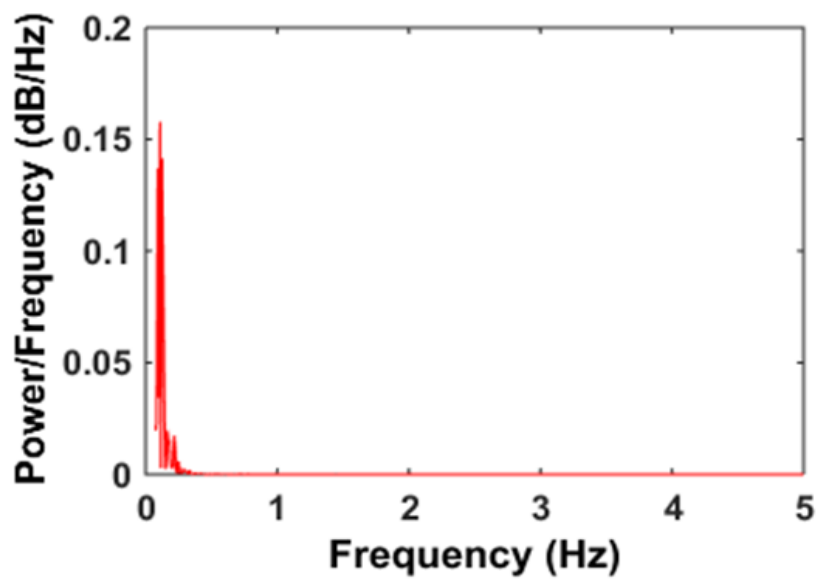


Figure 4-16: Power spectral density for sand-water flow regime (Moving Dune)

4.5 Equivalent Sand Thickness

The response of the sand sensor was converted (voltage) to equivalent sand thickness for each flow regime. The equivalent sand thickness presented was

obtained from the plot of sand height against normalized voltage in Figure A-5 in Appendix A.2. The equivalent sand thickness of each sand-water flow regime for 212 microns at concentration of 200lb and 500lb per 1000bbl are shown in Figure 4-17. The sand sensor response in the form of equivalent sand thickness from Figure 4-17 indicates that the suspension flow regime exhibits low equivalent sand thickness, while the moving dune exhibits the highest equivalent sand thickness among the entire sand-water flow regimes observed in this study. The response of the sand sensor also showed that saltation flow regimes exhibit a higher thickness when compared with suspension and streak. The response of the sand sensor, as equivalent sand thickness, is also used to compare concentration (212 microns, 200lb and 500lb per 1000bbl). It is shown in Figure 4-17 that the higher the concentration for each sand-water flow regime, the higher the equivalent sand thickness. Comparing the moving dune of 200lb and 500lb per 1000bbl at the same liquid superficial velocity (0.15m/s), it can be seen from Figure 4-17 that the response of the sand sensor as equivalent sand thickness for 500lb is higher than 200lb per 1000bbl, likewise for other flow regimes (streak and saltation). However, the equivalent sand thickness for suspension is the same for both 200lb and 500lb per 1000bbl. This is because in the suspension, sand particles are being suspended and make less contact with the sand sensor.

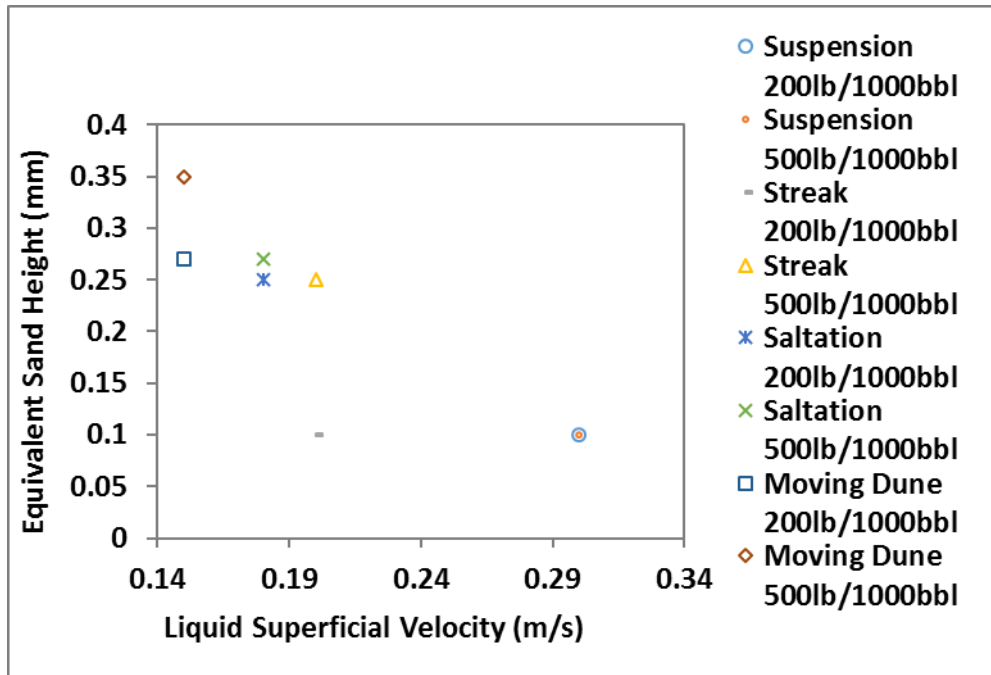


Figure 4-17: Equivalent height against sand-water flow regimes (212 microns, 200 and 500lb/1000bbl)

4.6 Liquid Velocity at Minimum Transport Condition

Experimental works were carried out to determine the MTC for particle size (diameter) of 212, 500 and 800 microns in water (water-sand). Table 4-3 depicts the experimental results for sand-water at MTCs.

Table 4-3: Actual Liquid Velocity at Minimum Transport Condition

Particle Diameter micron	V_L at MTC for sand – water (ms^{-1}) (200lb per 1000bbl)	V_L at MTC for sand – water (ms^{-1}) (500lb per 1000bbl)
212	0.29	0.30
500	0.30	0.32
800	0.31	0.33

4.6.1 Comparison of MTC in Sand-Water Flow

Figures 4-18, 4-19 and 4-20 show the comparison between experimental MTC of 212, 500 and 800 microns respectively in a 2-inch pipeline (this work) with published correlations.

It is shown in Figure 4-18 that Danielson (2007) and Stevenson and Thorpe (2002) over-predicted the MTC (velocity) for 212 microns at 200lb and 500lb per 1000bbl, while Thomas Lower model (1962) under predicted MTC for 200lb and 500lb per 1000bbl. In Figure 4-19, Stevenson and Thorpe (2002), Danielson (2007) and Thomas Lower model (1962) over-predicted the MTC (velocity) for 500 microns at concentrations of 200lb and 500lb per 1000bbl. Furthermore, in Figure 4-20, Thomas (1962) lower model, and Danielson (2007) over-predicted the MTC for 800 microns at 200lb and 500lb per 1000bbl. However, Stevenson and Thorpe (2002) predicted the MTC's result exactly as the result from experimental work for 200lb per 1000bbl, but Stevenson and Thorpe (2002) under-predicted MTC for 500lb per 1000bbl for 800 microns. The over-prediction of Thomas lower model (1962), for 500 and 800 microns may be due to the fact that the model was developed using a small particle size (less than 100 microns).

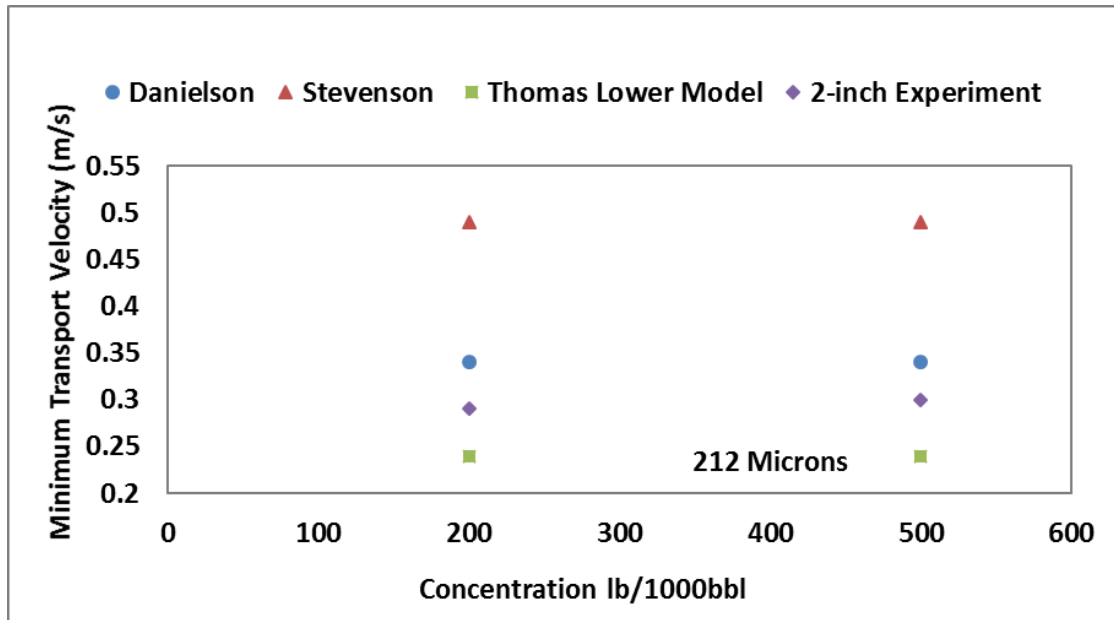


Figure 4-18: Comparison of experimental MTC with that predicted for 212 microns

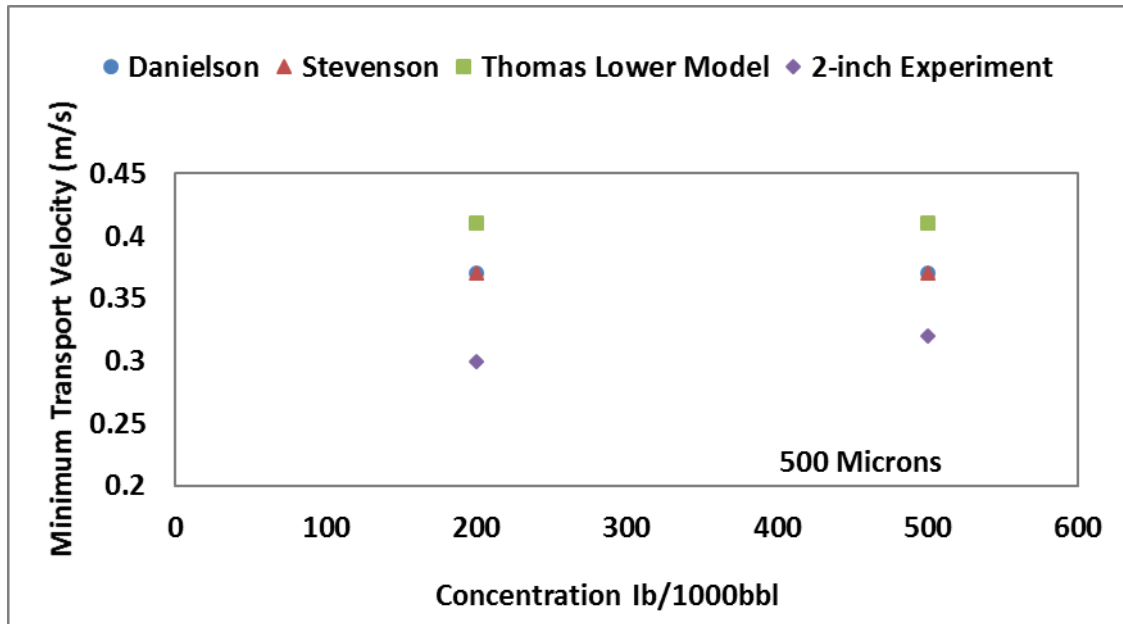


Figure 4-19: Comparison of experimental MTC with that predicted for 500 microns

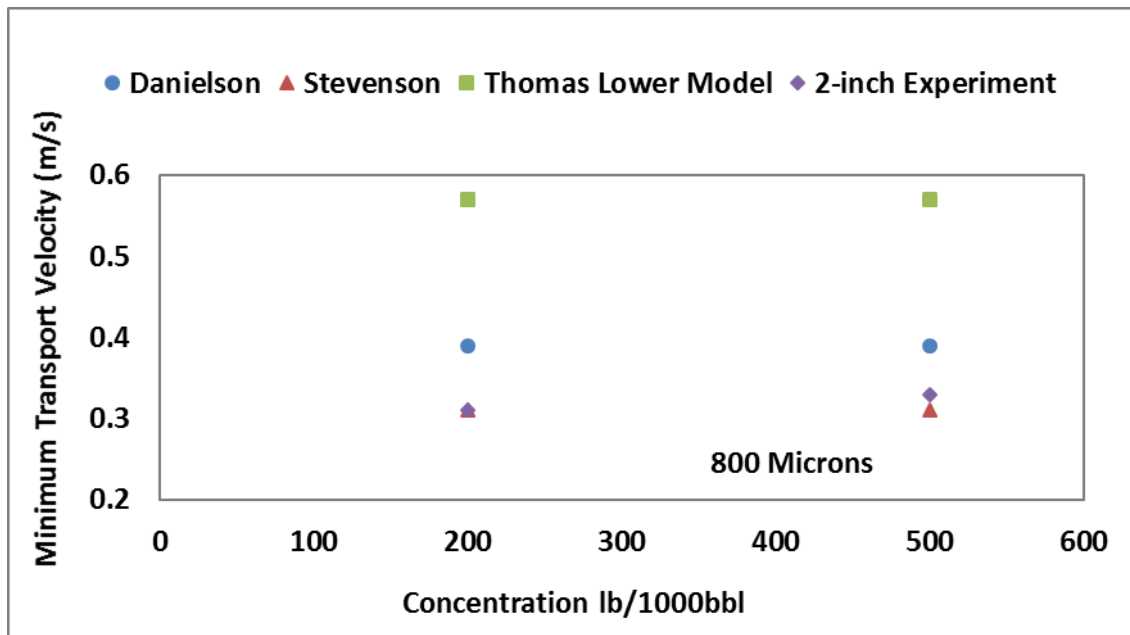


Figure 4-20: Comparison of experimental MTC with that predicted for 800 microns

4.6.2 Percentage Relative Error

Tables 4-4 and 4-5 depict the relative percentage error of different correlations when compared with MTC from 2-inch pipe. The percentage relative error of Danielson (2007) is minimal when compared with Stevenson and Thorpe (2002)

and the Thomas lower model (1962). This indicates that Danielson (2007) predicted better than both Stevenson and Thorpe (2002) and the Thomas lower model (1962). It is also seen from Tables 4-4 and 4-5 that for higher sized particles at different concentrations, Stevenson and Thorpe (2002) exhibit lower percentage relative error and predict better as the particle size increases. Furthermore, as the particle size increases for a specific concentration, the percentage relative error for the Thomas Lower model (1962) and Danielson (2007) also increases. However, their percentage relative error decreases with an increase in concentration.

Table 4-4: Percentage relative error of predicted MTC for 200lb per 1000bbl

% Relative Error for 200lb per 1000bbl			
Author (Correlation)	212 microns	500 microns	800 microns
Danielson (2007)	17.24	23.33	25.80
Stevenson (2001)	68.96	23.33	0.00
Thomas Lower Model (1962)	17.24	36.67	83.87

Table 4-5: Percentage relative error of predicted MTC for 500lb per 1000bbl

% Relative Error for 500lb per 1000bbl			
Author (Correlation)	212 microns	500 microns	800 microns
Danielson (2007)	13.33	15.63	18.18
Stevenson (2001)	63.33	15.63	6.06
Thomas Lower Model (1962)	17.24	28.12	72.73

4.7 Pressure Gradient

The pressure gradients for 212 microns at 200lb and 500lb per 1000bbl are depicted in Figures 4-21 and 4-22 respectively. The friction loss and pressure gradient increase as the liquid superficial velocity increases. Figures 4-21 and 4-22 indicate a higher pressure gradient at a superficial liquid velocity of 0.18 m/s (saltation) when compared with streak (Vsl 0.20m/s) for both 200lb and 500lb per

1000bbl. The higher pressure gradient at 0.18 m/s, may be due to the fact that there was sedimentation, where the velocity of sand is either near zero or the flow passage became smaller as a result of low liquid superficial velocity to transport sand particles. This phenomenon was also reported by Jason and Shook (2000).

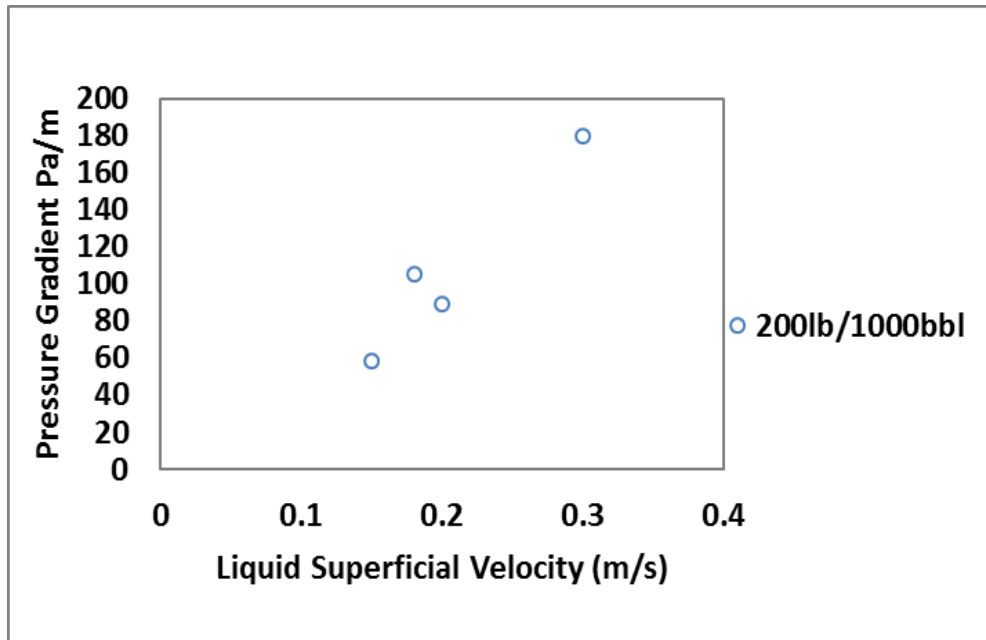


Figure 4-21: Pressure gradient for 200lb per 1000bbl (212 microns)

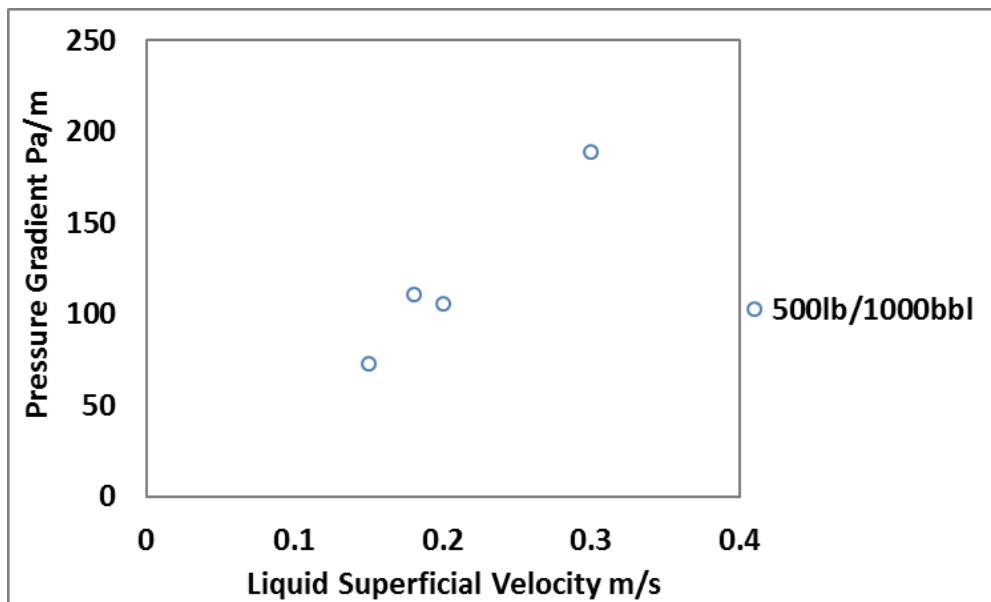


Figure 4-22: Pressure gradient for 500lb per 1000bbl (212 microns)

4.8 Chapter Summary

This section summarises Chapter 4: the sand-water flow regime; identification of sand-water flow regimes with the aid of a sand sensor; pressure gradient; comparison of sand sensor signals with conductivity ring signals for a sand-water flow regime; and analysis of sand using a conductivity sensor.

In this study, sand-water flow regimes were developed for different sand particle diameters (212, 500 and 800 microns) at concentrations of 200lb and 500lb per 1000bbl based on sand sensor analysis and visual observation. However, 212 microns' results were presented, analysed and served as representative of other particle diameters. Based on the analysis of the sand sensor with visual observation, four sand-water flow regimes were identified with MTC: suspension, streak, saltation and moving dune flow regimes. Suspension occurs at the highest liquid flow rate and a gradual reduction of the liquid flow rate caused MTC and other sand-water flow regimes to appear. The signals of suspension, streak and saltation flow regimes are similar, but are different in closeness to unity (1) while the signal of the moving dune is totally different from other sand-water flow regimes. The mean normalized voltage of each flow regime is also different; suspension has the highest while moving dune has the lowest.

Statistical methods such as PSD and coefficient of variation were used to analyse each sand-water flow regime. It was observed that the moving dune has the highest coefficient of variation while suspension has the lowest when compared with other sand-water flow regimes (streak and saltation). Conductivity ring sensors are less sensitive to the measurement of a sand-water flow regime because its response is across the cross-sectional area while the concentric geometry of the sand sensor allows the measurement to be reasonably localized.

5 AIR-WATER AND SAND-AIR-WATER EXPERIMENTAL RESULTS AND ANALYSIS

This chapter describes and examines the results of the air-water and sand-air-water experiments carried out on a 2-inch horizontal facility.

5.1 Air-Water Flow Regime Map

Prior to the investigation of sand transport in air-water, the flow regime map for stratified flow was developed and analysed because this work is focused on sand transport in wet gas pipelines.

The air-water flow regimes in this study were observed visually, and analyses were also carried out from the conductivity ring. The flow regime map for different stratified flows in the pipeline were developed by plotting different liquid superficial velocities against gas superficial velocities.

Air-water flow experiments were conducted on the 2-inch test facility for specific liquid superficial velocity, to determine flow conditions before the sand-air-water experiment. The experiments were carried out in such a way that the liquid superficial velocity was fixed for each specific value and gas superficial velocities were varied at each specific value for liquid superficial velocity. Figure 5-1 shows the air-water flow regime map for liquid superficial velocities of 0.06, 0.07, 0.08 and 0.09m/s with varying gas superficial velocities.

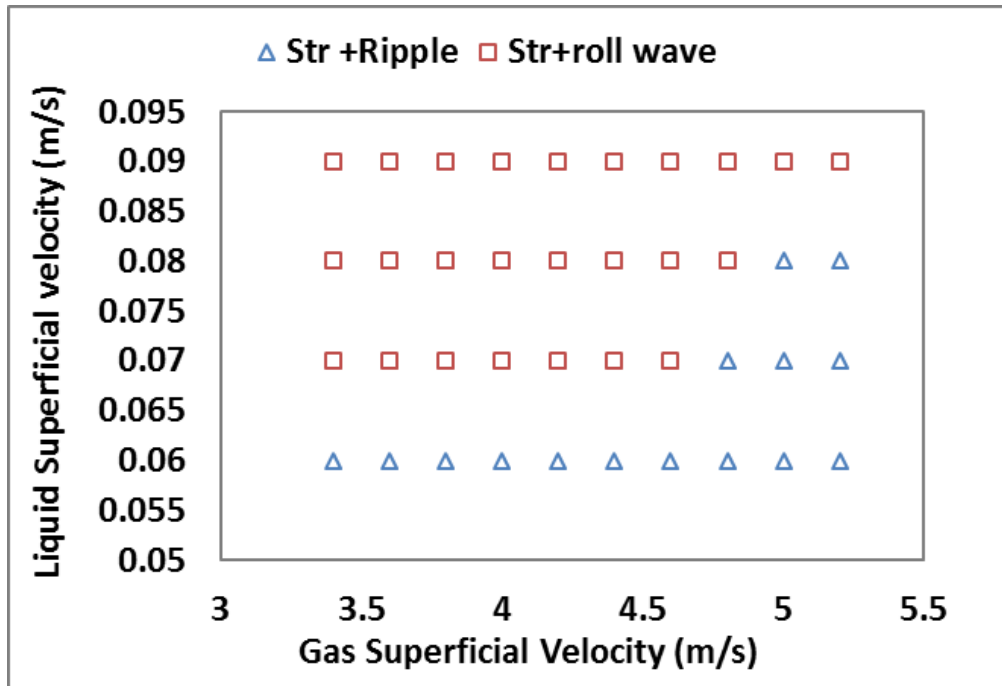


Figure 5-1: Air-water flow regime map used in this work

5.2 Hold-up

The liquid hold-up was measured using conductivity ring sensors (CR1 and CR2) installed on the 2-inch horizontal test facility used for this study. The conductivity ring sensors (CR1 and CR2) were flush-mounted on the 2-inch pipe. Figure 5-2 shows the plot of liquid hold-up against gas superficial velocity. It can thus be deduced from Figure 5-2 that as the gas superficial velocity increases, the hold-up tends to decrease. Furthermore, as the liquid superficial velocity increases, the hold-up also increases.

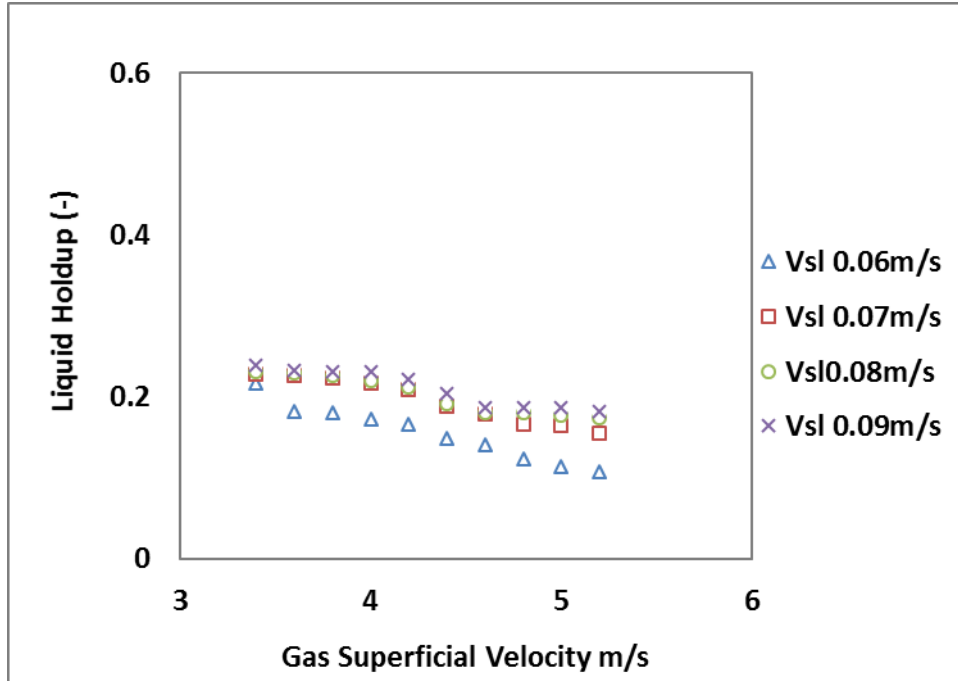


Figure 5-2: Liquid hold-up against gas superficial velocity

Two patterns of stratified wavy flow were encountered in this study (Stratified plus ripple wave and Stratified plus energetic roll wave). The signal and snapshot of stratified plus ripple wave and stratified plus energetic roll wave are shown in Figures 5-3, 5-4, 5-5 and 5-6 respectively. The signals shown in Figures 5-3 and 5-5 were identified with the use of a conductivity ring sensor. Stratified plus ripple wave can be identified by the peak to valley wave which occurs frequently or periodically (visual observation). Stratified plus energetic roll wave is a flow pattern in which the back of the wave is less steep when compared with its front (visual observation). The wave occurs as a result of the transfer of energy from the gas phase to the liquid phase. Furthermore, stratified plus energetic roll wave and stratified ripple structures are found to have different wave amplitudes. Stratified plus energetic roll wave is active and more energetic when compared with stratified plus ripple wave.

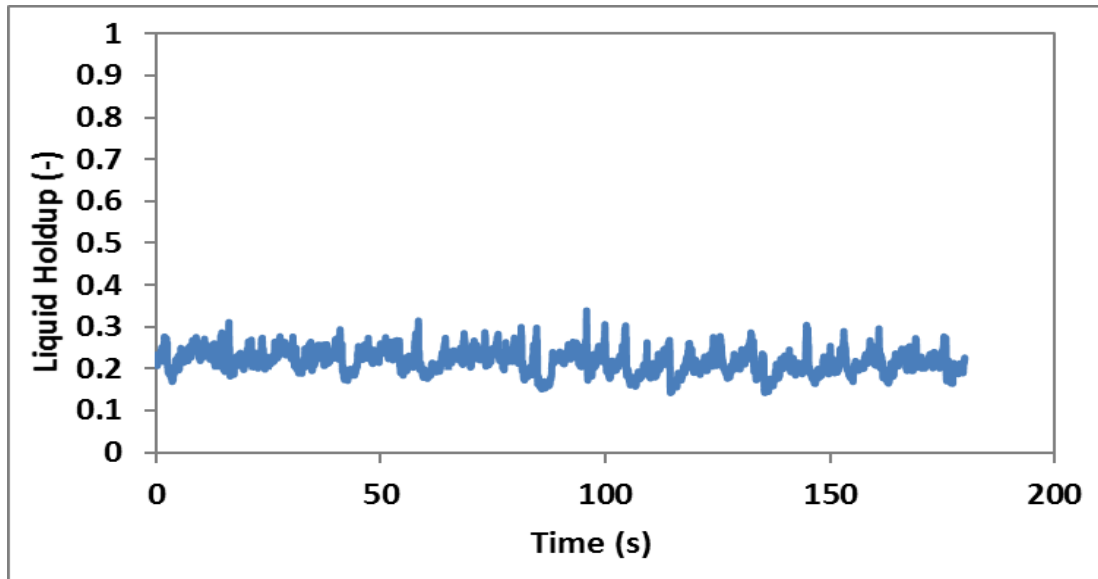


Figure 5-3: Signal view of stratified plus ripple wave from the conductivity ring (Vsl 0.07m/s, Vsg 5.0m/s)

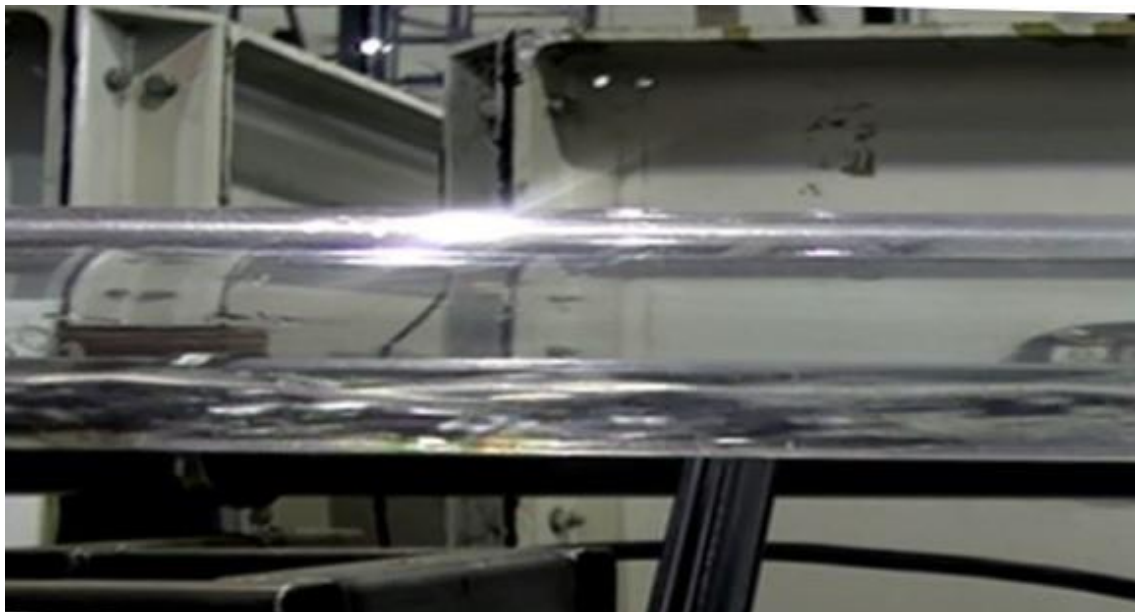


Figure 5-4: Snapshot of stratified plus ripple wave (Side view, flow from left to right 0.07m/s, Vsg 5.0m/s)

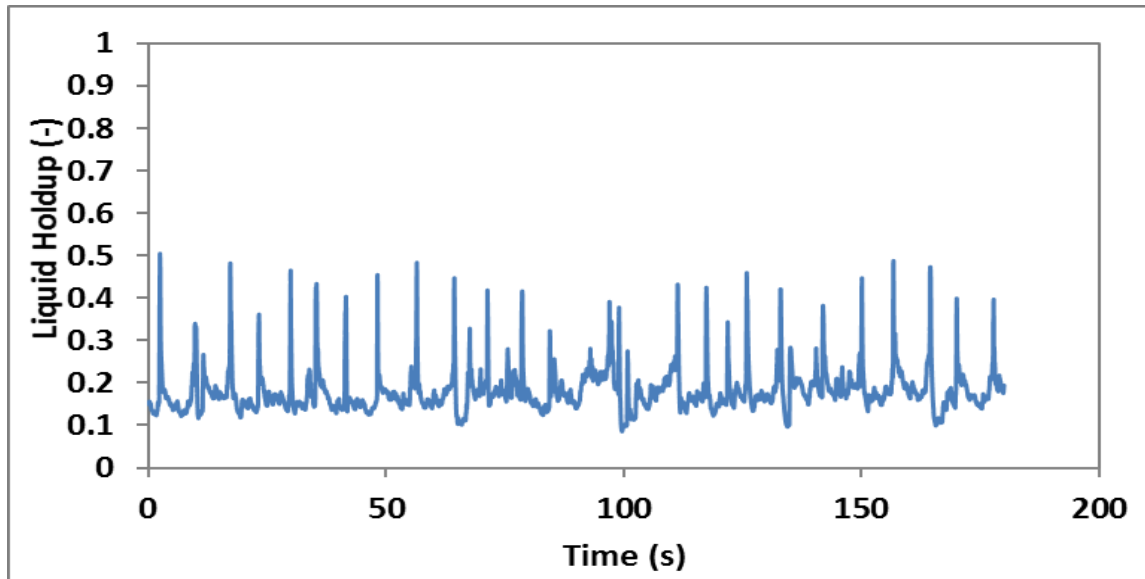


Figure 5-5: Signal view of stratified plus energetic roll wave from the conductivity ring (V_{sl} 0.07m/s, V_{sg} 3.6m/s)

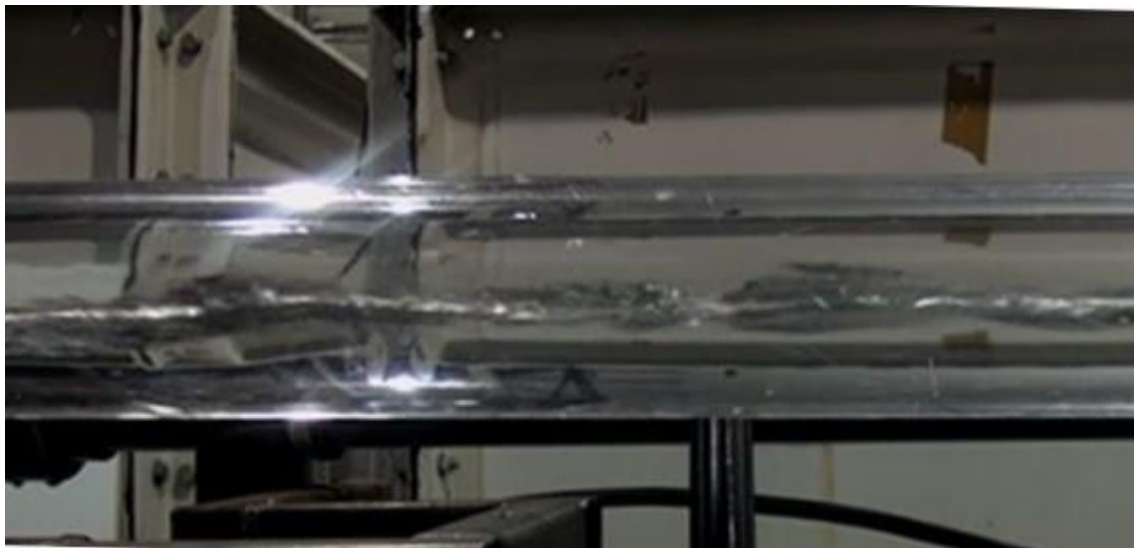


Figure 5-6: Snapshot of stratified plus energetic roll wave (Side view, flow from left to right V_{sl} 0.07m/s, V_{sg} 3.6m/s)

5.2.1 Comparison of Hold-up with Published Work

Liquid hold-up from the present work was compared with the predicted liquid hold-up generated from the correlation developed by different authors who have done similar work. This is achieved based on the flow conditions with the liquid hold-up data obtained from the present work.

The correlation from Beggs and Brill (1973) in Figure 5-7 under-predicted the results for this work. The reason for the deviation in the liquid hold-up is due to different perimeter to area ratios for small and large pipes; large diameter pipes will result in high liquid hold-up when compared with small diameter pipes. Furthermore, as the pipe diameter increases, the liquid hold-up also increases. Beggs and Brill's (1973) experimental works were carried out with pipe diameters of 1 and 1.5 inches. These are less than the pipe diameter used in this present work which is 2 inches.

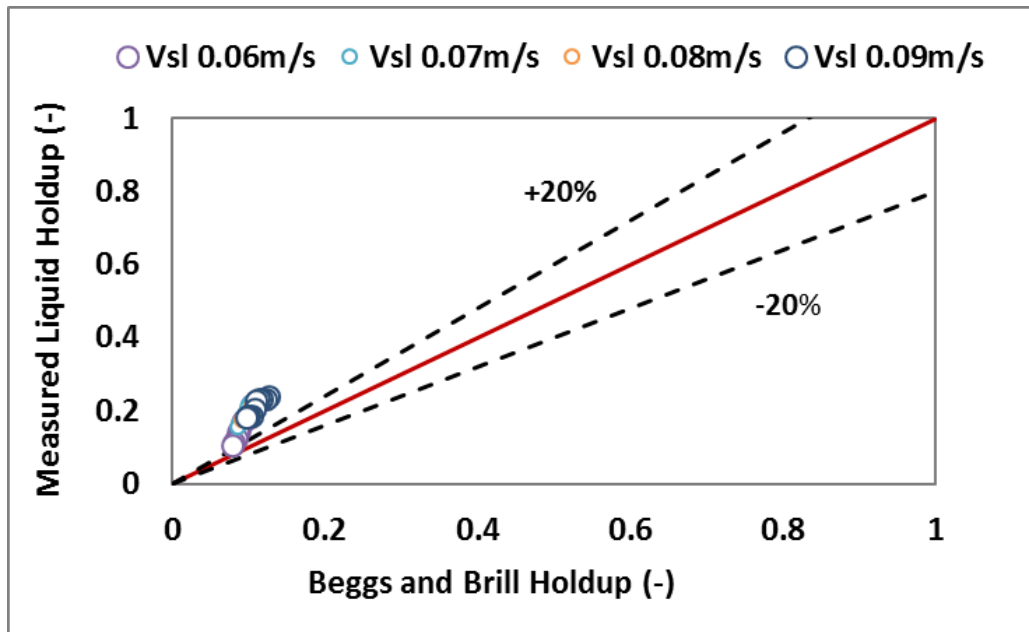


Figure 5-7 Comparison of measured overall liquid hold-up and that predicted by Beggs and Brill, 1973.

The correlation from Zuber and Findlay (1965) in Figure 5-8 predicts almost the same as this work and predicts better when compared with Beggs and Brill's (1973) correlation for this work

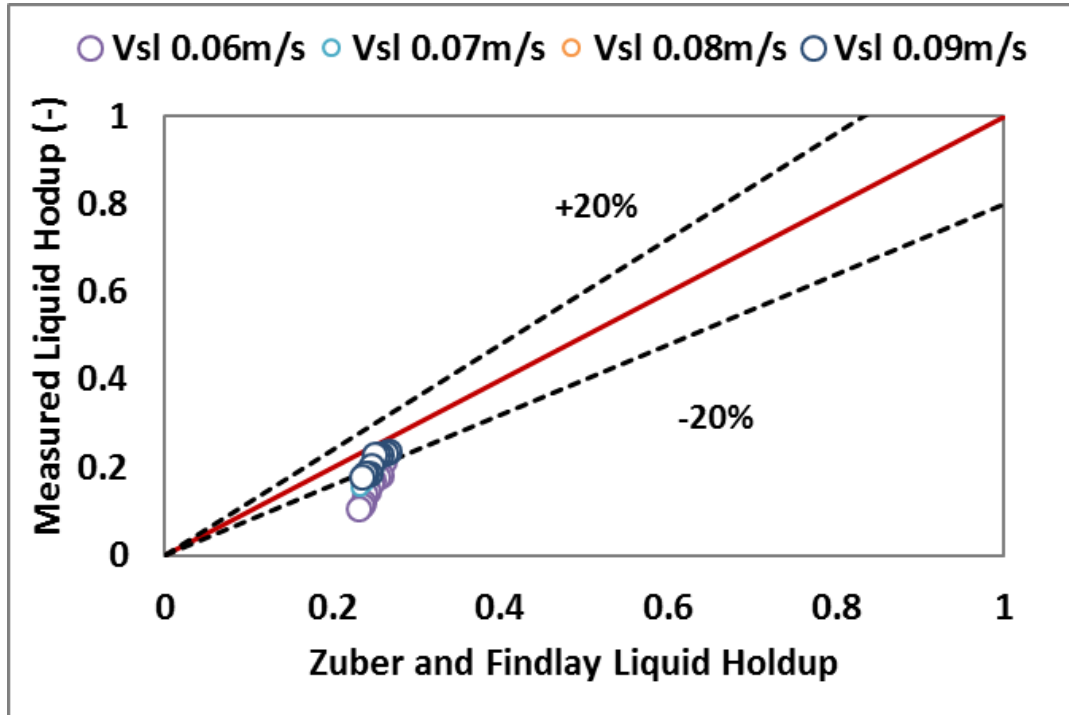


Figure 5-8: Comparison of measured overall liquid hold-up and that predicted by Zuber and Findlay, 1965.

Bestion's (1990) hold-up model (Figure 5-9) over-predicted the liquid hold-up when compared with the hold-up obtained from this study. The large discrepancy that exists between the liquid hold-up obtained by using the Bestion correlation and the experimental liquid hold-up is as a result of Bestion's (1990) liquid hold-up correlation model being developed based on large diameter pipes (up to 27-inch). Due to different perimeter to area ratios for small and large pipes, large diameter pipes will result in high liquid hold-up when compared with small diameter pipes.

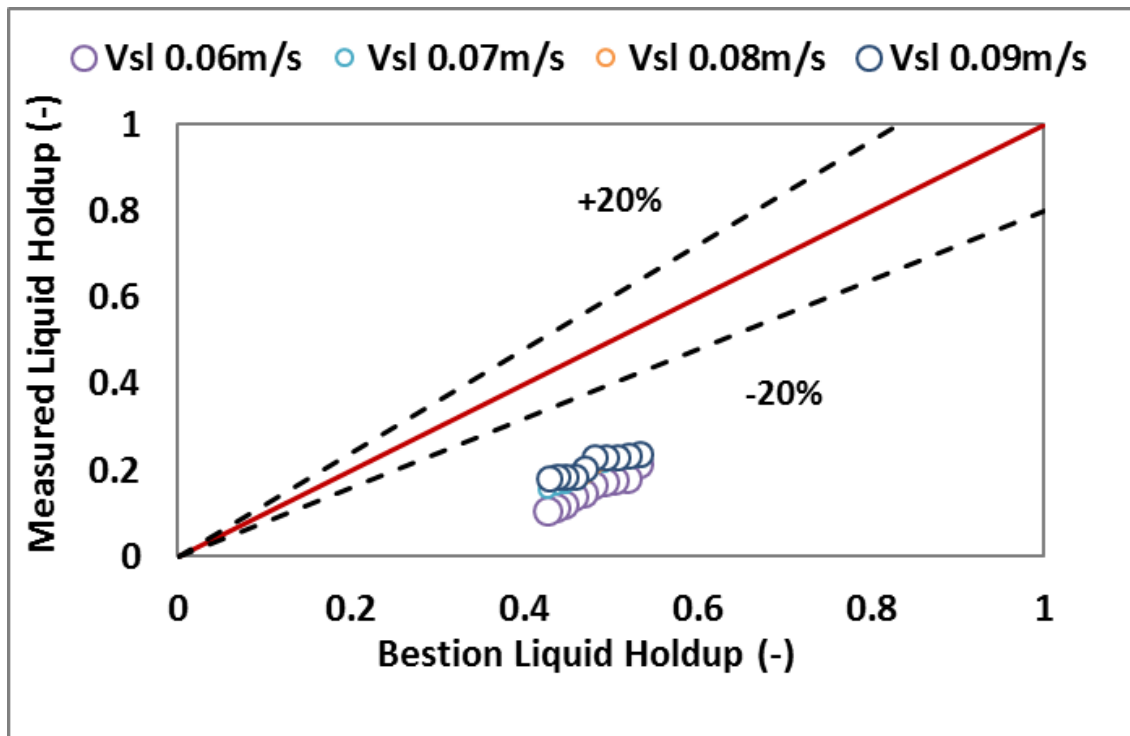


Figure 5-9: Comparison of measured overall liquid hold-up and that predicted by Bestion, 1990.

5.3 Pressure Gradient

The measured pressure gradient at different superficial gas and liquid velocities for the air-water experiment is depicted in Figure 5-10, which indicates that, as the gas superficial velocity increases at a specific liquid velocity, the pressure gradient also increases. Furthermore, as the liquid superficial velocity increases at a specific gas superficial velocity, the pressure gradient increases.

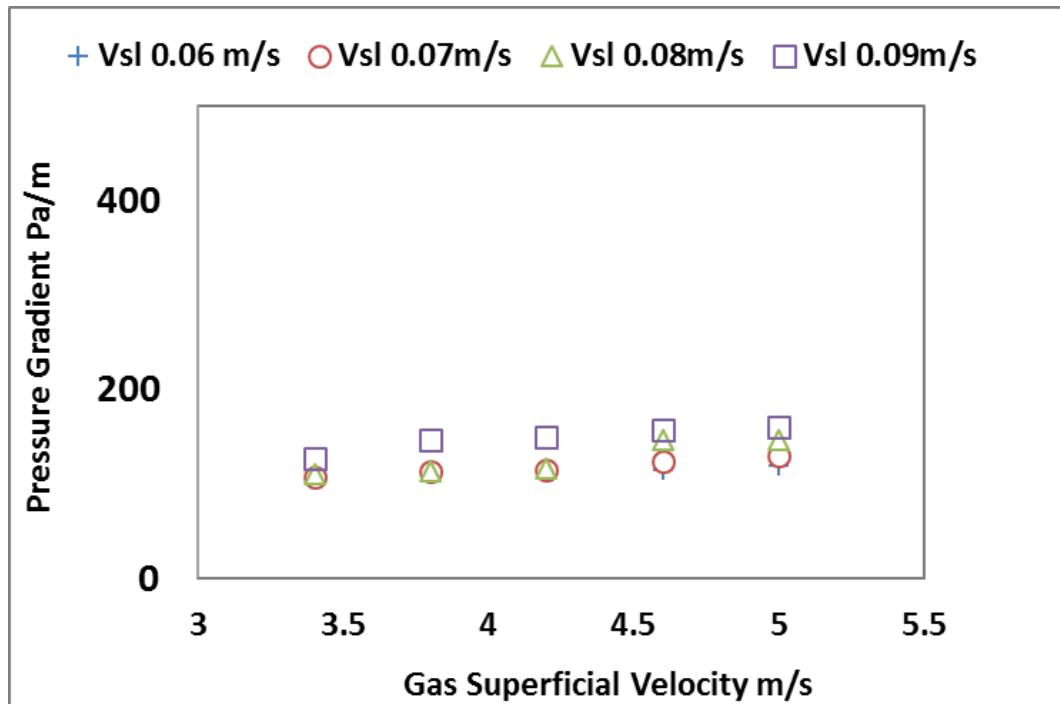


Figure 5-10: Pressure gradient against gas superficial velocity for air-water

5.3.1 Comparison of Measured Pressure Gradient with Beggs and Brill (1973)

Measured pressure gradients were compared with those of Beggs and Brill (1973) at the same gas superficial velocity. These are depicted in Figures 5-11 and 5-12, which show that Beggs and Brill (1973) over-predicted the pressure gradient when compared with the measured pressure gradient at the same gas superficial velocity. This may be as a result of differences in pipe diameter. The pipe diameters used by Beggs and Brill to develop the pressure gradient correlation (1 and 1.5 inches) were smaller when compared with the 2-inch pipe used to obtain the measured pressure gradient. The small diameter pipe tends to have a higher pressure gradient than a large diameter pipe for the same flow condition. The plot of Figure 5-12 also confirmed that Beggs and Brill's (1973) model over-predicted pressure gradient.

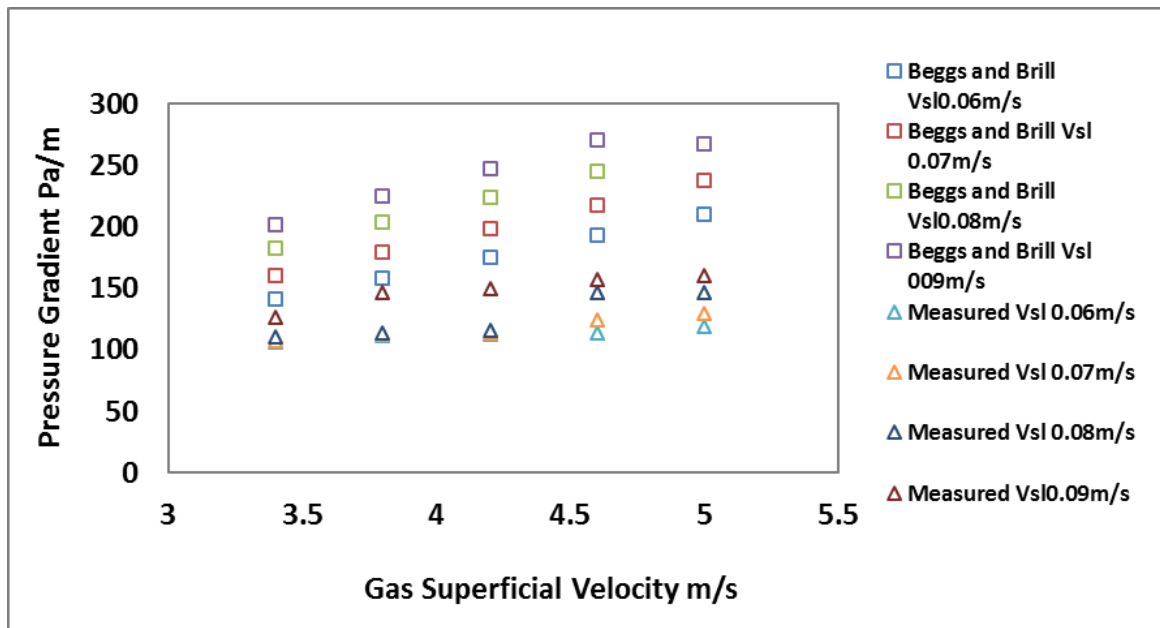


Figure 5-11: Measured pressure gradient and Beggs and Brill (1973) against gas superficial velocity

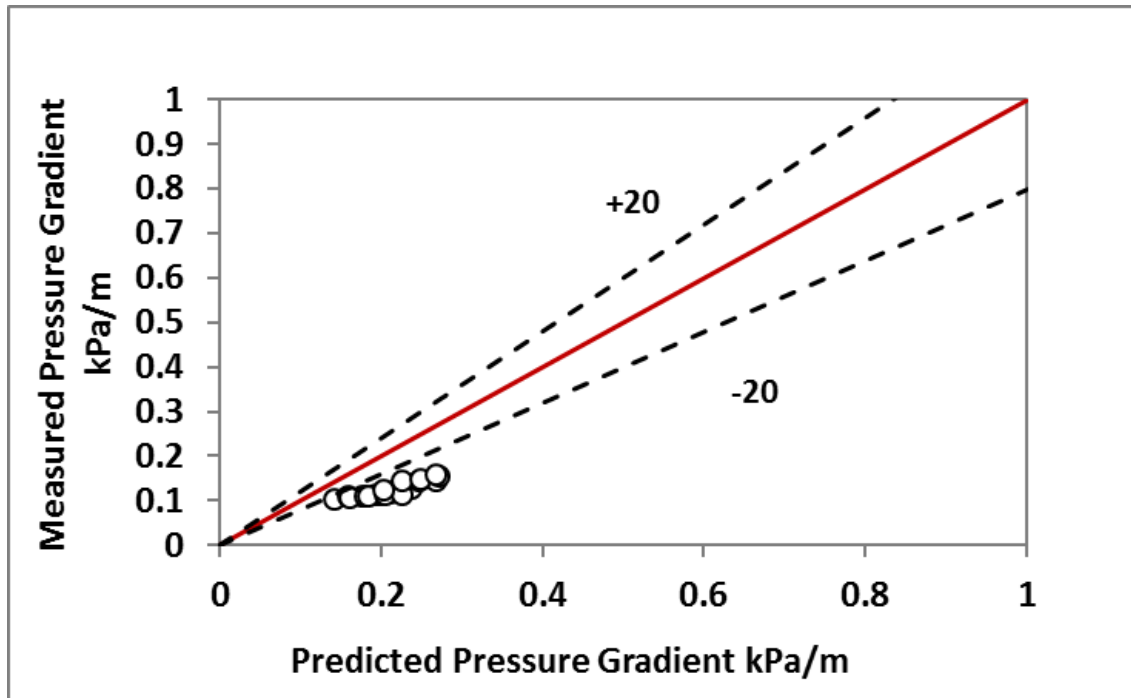


Figure 5-12: Comparison of measured pressure gradient against Beggs and Brill 1973

5.4 Sand-Air-Water Experimental Results and Analysis

5.4.1 Sand-Air-Water Flow Regime

This section describes and examines the results of the sand-air-water experiment carried out in a 2-inch horizontal facility. The objective of this section is to acquire a better understanding of sand behaviour in air-water (stratified flow) based on visual observation, photographic analysis and analysis by sand sensor. Furthermore, actual liquid velocities at MTC are determined experimentally for specific sand volume concentration at specific gas superficial velocity. Based on the investigation and observation from this study, ***the minimum transport condition*** (velocity) for sand particles under stratified flow regime *can be defined as the combined minimum gas and liquid velocities at which all sand particles have sufficient energy to keep them moving in the liquid phase along the pipe.*

Prior to the investigation of sand transport in air-water (stratified flow), air-water flow regimes were developed and analysed. This assists by giving a better understanding of sand transport in air-water two phase flow (stratified flow).

5.5 Sand Sensor Analysis with Respect to Sand-Air-Water Flow Behaviour

Most of the work done on sand transport in air-water flow prior to this work at Cranfield University were based on visual observation. However, in this work, analyses of sand sensors were combined with visual observation to monitor sand transport in air-water flow in the pipeline. Data from conductivity sensors for each sand-air-water experiment was recorded for 180 seconds (3 minutes). Based on the similarity of sand transport behaviour in air-water flow for different particle diameters and concentrations. The results of 212 microns at liquid superficial velocity of 0.06m/s with varied gas superficial velocities at concentrations of 200lb and 500lb per 1000bbl are presented below to represent other particle diameters and concentrations in this work. The sand-air-water flow patterns with MTC for 212 microns, V_{sl} 0.06m/s; at concentration of 200lb and 500lb per 1000bbl are summarised in Tables 5-3 and 5-4 respectively.

5.5.1 Sand Transport above MTC (0.06m/s, Vsg 4.4m/s)

The sand settling experiment in air-water flow was carried out by reducing the gas superficial velocity from 5.0m/s to 4.4m/s. At 4.4m/s gas superficial velocity, all sand particles were still suspended in the liquid phase and none was seen moving at the bottom of the pipe.

The snapshot and sand sensor signal when sand transport is above MTC (V_{sl} 0.06m/s, V_{sg} 4.4m/s) for sand particles with a diameter of 212 microns at a concentration of 200lb/1000bbl are shown in Figures 5-13 and 5-14 respectively. It can be observed from Figure 5-14 that the normalized voltage value is very close to 1.0 (unity). This shows that sand particles are not in contact with the sand sensor and also signifies that all of the sand particles are suspended in the liquid phase.



Figure 5-13: Snapshot of sand transport above MTC, (200lb/1000bbl, 212 microns, V_{sl} =0.06m/s, V_{sg} =4.4m/s. Flow: left to right, View: Bottom)

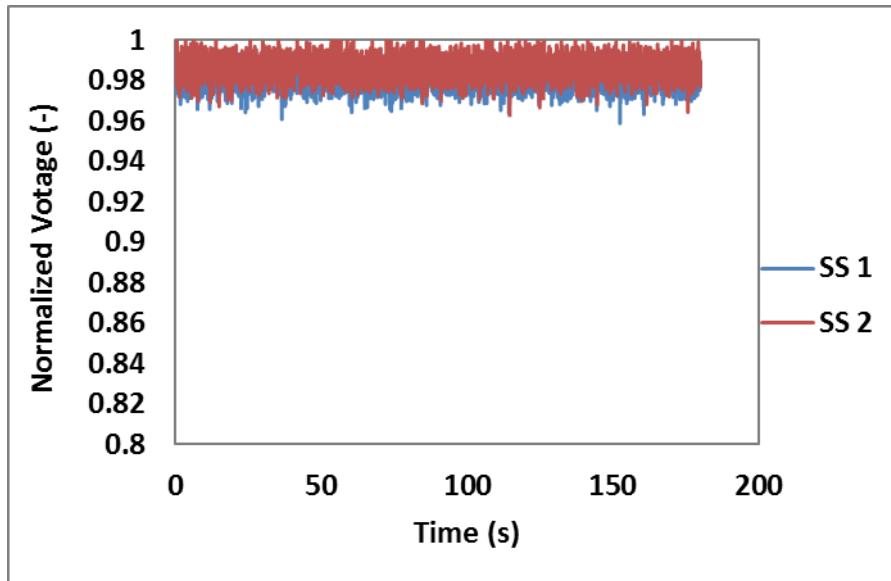


Figure 5-14: Signal of sand transport from the sand sensor above MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg} 4.4\text{m/s}$)

5.5.2 Sand Streak at MTC (V_{sl} , 0.06m/s , $V_{sg} 4.1\text{m/s}$)

The reduction of gas superficial velocity from 4.4m/s to 4.1m/s at the same liquid superficial velocity of 0.06m/s caused sand particles to be at MTC. At this air-water flow condition, a few sand particles were transported as streak at the bottom of the pipe within the liquid phase. Figures 5-15 and 5-16 depict the sand-air-water flow of 212 microns at a concentration of 200lb per 1000bbl at MTC. The signal (Figure 5-16) of sand transport from the sand sensors at MTC is a little lower and deviates more from unity when compared with sand transport above MTC. This is because few sand particles are transported over the sand sensor. This tends to influence the output of the sand sensor by decreasing it. Furthermore, the mixture of sand-air-water at MTC tends to increase the resistivity of the sand sensor, thereby influencing the lower voltage output of the sensor at MTC.



Figure 5-15: Snapshot of sand streak at MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}= 4.1\text{m/s}$. Flow: left to right, View: Bottom)

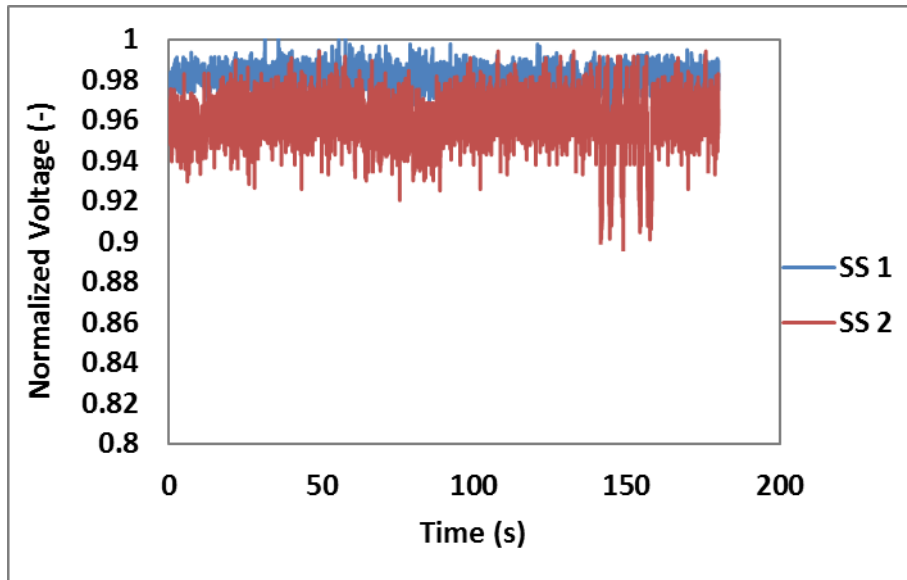


Figure 5-16: Signal of sand streak from the sand sensor at MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}= 4.1\text{m/s}$)

5.5.3 Sand Streak below MTC (V_{sl} , 0.06m/s, V_{sg} 3.9m/s)

A dense streak of sand appeared at the bottom of the pipe as the gas superficial velocity is below gas superficial velocity at MTC. This occurred when the gas superficial velocity was reduced from 4.1m/s to 3.9m/s. Figures 5-17 and 5-18 depict sand-air-water flow regimes below the MTC (V_{sl} 0.06m/s, V_{sg} 3.9m/s).



Figure 5-17: Snapshot of sand streak below MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}=3.9\text{m/s}$, Flow: left to right, View: Bottom)

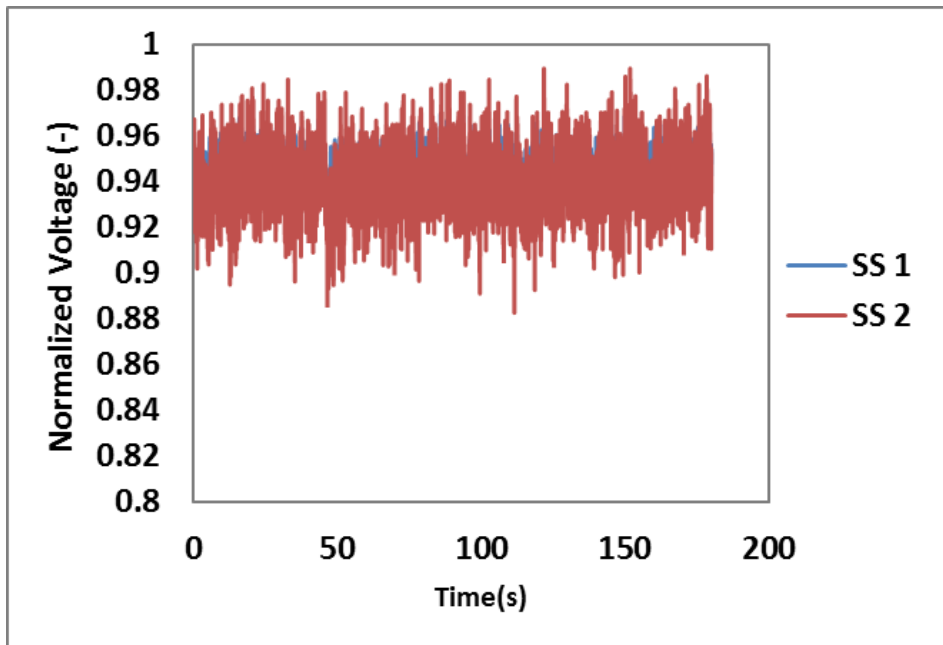


Figure 5-18: Signal of sand streak from the sand sensor below MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}=3.9\text{m/s}$)

5.5.4 Sand Dunes (V_{sl} , 0.06m/s, V_{sg} 3.73m/s)

Figures 5-19 and 5-20 depict the sand moving dunes (sand-air-water) flow regime of sand particles with a size of 212 microns at a concentration of 200lb/1000bbl with a liquid superficial velocity of 0.06m/s. The sand moving dunes appear as

the gas superficial velocity was reduced from 3.9m/s to 3.73m/s. The reduction of gas superficial velocity resulted into sand particles becoming denser at the bottom of the pipe when compared with the sand-air-water flow regime at a gas superficial velocity of 3.9m/s. The normalized time trace of this flow regime (V_{sl} 0.06m/s, V_{sg} 3.73m/s) is far from one (unity). Therefore, it is the farthest when compared with the other sand-air-water flow regimes in a normalized time trace. The sand moving dunes influenced the sensor output by causing a reduction in conductivity between the electrodes of the sensor, thereby resulting in the several dips that appear on the signal (Figure 5-20).

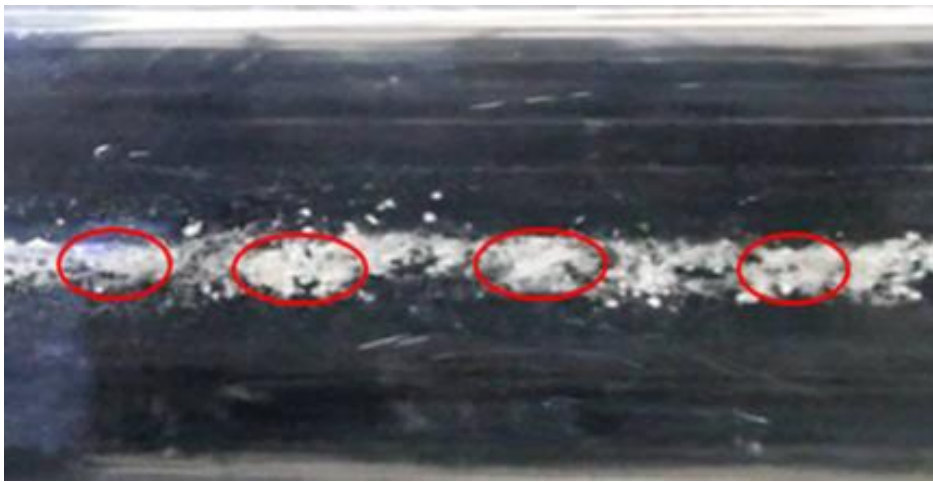


Figure 5-19: Snapshot of sand dunes below MTC, (200lb/1000bbl, 212 microns V_{sl} =0.06m/s, V_{sg} =3.7m/s, Flow: left to right, View: Bottom)

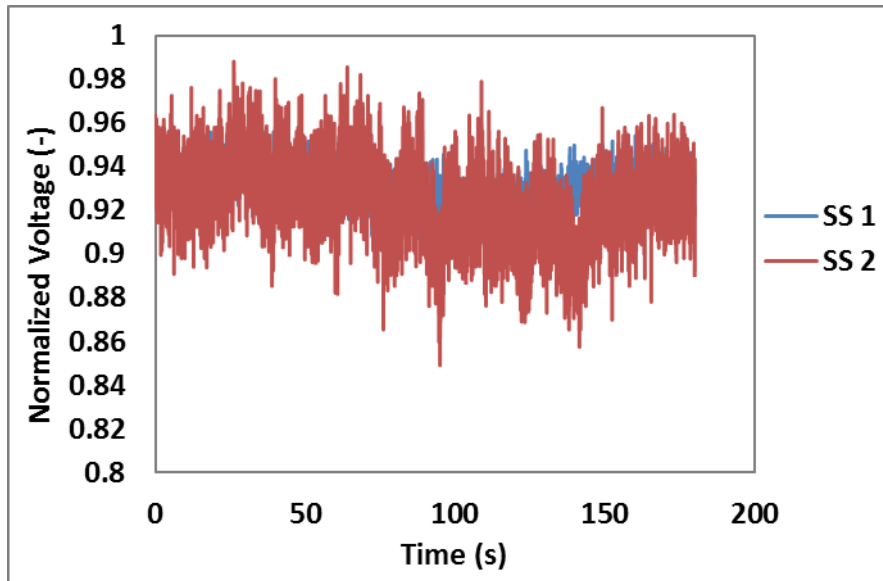


Figure 5-20: Signal of sand dunes from the sand sensor below MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}=3.73\text{m/s}$)

Note: The sand-air-water flow regimes identified using sand sensors (212 microns at concentrations of 200lb and 500lb per 1000bbl) are summarised in Tables 5-3 and 5-4 respectively, while the summary of the PSD of these flow regimes obtained from sand sensors can be found in Tables 5-5 and 5-6.

5.6 Power Spectral Density of Sand Sensor

The PSD of the sand sensor for each sand-air-water flow regime (V_{sl} , 0.06m/s, 212 microns, 200lb/1000bbl with varying gas velocities) are depicted in Figures 5-21 to 5-24. Figure 5-21 shows that PSD for suspension is characterised with several peaks which spread from 0 to 5Hz and the dominant frequency occurred at 0.9Hz. Figure 5-22 represents PSD for MTC. The PSD for MTC (V_{sl} 0.06m/s, V_{sg} 4.1m/s) constitutes several peaks which spread between 0 and 3Hz and started disappearing at around 3.1Hz with a dominant frequency at 0.1Hz. The PSD of the streak flow regime (V_{sl} 0.06m/s, V_{sg} 3.9m/s below the MTC) is depicted in Figure 5-23. The PSD of this sand-air-water flow pattern is characterised by several peaks from 0 to 0.7Hz with the dominant frequency occurring at ~0.3Hz. The moving dune (V_{sl} 0.06m/s, V_{sg} 3.73m/s) in Figure 5-24 has its pronounced frequency between 0 and 0.1Hz and the dominant frequency

occurs at $\sim 0.1\text{Hz}$. By considering the PSD from the moving dune to suspension (i.e. Figures 5-24 to 5-21), shows that as the gas superficial velocity increases the sand particles transported over the sand sensor become less concentrated and the spectral peaks of the PSD spread out from the left to the right and their amplitudes increased from the moving dune to suspension. This indicates that the energy needed to transport sand particles in a moving dune flow regime was lower than that of suspension. Therefore, energy increases with increased flow rate. This phenomenon was also observed in the PSD of sand-water flow.

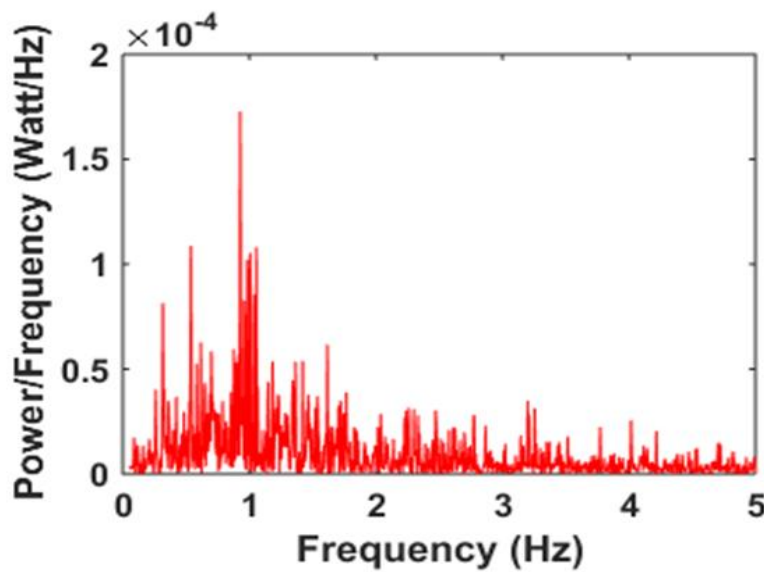


Figure 5-21: Power spectral density of sand transport above MTC, (200lb/1000bbl, 212 microns, $V_{sl}=0.06\text{m/s}$, $V_{sg}=4.4\text{m/s}$.)

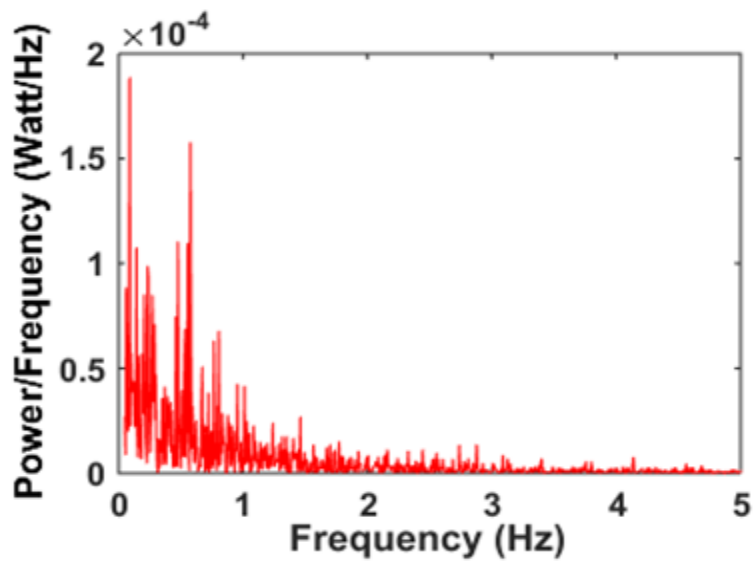


Figure 5-22: Power spectral density of sand streak at MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}= 4.1\text{m/s}$)

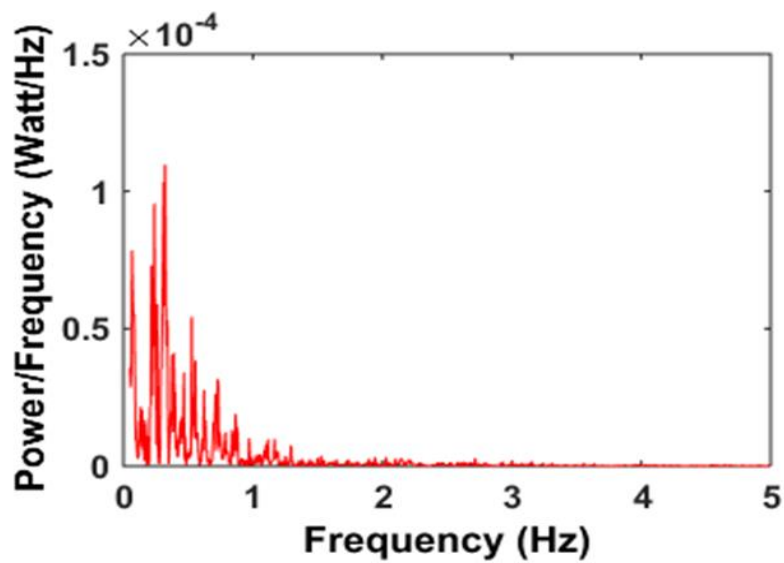


Figure 5-23: Power spectral density of sand streak below MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}= 3.9\text{m/s}$)

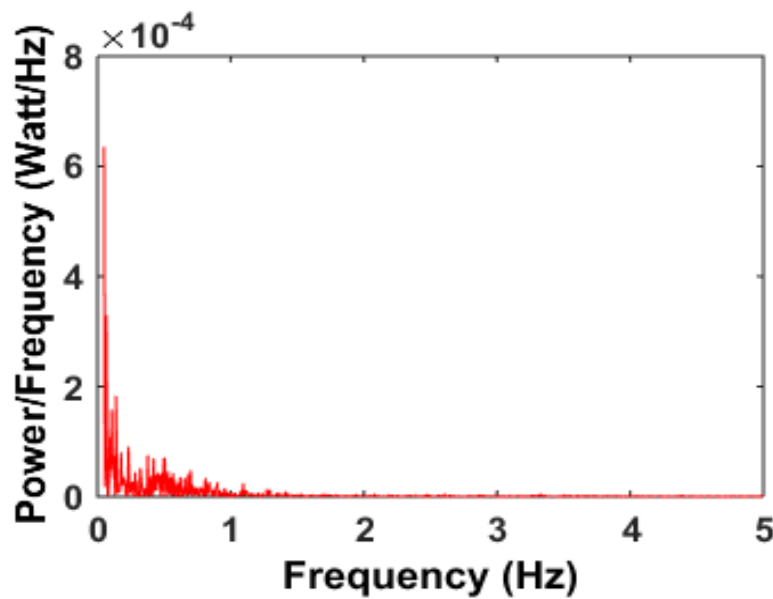


Figure 5-24: Power spectral density of sand dunes below MTC, (200lb/1000bbl, 212 microns $V_{sl}=0.06\text{m/s}$, $V_{sg}=3.73\text{m/s}$)

5.7 Statistics Analysis of Sand-Air-Water Flow Regimes from the Sand Sensor

The coefficient of variation, standard deviation, mean normalized voltage and equivalent sand thickness for each sand-air-water flow regime for 212 microns at volume concentrations of 200lb and 500lb per 1000bbl obtained from the analysis of sand sensors, are shown in Tables 5-1 and 5-2 respectively. In Tables 5-1 and 5-2, the coefficient of variation and mean normalized voltage for the suspension of 212 microns at 200lb and 500lb per 1000bbl are 0.28% and 0.98. The coefficients of variation for suspension flow regimes are the lowest among all sand-air-water flow regimes and this implies that the data points for suspension are close. The lower variability of the coefficient of variation for the suspension flow regime could be as a result of sand particles not being in contact with the sand sensor. However, the coefficient of variation for streak below MTC and moving dune flow pattern at concentration of 200lb and 500lb per 1000bbl are higher and their data points are highly dispersed when compared with the coefficient of variation from the suspension flow pattern. It could also be noted

from Tables 5-1 and 5-2 that as the gas superficial velocity decreases, the mean normalized voltage decreases while the coefficient of variation and standard deviation increases. This is because sand particles tend to accumulate as a sliding streak or moving dune as the gas superficial velocity decreases for specific liquid superficial velocity. It is also shown that the mean normalized voltage values for 500lb per 1000bbl are higher than 200lb per 1000bbl at various sand-air-water flow regimes, except for suspension.

Sand particles will be transported as suspension in stratified flow (air-water) when the data points from the sand sensor are close to their mean values, consistent and the coefficient of variation is low. However, they could be transported as a moving dune when the data points are far from their mean values with a high coefficient of variation.

Equivalent sand thickness for each sand-air-water flow regime for 200lb and 500lb per 1000bbl were also determined and can be explained from Tables 5-1 and 5-2. The equivalent sand thickness for 500lb per 1000bbl is higher than 200lb per 1000bbl, except for suspension. The reason for 200lb and 500lb per 1000bbl having the same equivalent sand thickness is because in suspension, sand particles in the mixture have little effect on the sand sensor. This is because sand particles are not in contact with the sand sensor.

Table 5-1: Analysis of sand-air-water flow regimes using a sand sensor

Sand Sensor						
212 microns, 200lb/1000bbl						
Flow Regime	Vsl	Vsg	Mean Normalized Voltage	Equivalent Sand Thickness	Standard Deviation of Normalized Voltage	Coefficient of Variation
	(ms⁻¹)	(ms⁻¹)		(mm)		(%)
Suspension	0.06	4.40	0.98	0.10	±0.0027	0.28
Streak at MTC	0.06	4.10	0.97	0.22	±0.0047	0.48
Streak below MTC	0.06	3.90	0.95	0.23	±0.0072	0.76
Moving Dune	0.06	3.73	0.93	0.25	±0.0099	1.07

Table 5-2: : Analysis of sand-air-water flow regimes using a sand sensor

Sand Sensor						
212 microns, 500lb/1000bbl						
Flow Regime	Vsl	Vsg	Mean Normalized Voltage	Equivalent Sand Thickness	Standard Deviation of Normalized Voltage	Coefficient of Variation
	(ms⁻¹)	(ms⁻¹)		(mm)		(%)
Suspension	0.06	4.40	0.98	0.10	±0.0027	0.28
Streak at MTC	0.06	4.30	0.96	0.25	±0.0056	0.58
Streak below MTC	0.06	4.20	0.93	0.25	±0.0089	0.96
Moving Dune	0.06	4.00	0.92	0.26	±0.017	1.85

Table 5-3: Summary of sand-air-water flow regimes from the sand sensor (200lb per1000bbl)

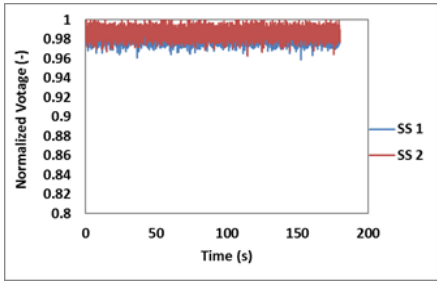
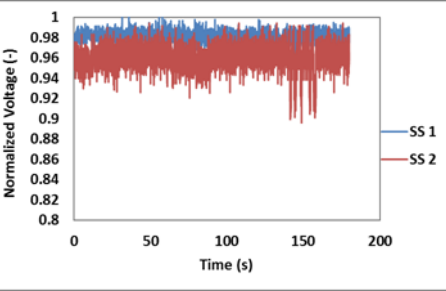
Vsl (ms⁻¹)	Vsg (ms⁻¹)	Snapshot	Sand Sensor Signal	Comment
0.06	4.4			<ol style="list-style-type: none"> 1. Sand particles are suspended 2. Sensor signal is closer to unity (1)
0.06	4.1			<ol style="list-style-type: none"> 1. Sand transport at MTC 2. Less dense sliding sand streaks are observed at the bottom of the pipe 3. Sensor signal deviated more from unity when compared with suspension

Table 5-3 Continued.

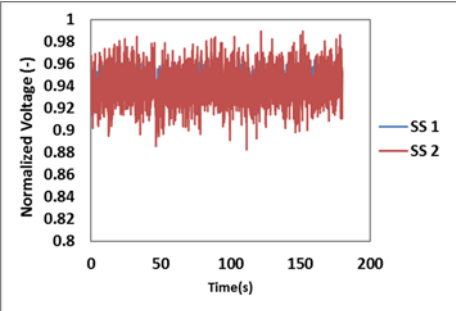
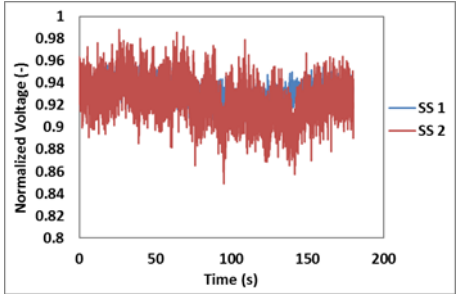
Vsl (ms ⁻¹)	Vsg (ms ⁻¹)	Snapshot	Sand Sensor Signal	Comment
0.06	3.9			<ol style="list-style-type: none"> 1. Denser sliding sand streaks are observed at the bottom of the pipe 2. Sensor signal is farther from unity when compared with signal from suspension and MTC
0.06	3.73			<ol style="list-style-type: none"> 1. Sand dune comes into existence. 2. The sand sensor exhibits several dips and is the farthest when compared with other sand-air-water flow regimes

Table 5-4: Summary of sand-air-water flow regimes from the sand sensor (500lb per 1000bbl)

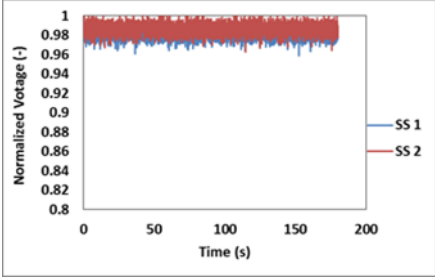
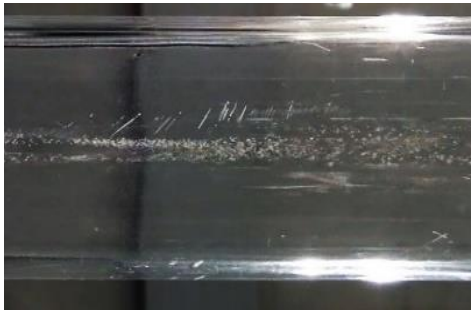
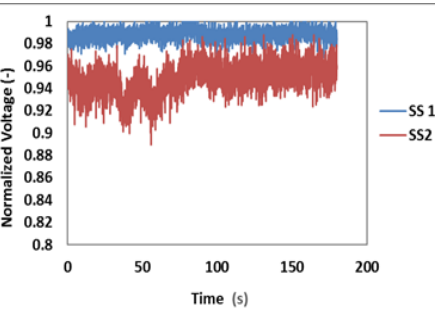
Vsl (ms⁻¹)	Vsg (ms⁻¹)	Snapshot	Sand Sensor Signal	Comment
0.06	4.4			<ol style="list-style-type: none"> 1. Sand particles are suspended 2. Sensor signal is closer to unity (1)
0.06	4.3			<ol style="list-style-type: none"> 1. Sand transport at MTC 2. Less dense sliding sand streaks are observed at the bottom of the pipe but denser than 200lb per 1000bbl 3. Sensor signal deviated more from unity when compared with suspension and farther than 200lb per 1000bbl

Table 5-4 Continued.

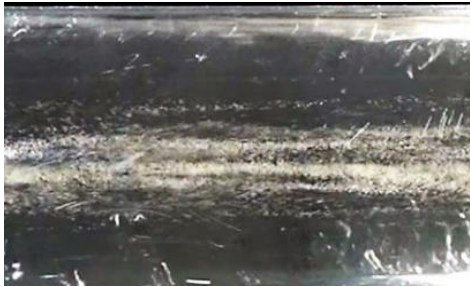
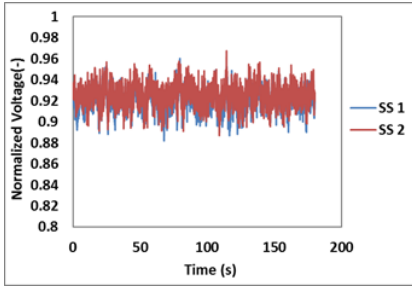
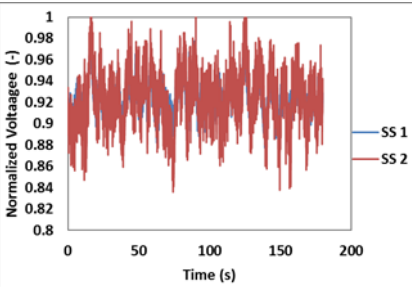
Vsl (ms ⁻¹)	Vsg (ms ⁻¹)	Snapshot	Sand Sensor Signal	Comment
0.06	4.2			<ol style="list-style-type: none"> 1. Denser sliding sand streaks are observed at the bottom of the pipe 2. Sensor signal is farther from unity when compared with signal from suspension and MTC 3. Sensor signal exhibits some small dips
0.06	4.0			<ol style="list-style-type: none"> 1. Moving sand dune comes into existence. 2. The sand sensor exhibits several dips which are more pronounced when compared with 200lb per 1000bbl and the signal is the farthest when compared with other sand-air-water flow regimes

Table 5-5: Summary of power spectral density for sand-air-water flow regimes from sand sensor (200lb per 1000bbl)

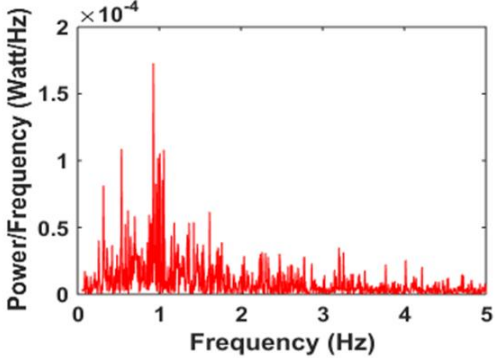
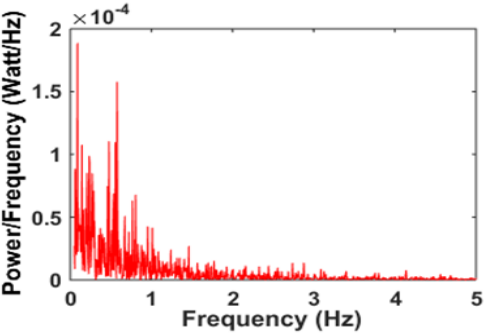
Vsl (ms⁻¹)	Vsg (ms⁻¹)	Power Spectral Density Sand Sensor	Comment
0.06	4.4		<p>Above MTC</p> <ol style="list-style-type: none"> 1. The PSD for suspension has several peaks that spread from 0 to 5Hz 2. Dominant frequency occurs at 0.9Hz
0.06	4.1		<p>At MTC</p> <ol style="list-style-type: none"> 1. The peaks at the MTC spread from 0 to 3Hz and disappear from 3 to 5Hz 2. The dominant frequency occurs at about 0.1Hz

Table 5-5 Continued.

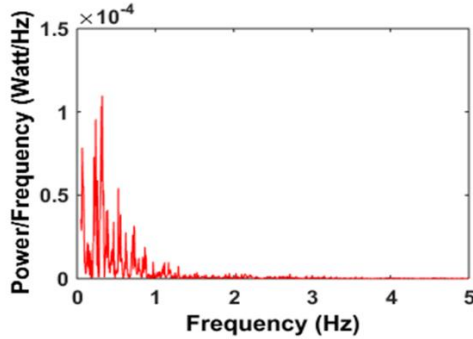
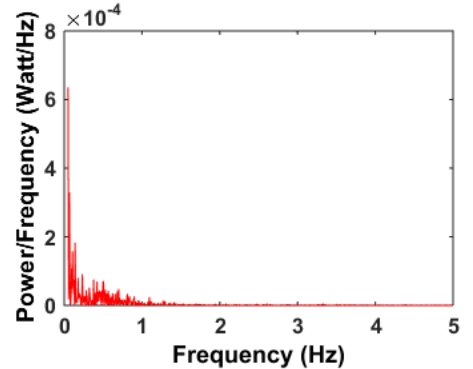
Vsl (ms ⁻¹)	Vsg (ms ⁻¹)	Power Spectral Density Sand Sensor	Comment
0.06	3.9		<p>Below MTC</p> <ol style="list-style-type: none"> 1. The peaks of the frequency for this flow regime occurred at the frequency between 0 and 0.8Hz while the dominant frequency occurs at about 0.4Hz
0.06	3.73		<p>Moving dunes</p> <ol style="list-style-type: none"> 1. The dominant frequency of moving dunes occurs at 0.1Hz 2. The peaks in this flow regime started emerging from 0.6Hz 3. The PSD for moving dunes in sand-air-water is similar to the PSD of moving dunes in sand-water

Table 5-6: Summary of power spectral density for sand-air-water flow regimes from the sand sensor (500lb per 1000bbl)

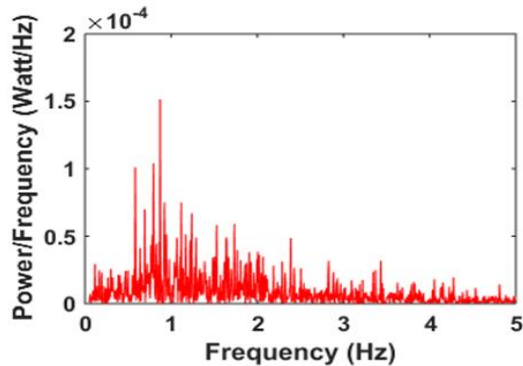
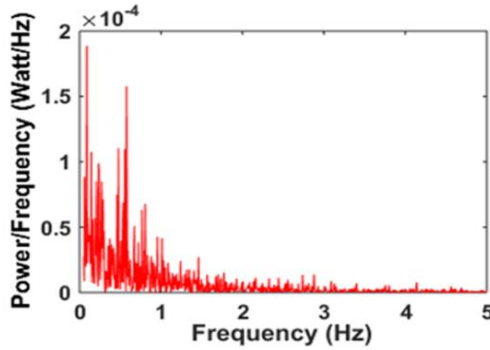
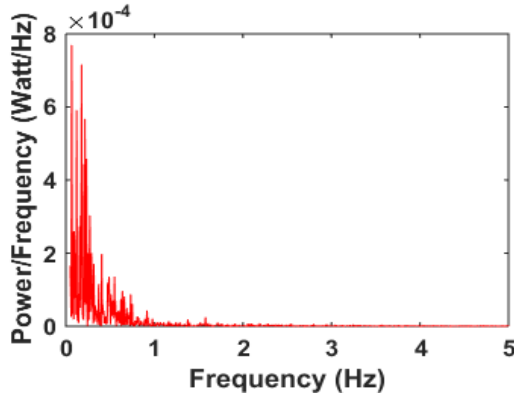
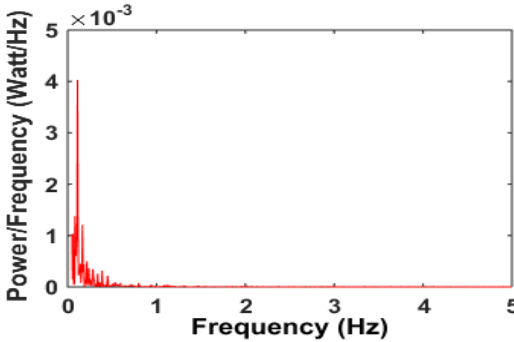
Vsl (ms⁻¹)	Vsg (ms⁻¹)	Power Spectral Density Sand Sensor	Comment
0.06	4.4		<p>Above MTC</p> <ol style="list-style-type: none"> 1. The PSD for suspension has peaks that spread from 0 to 5Hz 2. Dominant frequency occurs at 0.9Hz
0.06	4.3		<p>At MTC</p> <ol style="list-style-type: none"> 1. The peaks at the MTC spread from 0 to 3Hz and decay from 3 to 5Hz 2. The dominant frequency occurs at about 0.1Hz

Table 5-6 Continued

Vsl (ms⁻¹)	Vsg (ms⁻¹)	Power Spectral Density Sand Sensor	Comment
0.06	4.2		<p>Below MTC</p> <ol style="list-style-type: none"> 1. The peaks of the frequency for this flow regime occurred at the frequency between 0 and 0.7Hz while the dominant frequency occurs at about 0.1Hz
0.06	4.0		<p>Moving dunes</p> <ol style="list-style-type: none"> 1. The dominant frequency of moving dunes occurs at 0.1Hz. 2. The peaks in this flow regime decay drastically to almost a single peak. 3. The PSD for moving dunes in sand-air-water is similar to the PSD of moving dunes in sand-water.

5.8 Actual Liquid Velocity at Minimum Transport Condition

Experiments were carried out to determine the MTC for particle size (diameter) of 212, 500 and 800 microns. The experiments were carried out in such a way that at each specific liquid superficial velocity and gas superficial velocity was varied until the particles were starting to fall out of the liquid phase to the bottom of the pipe. Tables 5-7, 5-8 and 5-9 depict actual liquid velocity and structure velocity (wave velocity) at MTC for sand particles with a diameter of 212, 500 and 800 microns at concentrations of 200lb and 500lb per 1000bbl. Tables 5-7, 5-8 and 5-9 show that the structure velocities are higher than the actual liquid velocities at MTC. The structure velocities (wave velocities) are higher than the actual velocities because gas travels at a higher velocity at the interface between gas and liquid which tends to initiate a fast moving wave.

Table 5-7: Actual liquid velocity and structure velocity at Minimum Transport Condition for 212 microns

212 microns						
Concentration (lb/1000bbl)	V_{sl} (ms⁻¹)	V_{sg} (ms⁻¹)	V_L at MTC (ms⁻¹)	Holdup	Film thickness (mm)	Structure Velocity at MTC (Ring Sensor) (ms⁻¹)
200	0.06	4.12	0.23	0.26	3.52	0.42
500	0.06	4.29	0.24	0.25	3.38	0.44
200	0.07	3.90	0.26	0.27	3.67	0.56
500	0.07	4.19	0.33	0.21	2.80	0.78
200	0.08	3.73	0.34	0.24	3.23	0.93
500	0.08	4.00	0.36	0.22	2.94	1.08
200	0.09	3.55	0.38	0.24	3.23	1.27
500	0.09	3.62	0.39	0.23	3.09	1.57

Table 5-8: Actual liquid velocity and structure velocity structure at Minimum Transport Condition for 500 microns

500 microns						
Concentration (lb/1000bbl)	Vsl (ms⁻¹)	Vsg (ms⁻¹)	V_L at MTC (ms⁻¹)	Holdup	Film thickness (mm)	Structure Velocity at MTC (Ring Sensor) (ms⁻¹)
200	0.06	4.33	0.24	0.25	3.38	0.44
500	0.06	4.70	0.25	0.24	3.23	0.45
200	0.07	4.20	0.33	0.21	2.80	0.77
500	0.07	4.30	0.35	0.20	2.66	1.17
200	0.08	4.00	0.35	0.23	3.09	1.40
500	0.08	4.20	0.36	0.22	2.94	1.40
200	0.09	3.78	0.39	0.23	3.09	1.40
500	0.09	4.00	0.45	0.20	2.66	1.40

Table 5-9: Actual liquid velocity and structure velocity structure at Minimum Transport Condition for 800 microns

800 microns						
Concentration	Vsl	Vsg	V_L at MTC	Holdup	Film thickness	Structure Velocity at MTC (Ring Sensor)
(lb/1000bbl)	(ms⁻¹)	(ms⁻¹)	(ms⁻¹)		(mm)	(ms⁻¹)
200	0.06	5.10	0.25	0.24	3.23	0.56
500	0.06	5.40	0.27	0.22	2.94	0.56
200	0.07	4.91	0.35	0.20	2.66	0.83
500	0.07	5.10	0.37	0.19	2.52	1.08
200	0.08	4.69	0.36	0.22	2.94	1.55
500	0.08	4.85	0.38	0.21	2.80	1.75
200	0.09	4.50	0.42	0.21	2.80	1.56
500	0.09	4.69	0.45	0.20	2.66	1.75

5.8.1 Combination of Gas and Liquid Velocities at Minimum Transport Conditions

Figures 5-25, 5-26 and 5-27 depict the MTCs for 212, 500 and 800 microns at a concentration of 200lb per 1000bbl. Furthermore, they are the combination of gas and liquid superficial velocities at MTC for each particle diameter (212, 500, 800 microns) respectively at a volume concentration of 200lb per 1000bbl. In Figures 5-25, 5-26 and 5-27, the regions beyond (above) the data points at the right hand side are the regions where particles are transported effectively while the regions below the data points are the regions where sand particles will or may not be transported effectively (regions towards the left hand side).

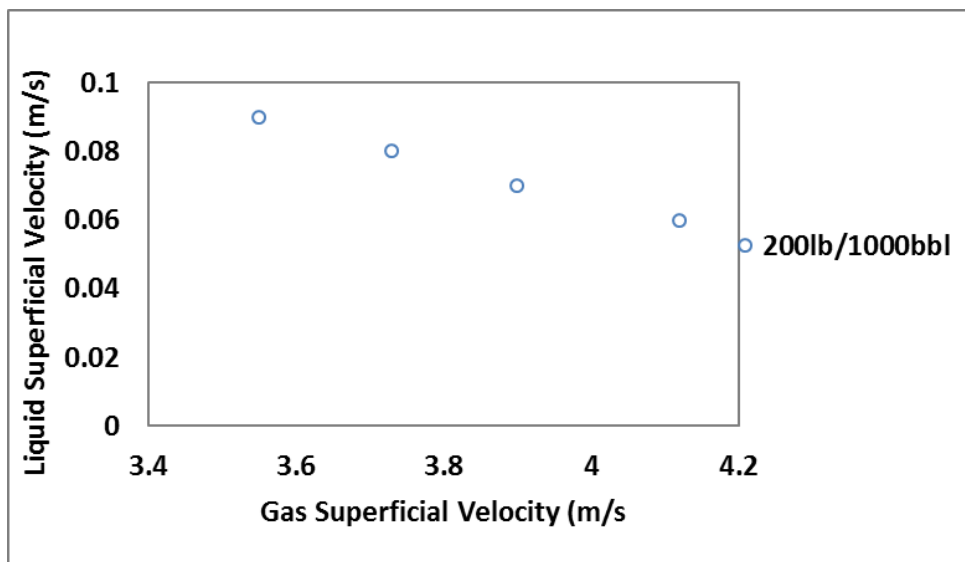


Figure 5-25: Minimum liquid (water) and gas superficial velocity region at which all sand particle grains will be transported effectively for 200lb/1000bbl (212microns)

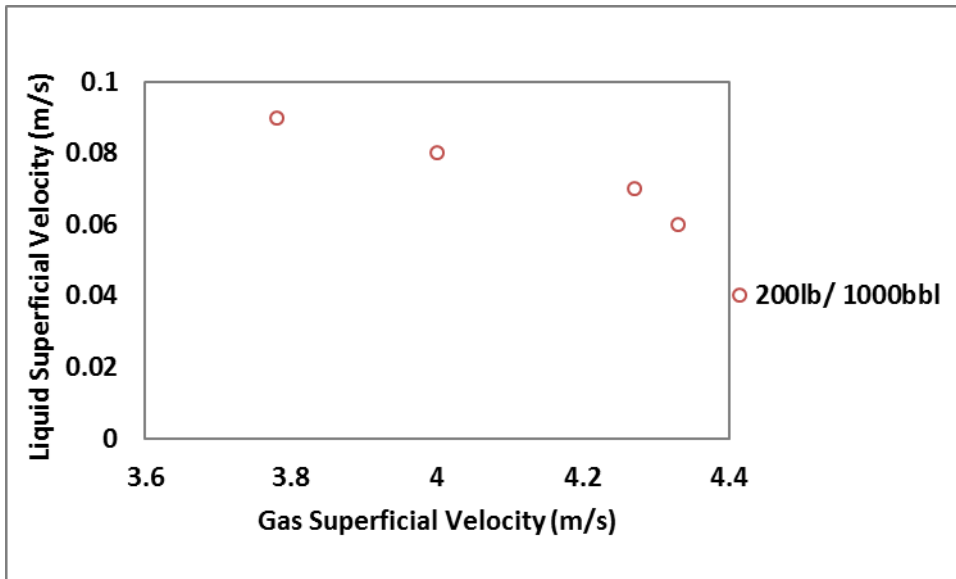


Figure 5-26: Minimum liquid (water) and gas superficial velocity region at which all sand particle grains will be transported effectively for 200lb/1000bbl (500microns)

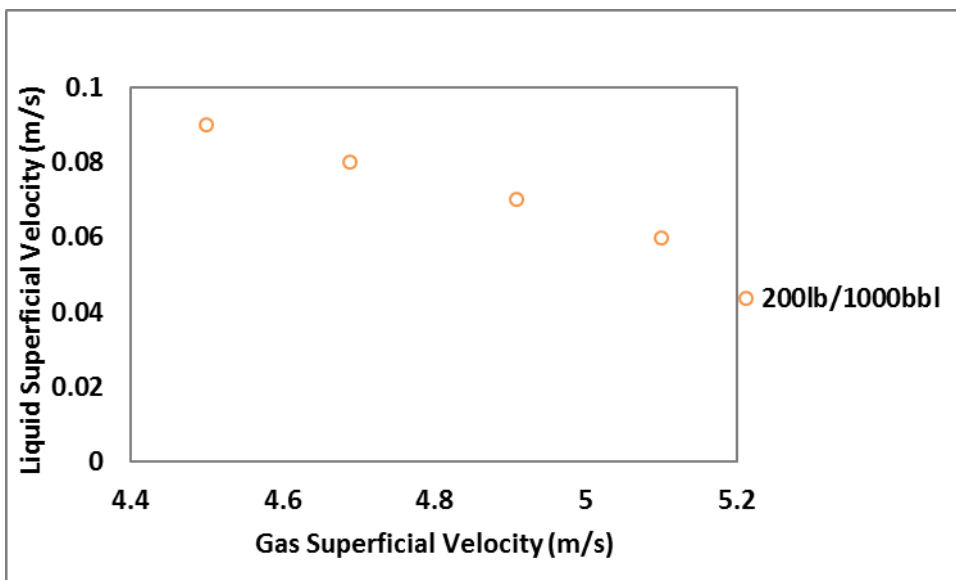


Figure 5-27: Minimum liquid (water) and gas superficial velocity region at which all sand particle grains will be transported effectively for 200lb/1000bbl (800microns)

5.9 Particle Size Effect on MTC in Stratified Flow

The effect of particle sizes on MTC was investigated in this study. Studies were carried out on three sand particle sizes (212, 500 and 800 microns) at the same volume concentration to determine the effect of particle size on MTC. Observation from Figure 5-28 shows that the MTC for 500 microns is higher than the MTC for 212 microns for the same volume concentration (200lb per 1000bbl). Therefore, as the particle diameter increases, the MTC also increases for the same volume concentration. The particles are transported in stratified wavy flow. The results from this study correspond with what Najmi et al. (2014) and Dabirian et al. (2015) reported. Table 5-10 summarises the effect of particle size on MTC for 200lb per 1000bbl, while 500lb per 1000bbl is presented in the Appendix in Table C-1.

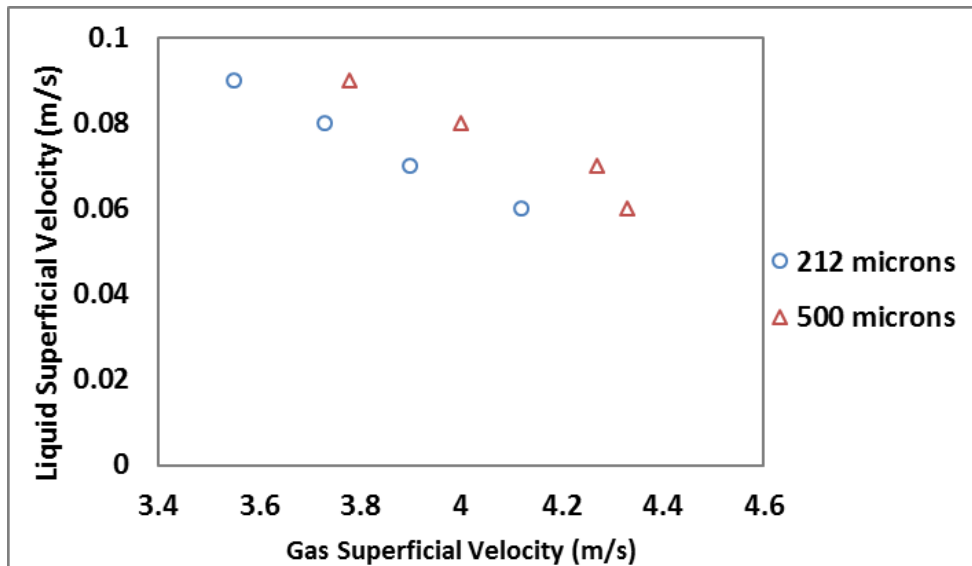


Figure 5-28: Minimum transport condition for particle size effect in stratified flow (air-water flow) concentration: 200lb per 1000bbl (212 and 500 microns)

Table 5-10: Effect of particle size at MTC

200lb/1000bbl			
Particle Diameter (lb/1000bbl)	Vsl (ms⁻¹)	Vsg (ms⁻¹)	V_L at MTC (ms⁻¹)
212	0.06	4.12	0.23
500	0.06	4.33	0.24
800	0.06	5.10	0.25
212	0.07	3.90	0.26
500	0.07	4.27	0.33
800	0.07	4.91	0.35
212	0.08	3.73	0.33
500	0.08	4.00	0.35
800	0.08	4.69	0.36
212	0.09	3.55	0.38
500	0.09	3.78	0.39
800	0.09	4.50	0.43

5.10 Effect of Sand Concentration on MTC in Stratified Flow

The effect of concentration on MTC for particle diameter in stratified flow was investigated in this study. In this study, two concentration volumes were investigated (200lb and 500lb per 1000bbl) with three different sized particles (212, 500 and 800 microns). However, only 212 microns was used in the analysis of the concentration. Considering Figure 5-29, it can be deduced that as the concentration increases, the MTC for particle diameter increases for each particle diameter investigated in this work. Therefore, the MTCs for 500lb per 1000bbl were higher than those of 200lb per 1000bbl. The particles are transported in stratified wavy flow. The results from this study correspond to what Najmi et al. (2014) and Dabirian et al. (2015) reported.

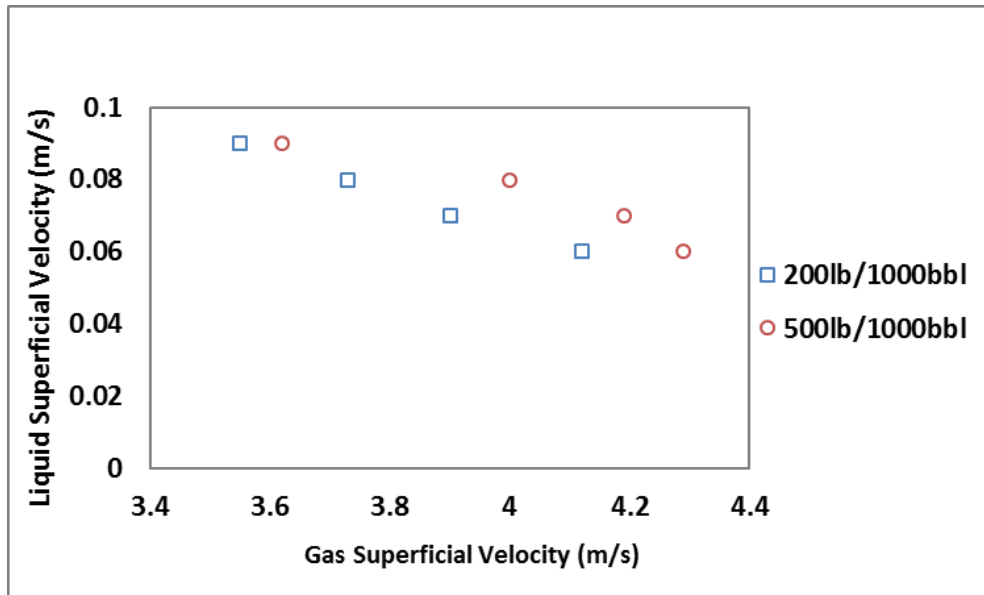


Figure 5-29: Minimum transport condition for particle concentration in stratified flow (air-water flow) particle size: 212 microns

5.11 Chapter Summary

Chapter 5 presents the results from the analysis of the air-water experiment, identification of sand-air- water flow with the aid of a sand sensor, effect of sand concentration on MTC, and the particle diameter effect on MTC. Air-water experimental results were compared with other work undertaken by different authors. Analyses were carried out with a sand sensor to identify various sand-air-water flow regimes which were complemented with snapshots and visual observations. Furthermore, comparisons of each sand-air-water flow regime were also analysed by employing the use of coefficient of variation and PSD. The effect of particle diameters was compared (212, 500 and 800 microns) for the same concentration on MTC in sand-air-water and it was found that the MTC increases with increases in particle diameter. Also, the effect of concentration on MTC was analysed for the same particle diameter and it was found that MTC increases with increases in concentration

6 DEVELOPMENT OF CORRELATION FOR MTC FOR SAND-GAS-LIQUID FLOWS AND PRESSURE GRADIENT ANALYSIS

6.1 Analysis of Pressure Gradient at MTC in Air-Water and Water Flows.

Wet gas pipeline design depends on pressure gradient. Analysis of pressure gradient is of great importance to this work. This is because this parameter influences the energy to transport sand particles in a wet gas pipeline.

6.1.1 Analysis of Pressure Gradient at MTC in Air-Water Flow

In this study, the pressure gradient for sand transport at MTCs was determined in both single phase water and air-water flows. King et al. (2001) assumed that at MTCs, the air-water pressure gradient at which sand particles are transported should be the same or a little higher than the pressure gradient when sand particles are transported in single phase water. Therefore, the energy required to keep sand particles in air-water flow at MTC must be equal to or greater than the energy required in single phase water. Thus, a multiphase flow pipeline can be designed based on this assumption. Based on this assumption, King et al. (2001) proposed an equivalent pressure gradient model to predict MTC for sand transport in air-water flow. Thomas' model (1962) was proposed to calculate the pressure gradient at MTC in sand-water flow and equalise it with pressure gradient calculated for air-water flow at MTC using Beggs and Brill (1973) for the purpose of multiphase flow pipeline design. However, in King et al. (2001), there was no confirmation that pressure gradients were measured. For this reason, pressure gradient was measured at MTC in single phase (water) and air-water at different sand concentrations in this work to confirm the validity of these concepts. The pressure gradient model by King et al. (2001) is given in equation 6-1:

$$\left(\frac{\Delta P}{\Delta L}\right)_{mtc} = \frac{4\rho_l(u_c^*)^2}{D} = \left(\frac{\Delta P}{\Delta L}\right)_{Beggs\ and\ Brill} \quad (6-1)$$

The pressure gradient for air-water flow at MTC for 212 microns at sand concentration of 200lb and 500lb per 1000bbl are depicted in Tables 6-1 and 6-2 respectively. The comparison of pressure gradient of sand-water with that of sand-air-water at MTC shows they are different. Considering Table 6-1, with a particle diameter of 212 at a concentration of 200lb per 1000bbl, the pressure gradient for air-water (V_{sl} 0.06m/s and V_{sg} 4.12m/s) at MTC is 75.38 Pa/m, while that of single phase water at this concentration is 180.15 Pa/m at MTC. The pressure gradient in single phase water was far higher than the pressure gradient of air-water flow at MTC. Therefore, based on this observation, the King et al. (2001) approach does not work for stratified flows. However, Yan (2010) compared the pressure gradient for sand-water and sand-air-water (slug flow) at MTC. According to Yan (2010), the pressure gradient for sand-air-water at MTC was equal to or higher than the pressure gradient for sand-water only. Thus, King et al.'s (2001) pressure gradient approach is valid in slug flow.

Table 6-1: Measured pressure gradients comparison at MTC for sand-air-water and sand-water flow in 2-inch pipe (212 microns 200lb/1000bbl).

212 microns					
Concentration (lb/1000bbl)	V_{sl} (ms^{-1})	V_{sg} (ms^{-1})	V_L at MTC (ms^{-1})	Measured Pressure Gradient in Air – Water at MTC ($Pa \cdot m^{-1}$)	Percentage Difference (%)
200	0.06	4.12	0.23	75.38	58.15
	0.07	3.90	0.26	63.71	64.63
	0.08	3.73	0.34	110.48	38.67
	0.09	3.55	0.38	116.61	35.27

Table 6-2: Measured pressure gradients comparison at MTC for sand-air-water and sand-water flow in 2-inch pipe (212 microns 500lb/1000bbl)

212 microns					
Concentration (lb/1000bbl)	V _{sl} (ms ⁻¹)	V _{sg} (ms ⁻¹)	V _L at MTC (ms ⁻¹)	Measured Pressure Gradient in Air – Water at MTC (Pa. m ⁻¹)	Percentage Difference (%)
500	0.06	4.29	0.24	85.44	57.78
	0.07	4.19	0.33	98.35	47.92
	0.08	4.0	0.36	111.35	41.03
	0.09	3.62	0.39	132.51	29.83

6.2 Analysis of Liquid Velocities at MTC in Water and Air-Water Flows

When sand particles are transported in single phase (water) the transportation takes place within the liquid phase. Furthermore, in stratified flow (air-water), sand transportation takes place within the liquid phase. The actual liquid velocities obtained at MTC for air-water flow were compared with actual liquid velocities in single phase water flow for 212 microns at concentrations of 200lb and 500lb per 1000bbl. The actual liquid velocities at MTC for 212 microns at 200lb and 500lb per 1000bbl in single phase water are 0.29m/s and 0.30m/s respectively. Comparison of these actual liquid velocities with sand-air-water at MTC by considering Tables 6-1 and 6-2 indicated that there are differences: some of the actual liquid velocities for sand-air-water were higher while some were lower than the actual liquid velocity of sand-water at MTC for the same particle diameter and concentration. These differences were due to variations in gas superficial velocities for different liquid superficial velocities. Tables 6-1 and 6-2 also show that as the liquid superficial velocity in the pipe increases, the actual liquid velocities at MTC increase with a decrease in gas superficial velocity. Therefore, understanding *liquid velocity* is important in sand transport.

6.3 Friction Factor and Actual Liquid Velocity

The friction factor is essential in the calculation of actual liquid velocities. Therefore, friction factors were obtained from the experimental pressure gradient in this study. Table 6-3 depicts the liquid and gas superficial velocities, actual liquid velocity, critical friction velocity, liquid hold-up and friction factor for 212 microns at concentrations of 200lb and 500lb per 1000bbl. Comparing the friction factor at MTC for the same liquid superficial velocity at different concentrations (for example V_{sl} 0.06m/s, 200lb/1000bbl and V_{sl} 0.06m/s, 500lb/1000bbl) in Table 6-3, it is shown that the friction factors obtained through experimental pressure gradient are different for the same liquid superficial velocity. However, using a generalised friction factor for calculating the actual liquid velocities for the same liquid superficial velocity at different gas superficial velocities may over or underestimate actual liquid velocities. For this reason, the friction factor was obtained from the measured pressure gradient.

Table 6-3: Flow condition with equivalent friction factor

212 microns						
Concentration	V_{sl}	V_{sg}	V_L at MTC	Critical Friction Velocity	Liquid Holdup	Equivalent Friction factor
(lb/1000bbl)	(ms^{-1})	(ms^{-1})	(ms^{-1})	(ms^{-1})	(—)	
200	0.06	4.12	0.23	0.049	0.25	0.091
500	0.06	4.29	0.24	0.053	0.244	0.097
200	0.07	3.90	0.25	0.046	0.27	0.063
500	0.07	4.19	0.33	0.059	0.21	0.064
200	0.08	3.73	0.33	0.062	0.24	0.069
500	0.08	4.00	0.36	0.063	0.22	0.061
200	0.09	3.55	0.38	0.064	0.24	0.058
500	0.09	3.62	0.39	0.069	0.23	0.061

6.4 Development of Sand Transport Correlation for MTC in Air-Water (Stratified Flow)

One of the objectives of this study is to advance the Thomas lower model to enhance its robustness. This study aims to derive a friction velocity that can predict sand transport in air-water flow at the MTCs usually in wet gas pipelines. From the Thomas lower model (1962), it was found that a concentration correction term has not been considered (Equation 2-20). Concentration is one of the important factors that affect sand transport at MTC in fluid flow. Furthermore, Thomas also proposed that the wall friction velocity is constant from a concentration of 0.01 to 0.06 v/v for sand particles smaller than the laminar sublayer. Therefore, shear velocity at infinite dilution was assumed to be $C_v = 0.01$ v/v. However, as a result of the absence of data for shear velocity, for concentrations lower than 0.01 v/v, this theory is unproven.

The thickness of the laminar sublayer can be calculated from equation 2-3. Based on this calculation, all the particle diameters used in this study (212, 500, 800 microns) at liquid superficial velocities of 0.06, 0.07, 0.08 and 0.09m/s are smaller than the laminar sub-layer thickness. In such cases, the Thomas lower model (1962) is applied. Comparison of Thomas lower model (1962) results with experimental results (MTC) from this study in Chapter 4 showed that there were discrepancies between them. The inaccuracies in the Thomas lower model may be attributed to the absence of a solid (sand) concentration factor.

To advance the Thomas lower model (1962), sand transport actual liquid velocity at MTCs in air-water was obtained through the experiment in the 2-inch horizontal pipe, described earlier. A concentration range of $5.39\text{E-}05$ v/v (50lb/1000bbl) to $5.39\text{E-}04$ v/v (500lb/1000bbl) was considered. The sand transport velocities in air-water at MTCs were first converted to actual liquid velocities and the friction factors were obtained from pressure gradient measurements.

The correlation in the form of $u_c^* - u_0^* = KC_v^\alpha$ will be used to advance the Thomas lower model. This type of correlation has been recommended by many investigators, such as Thomas (1962), and Zandi and Haydon (1971). The

structure of the correlation (friction velocity calculation with concentration) for very low sand concentration at different liquid superficial velocities is shown in Figure 6-1. Figures 6-2a and 6-2b depict the correlation curve fitting for the experimental data point at liquid superficial velocities 0.06m/s and 0.09m/s respectively. In this correlation, a friction velocity of 0.0000539 v/v (50lb/1000bbl) was used for the infinite dilution condition.

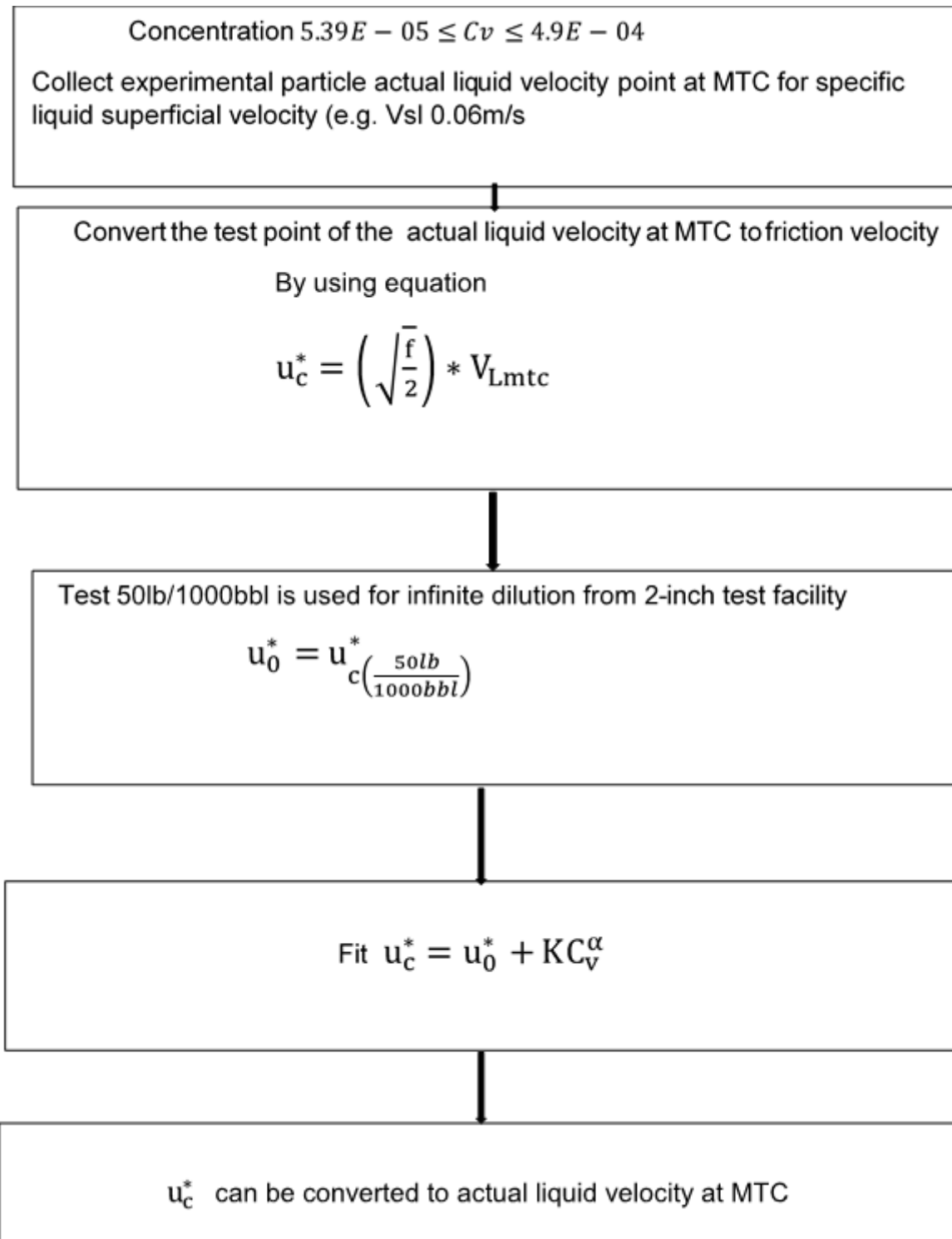


Figure 6-1: Friction velocity calculation with concentration correction term (V_{sl} 0.06 and 0.09m/s)

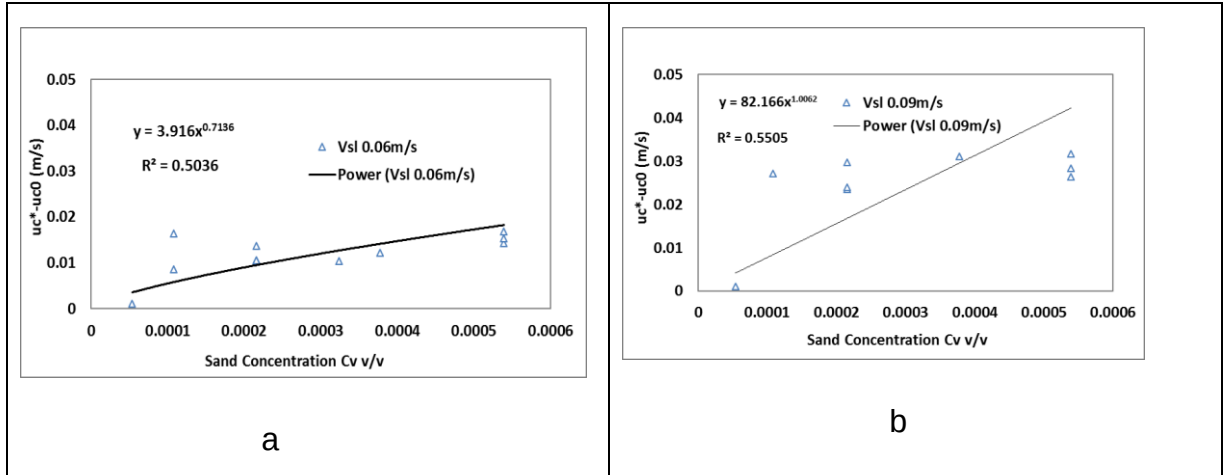


Figure 6-2: Correlation for data at liquid superficial velocities of 0.06m/s and 0.09m/s

6.4.1 Proposed Correlation

In order to have one correlation (final), all experimental data points at MTC in air-water flow from flow conditions (V_{sl} , 0.06, 0.07, 0.08 and 0.09 m/s) obtained from 2-inch test facilities were put together. Figure 6-3 shows the structure of the model. Also, the curve fitting for the final proposed correlation is shown in Figure 6-4

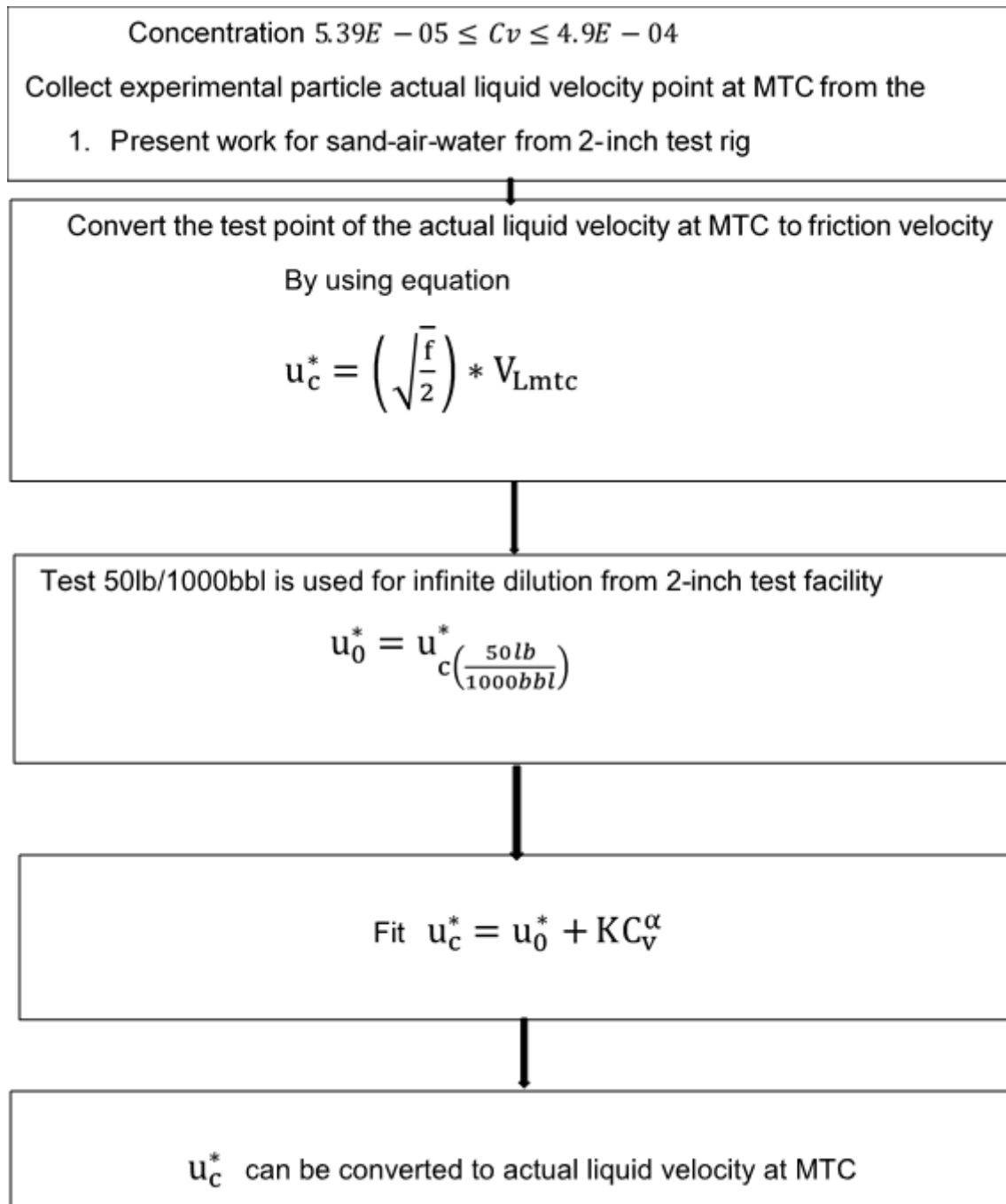


Figure 6-3: Friction velocity calculation with concentration correction term for the proposed correlation

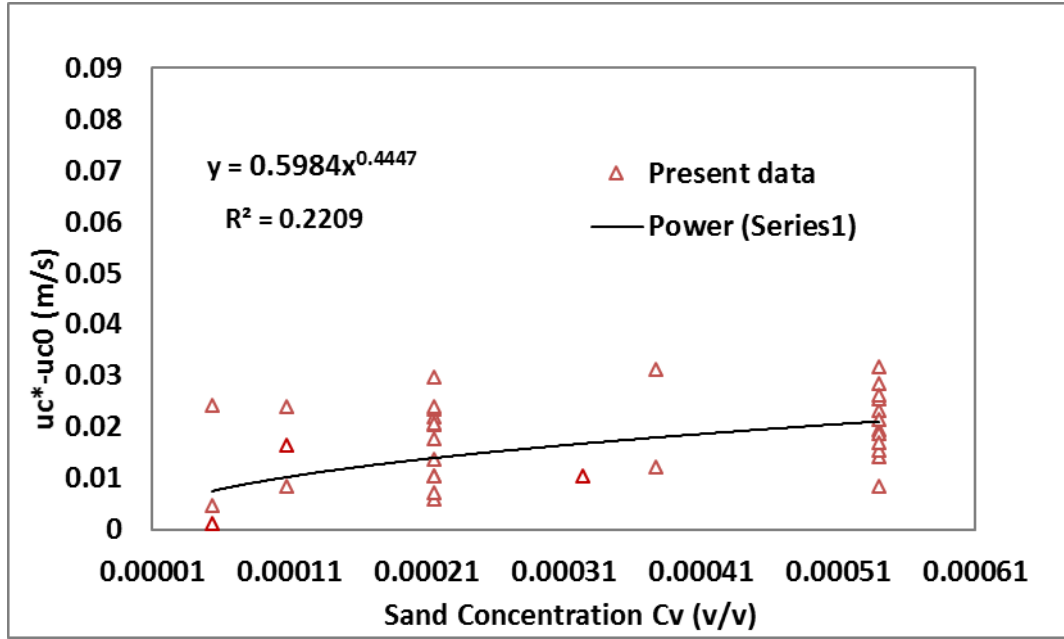


Figure 6-4: Proposed model

The newly proposed correlation for sand MTC in air-water (stratified flow) becomes 6-2:

$$u_c^* = u_0^* + 0.5984C_v^{0.4447} \quad (6-2)$$

where u_0^* is the Thomas lower model (1962)

$$u_0^* = \left[100u_t \left(\frac{v}{d_p} \right)^{2.71} \right]^{0.269}$$

$$u_c^* = \left(\sqrt{\frac{f}{2}} \right) * V_{Lmtc} \quad (6-3)$$

Equation 6-3 can now be used to calculate the actual liquid velocity at MTC.

6.4.2 Proposed Model Application

The newly proposed correlation for sand MTC in air-water (equation 6-2) can be used to determine the actual liquid velocity (V_{Lmtc}) at MTC by introducing it into equation 6-3. Sand will be transported if the actual liquid velocity (V_{Lmtc}) at MTC obtained by introducing equation 6-2 into equation 6-3 is higher than the experimental actual liquid velocity at MTC in Tables 6-4, 6-5, 6-6 and 6-7 for specific superficial liquid velocity, superficial gas velocity and sand volume concentration. However, sand will not be transported if the actual liquid velocity (V_{Lmtc}) at MTC obtained by introducing equation 6-2 into equation 6-3 is lower than the experimental actual liquid velocity at MTC in Tables 6-4 to 6-7 for specific superficial liquid velocity, superficial gas velocity and sand volume concentration.

6.4.3 Comparison of the Proposed Correlation with Experimental MTC

The proposed sand transport correlation results were compared with the experimental results from the sand transport at MTC in Tables 6-4, 6-5, 6-6 and 6-7 for liquid superficial velocities of 0.06, 0.07, 0.08 and 0.09m/s at different concentration and particle diameters. It was found that the proposed correlation predicted fairly when compared with the experimental results at MTC.

Table 6-4: Comparison of predicted MTC from proposed correlation with MTC from the experiment (Vsl0.06m/s)

Particle Diameter	Concentration	Vsl	Vsg	Predicted V_{Lmtc} using proposed Correlation (ms⁻¹)	Experiment V_{Lmtc} (ms⁻¹)
microns	(lb/1000bbl)	(ms⁻¹)	(ms⁻¹)		
212	200	0.06	4.12	0.25	0.23
212	500	0.06	4.29	0.28	0.24
500	200	0.06	4.33	0.26	0.24
500	500	0.06	4.70	0.28	0.25
800	200	0.06	5.10	0.25	0.25
800	500	0.06	5.4	0.29	0.27

Table 6-5: Comparison of predicted MTC from proposed correlation with MTC from the experiment (Vsl0.07m/s)

Particle Diameter	Concentration	Vsl	Vsg	Predicted V_{Lmtc} using proposed Correlation (ms⁻¹)	Experiment V_{Lmtc} (ms⁻¹)
microns	(lb/1000bbl)	(ms⁻¹)	(ms⁻¹)		
212	200	0.07	3.90	0.30	0.26
212	500	0.07	4.19	0.34	0.33
500	200	0.07	4.27	0.30	0.33
500	500	0.07	4.40	0.33	0.35
800	200	0.07	4.91	0.4	0.35
800	500	0.07	5.10	0.46	0.37

Table 6-6: Comparison of predicted MTC from proposed correlation with MTC from the experiment (Vsl0.08m/s)

Particle Diameter	Concentration	Vsl	Vsg	Predicted V_{Lmtc} using proposed Correlation (ms⁻¹)	Experiment V_{Lmtc} (ms⁻¹)
microns	(lb/1000bbl)	(ms⁻¹)	(ms⁻¹)		
212	200	0.08	3.73	0.34	0.33
212	500	0.08	4.00	0.35	0.36
500	200	0.08	4.00	0.37	0.35
500	500	0.08	4.20	0.38	0.36
800	200	0.08	4.69	0.37	0.36
800	500	0.08	4.85	0.38	0.38

Table 6-7: Comparison of predicted MTC from proposed correlation with MTC from the experiment (Vsl0.09m/s)

Particle Diameter	Concentration	Vsl	Vsg	Predicted V_{Lmtc} using proposed Correlation (ms⁻¹)	Experiment V_{Lmtc} (ms⁻¹)
microns	(lb/1000bbl)	(ms⁻¹)	(ms⁻¹)		
212	200	0.09	3.55	0.39	0.38
212	500	0.09	3.62	0.35	0.39
500	200	0.09	3.78	0.40	0.39
500	500	0.09	3.98	0.41	0.45
800	200	0.09	4.50	0.43	0.43
800	500	0.09	4.69	0.46	0.45

6.5 Chapter Summary

This chapter discussed the analysis and comparison of the pressure gradient of sand-water flow and sand-air-water flow at MTCs, the comparison of actual liquid velocity of sand-water and sand-air-water at MTCs and the development of a new model to estimate sand transport MTC in air-water by advancing the Thomas lower model (1962).

King et al. (2001) proposed an equivalent pressure gradient model to predict MTC for sand transport in air-water flow. The Thomas model (1962) was proposed to calculate the pressure gradient at MTC in sand-water flow and equalise it with the pressure gradient calculated for air-water flow at MTC using Beggs and Brill (1973) for the purpose of multiphase flow pipeline design. If the pressure gradient of air-water predicted by the Beggs and Brill (1973) model at MTC is higher than the pressure gradient at MTC for sand-water, sand will be transported (King et al., 2001). However, in this study, the equivalent pressure gradient at MTC for sand-water is higher than the pressure gradient for sand-air-water at MTC. This study proved that King et al.'s (2001) idea of equivalent pressure gradient does not hold for stratified flows. Therefore, the concept cannot be used to design wet gas pipelines.

Comparison of the actual liquid velocities of sand-water and sand-air-water at MTC in Tables 6-1 and 6-2 showed that there were variations. Some of the actual liquid velocities for sand-air-water were higher while some were lower than the actual liquid velocity of sand-water at MTC for the same particle diameter and concentration. The differences were due to variations in gas superficial velocities for different liquid superficial velocities.

The Thomas lower model (1962) may not be ideal to estimate sand transport at MTC in air-water flow. However, this study modified the Thomas lower model to estimate sand transport at MTC in air-water flow.

7 CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The MTCs and sand transport behaviour in single phase (water) and multiphase (air-water) flows have been investigated in a 2-inch horizontal Perspex pipe using a sand sensor (similar to those employed to measure liquid film thickness) and visual observation, and the outcomes of the investigation are as follows:

- The sand sensor had only been designed to measure the thickness of films in multiphase flow. Several researchers had used this sensor for this purpose but it has not been used to monitor sand behaviour in multiphase flow and identify sand dunes' flow regimes from other sand flow regimes, such as suspension, streak and saltation. This study has successfully applied a sand sensor to identify sand dune flow regimes and monitor sand behaviour in sand-water and sand-air-water (stratified flow) flow regimes. The signal of a sand dune from the sand sensor is characterised with several dips. Each dip in the signal showed that a sand dune was passing the sand sensor. The passing of a sand dune tends to reduce the conductivity that exists between the electrodes of the sensor. The streak in-between each sand dune consists of a few sand grains with a large amount of water. The results were in good agreement with visual observation. Therefore, a sand sensor (film thickness sensor) can be used to monitor sand transport in single phase (water) and multiphase (air-water, stratified flow). In stratified flow, sand is transported within the liquid film (water) at the bottom of the pipe. This enables sand sensors to monitor the movement of the sand. Sand dunes occur at low gas and liquid velocities when compared with other flow regimes (streak and saltation). Positioning the sensor at the base of the pipe will help to monitor sand transport properly in stratified flow or wet gas pipelines. The geometry of the sand sensor should be concentric for the sensor to be sensitive to the movement of sand-water and sand-air-water. This is because the

concentric geometry of the sand sensor allows the measurement to be reasonably localized.

- Similar sand behaviours were observed in sand-water and sand-air-water (stratified) flows for different particle diameters (212, 500 and 800 microns) and at different sand concentrations (200lb and 500lb per 100bbl) tested on the 2-inch horizontal pipe, in this study.
- Investigations carried out on the effect of particle size on MTC in this study for both sand-water and sand-air-water showed that MTC increases with increased particle size at the same sand concentration.
- Investigations on the effect of sand concentration on MTC for sand-water and sand-air-water for the same sand particle diameter showed that at different sand concentrations, MTC increases with increased sand concentration.
- The transport of sand in stratified flow is enhanced by gas superficial velocities. However, sand particles were never observed crossing into the gas phase or transported across the gas-liquid interface. Thus sand is transported within the liquid film in stratified flow.
- Thomas lower model is devoid of concentration. This model was advanced to account for concentration. Actual liquid velocities at MTCs in air-water were obtained through the experiment in a 2-inch horizontal pipe. A concentration range of $5.39\text{E-}05$ v/v (50lb/1000bbl) to $5.39\text{E-}04$ v/v (500lb/1000bbl) was considered. The sand transport velocities in multiphase (air-water) at MTCs were first converted to actual liquid velocities and then to friction velocities. The friction factors were obtained from pressure gradient measurements. The proposed correlation with concentration was incorporated into the Thomas lower model for the prediction of friction velocity at MTCs for multiphase flow. The predicted results from the proposed correlation were in good agreement with the experimental results.

- In this study, the pressure gradients in sand-air-water flow (stratified flow) were compared with pressure gradients in sand-water at MTC for the same particle size and concentration. It was found that the two pressure gradients were different. The pressure gradient of sand-water flow at MTC was higher than the pressure gradient of sand-air-water flow at MTC. For this reason, King et al.'s (2001) pressure gradient concept does not work for stratified flow. Therefore, King et al.'s (2001) pressure gradient approach cannot be used to design wet gas pipelines.

7.2 Recommendations and Future Work

- The particle diameters investigated in this study are in the stratified flow, range between 212 and 800 microns. Investigation needs to be carried out on the effect of particle diameter on MTC in stratified flow for particle sizes less than 50 microns in a horizontal pipe. This is because screens and gravel packs are designed to allow particles measuring less than 50 microns to be produced with production fluids. Particles of this size can wreak havoc on the pipeline if they are deposited.
- In this study, pressure gradients in sand-air-water flow (stratified flow) were compared with pressure gradients in sand-water flow at MTC for the same particle size and concentration. It was found that the two pressure gradients were different. However, Yan (2010) reported that the pressure gradients in sand-air-water flow (slug) and sand-water flow were the same at MTC. This proved that King et al.'s (2001) pressure gradient concept is true for this flow condition. Therefore, investigation needs to be carried out on pressure gradients for sand transport in other flow regimes, such as plug and bubbly flows in a horizontal pipe. This will prove the validity of King et al.'s (2001) pressure gradient concepts in other air-water flow regimes and enhance appropriate pipe design.
- This study investigated the effect of particle diameter on MTC with different sand concentrations in a horizontal 2-inch pipe. Investigation of the effect of particle diameter on MTC with different sand concentrations should be

carried out in both small and large pipes in vertical orientation. This will enhance the understanding of sand transport behaviour in risers.

- Currently, investigation on sand transportation in an annular flow regime, where sand particles can be transported in gas core or liquid film, is limited. Furthermore, while investigating sand transport in an annular flow regime, erosion must be considered since annular flow occurs at high gas velocities. There is the possibility of sand being transported within the gas core, which can erode the surface of the pipe and sensors.
- Air and water were used as fluid in this study. The effect of viscosity was not tested. Investigation into solid transportation in multiphase systems, when the properties of the fluids are not air-water, will enhance the understanding of sand transport in oil and gas pipelines. Therefore, the effect of viscosity on solid transportation in stratified multiphase flow should be investigated using oil as the liquid phase in the pipe.
- Data on MTCs for sand transportation are limited for multiphase pipelines deviating from horizontal positions. Investigation needs to be undertaken to acquire data for sand transportation in this pipeline orientation. The information can then be used to solve the problem of sand transport in hilly terrains.

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APPENDICES

Appendix A: Conductivity Sensor Calibration

A.1 Air-Water Calibration

A.1.1 Conductivity Sensor

Conductivity of any substance can be defined as the measure of that substance's ability to permit the flow of electric current. This is the reciprocal of its resistivity. The unit of conductivity is Siemens per metre and its symbol is σ (sigma). The current flowing through a material creates an electric field therefore, conductivity is also defined as the ratio of current density to the electric field generated by the material when the electric current is flowing through the material.

A.1.2 Conductivity Ring Calibration with Water

The importance of conductivity ring calibration with water only, is to help in determining liquid hold-up from impedance readings of the dynamic experimental test. Furthermore, it also ensures the fixed voltage range of the output signal from the conductivity ring's sensors. Calibration of the conductivity ring spool was done by using municipal tap water, which is the same liquid (water) used in the experimental tests.

The conductivity ring calibrations were carried out by connecting two pairs of electrodes to a conductivity electronic box which has an output of 22kHz A.C.

The procedures for conductivity sensor calibration for air-water experiments are described as follows:

Calibration procedures for conductivity sensors for air-water experiments are reported as follows:

1. Firstly, clean and dry the conductivity ring spool and adjust the knob of the conductivity box to set air *in situ* value. The air *in situ* values can be set as 1.5 volts for box 1 and 1.5 volts for box 2.

2. The conductivity spool unit is filled with water and the output voltage is recorded when the unit is full of water.
3. Remove all water from the conductivity ring spool after recording the voltage when the spool is full of water. Clean and dry the spool again after removing the water; this brings the output voltage to the conductivity ring spool to initial empty pipe voltage.
4. Fill the conductivity ring spool with constant weight of water stepwise and record the voltage while adding a constant weight of water to the spool (for example 1g of water; for each 1g of water added to the spool the output voltage is recorded)
5. Record the output voltage of the two sensors while adding a constant weight of water stepwise has been described in step 4.

Calibration of the conductivity sensor was carried out three times and liquid hold-up was plotted against the average normalized voltage to develop the calibration curve for the conductivity ring sensor. The calibration curves are depicted in A-1 and A-2

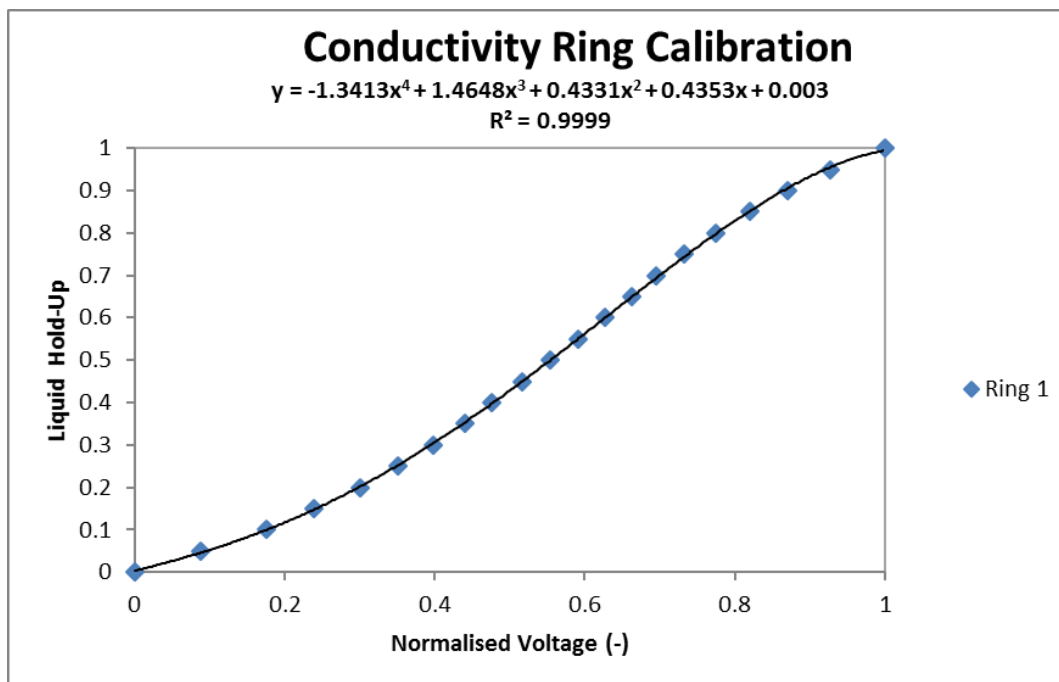


Figure A- 1: Calibration curve and equation for air-water from conductivity ring 1

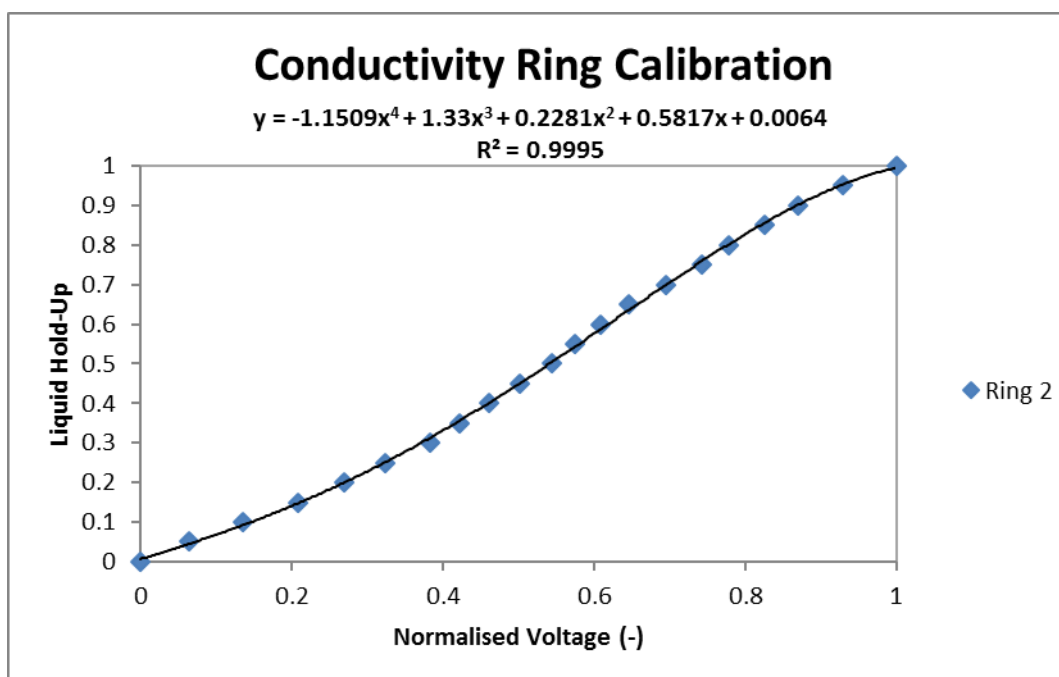


Figure A- 2: Calibration curve and equation for air-water from conductivity ring 2

A.2 Appendix: Sand Sensor Calibration

A.2.1 Sand-Water Calibration

One important parameter that needs to be determined in the design and operation of a liquid-solid and gas-liquid-solid multiphase in a pipeline transportation system is sand hold-up. The calibration equation was determined from the curve by converting output normalized voltage values into sand fractions. Figures A-4 and A-5 depict the curves of sand fraction against normalized voltage and sand height against normalized voltage respectively.

The calibration of conductivity sand sensors in low sand concentration is of great importance in this work.

The procedures for sand sensor calibration are as follows:

1. The pipe spool holding the sand sensor is blinded at one side and half blinded at the second side with plastic flanges to prevent leakages.
2. The spool carrying the sand sensor is attached to a retort stand and adjusted to work-bench level in a horizontal position.
3. The sand sensor is connected to one of the channels in the conductivity box (e.g. Channel 1).
4. Connect two multi-meters to the corresponding channel output of the conductivity box and set to an appropriate voltage range.
5. Tune the knob of the conductivity box to obtain 1.5 volts on the multi-meter that correspond to dry and empty sand sensor. This fixes the lower range value of the sensor. Adjust the output voltage to a value different from 0 volts to confirm its functionality and when the conductivity section is empty and dry. This gives the voltage value for air.
6. Fill the sand sensor to saturation point with water to achieve the maximum output voltage for air-water only. Record the maximum output voltage.

7. Add known weight of sand stepwise into the water in contact with the sand sensor. This will displace certain volume of water within the spool. Record the output voltage.

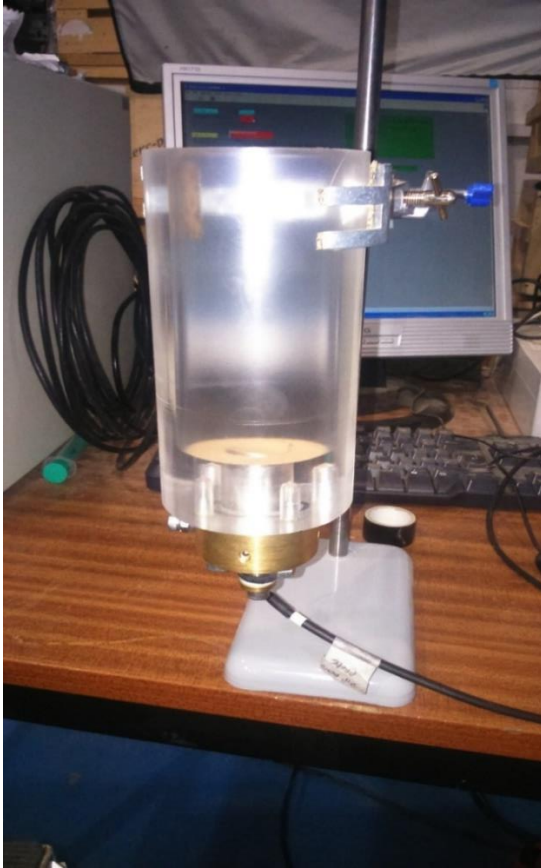


Figure A-3: Sand sensor spool

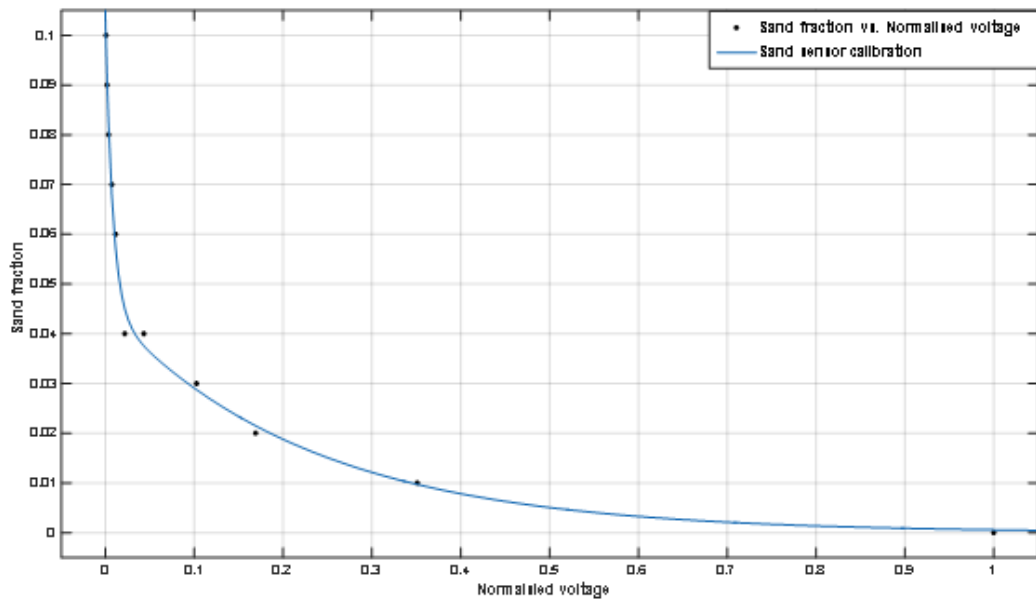


Figure A-4: Sand sensor sand calibration (sand fraction against normalized voltage)

The calibration equation for the sand sensor calibration is given equation as A-1 below;

$$y = 3.667^{-10} \exp(-36.35x) + 0.0228 \exp(-1.31x) \quad (\text{A-1})$$

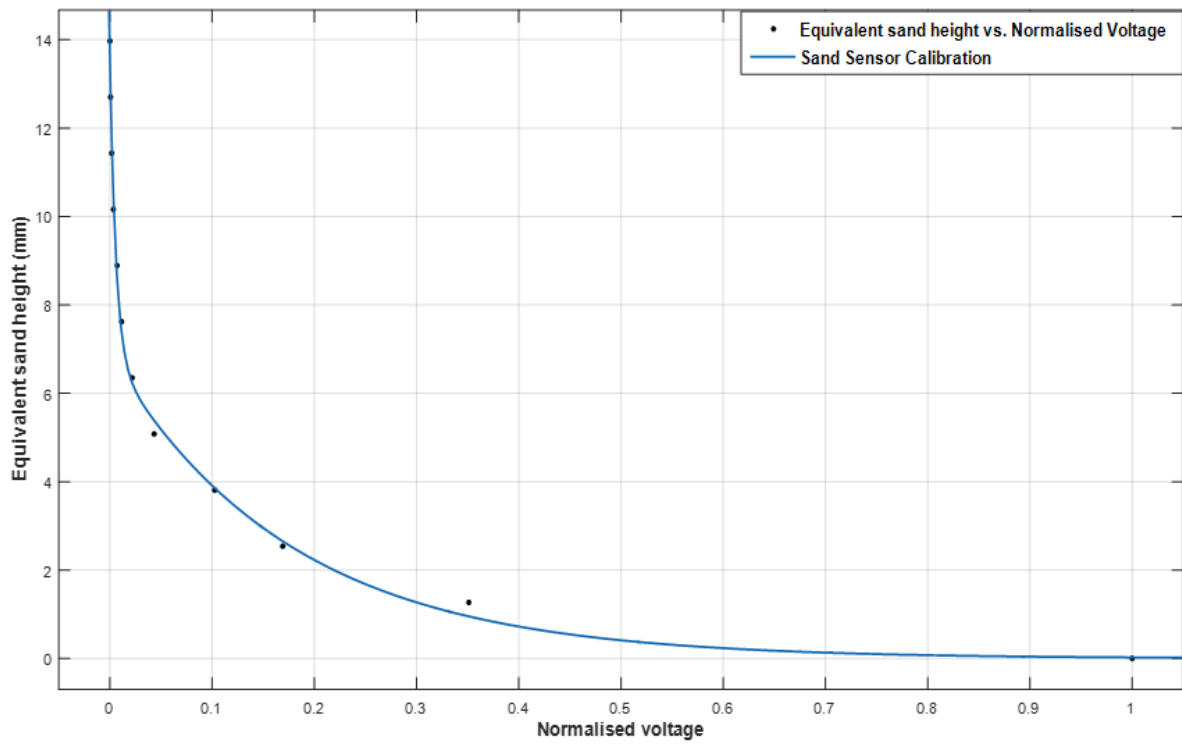


Figure A- 5: Plot of sand height against normalized voltage

A.3 Sand-Water Signal from Sand Sensor

Tables A-1 to A-4 depict signals, mean normalized voltage, standard deviation of normalized voltage, coefficient of variation, sand thickness and PSDs obtained by analysing sand sensor for sand-water flow.

Table A- 1: Summary of sand-water flow regimes from sand sensor

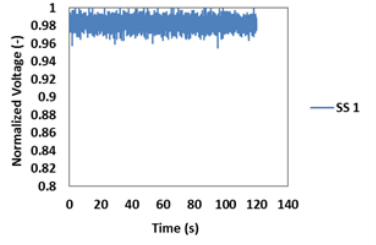
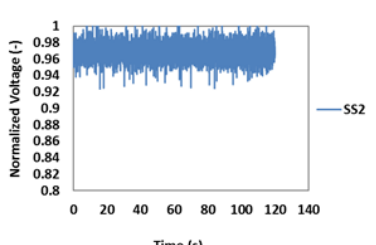
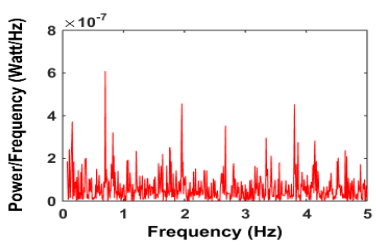
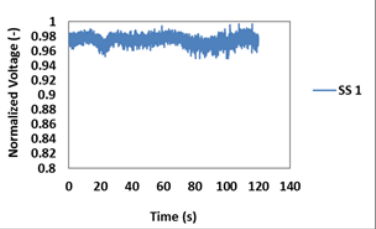
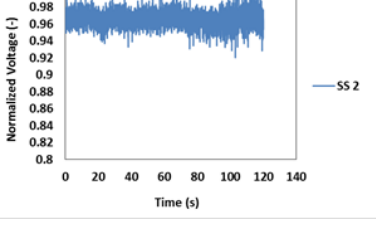
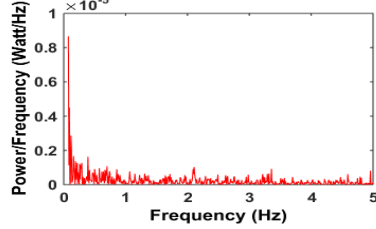
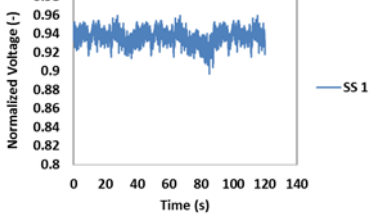
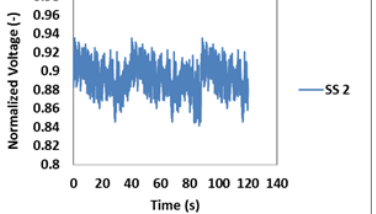
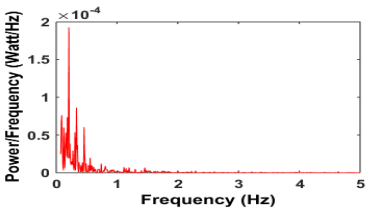
212micron, 200lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation (%)	Equivalent Sand Thickness (mm)	Power Spectral Density
Suspension	0.31			0.98	± 0.0023	0.24	0.10	
Streak	0.20			0.97	± 0.0044	0.45	0.22	
Saltation	0.18			0.92	± 0.0080	0.87	0.25	

Table A- 1 Continued

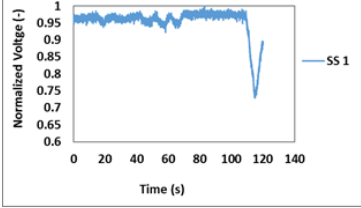
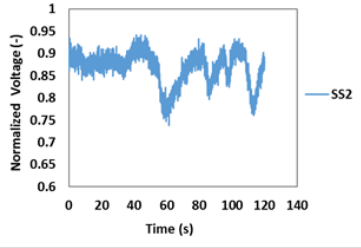
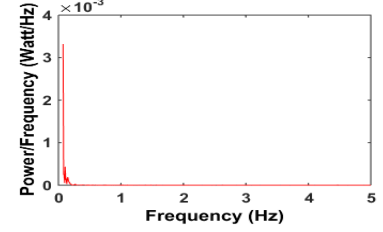
212micron, 200lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Moving Dune	0.15			0.91	± 0.033	3.63	0.27	

Table A- 2: Summary of sand-water flow regimes from sand sensor

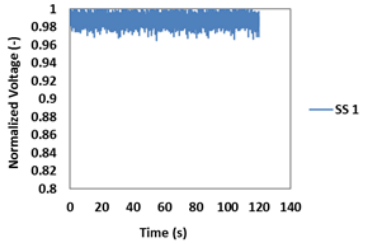
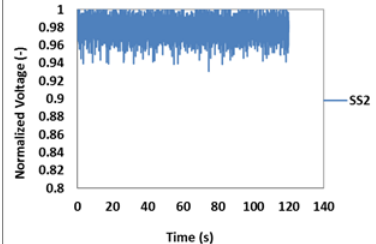
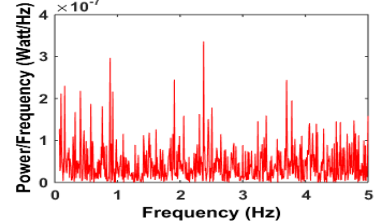
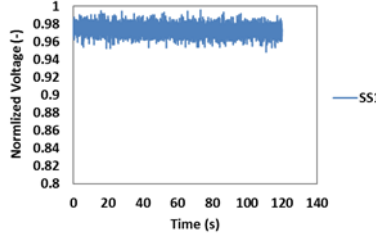
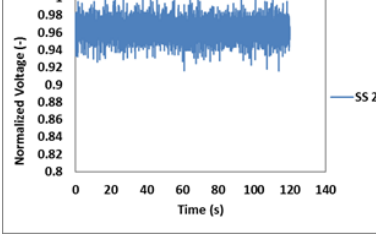
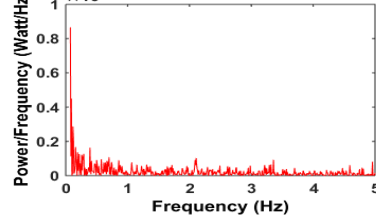
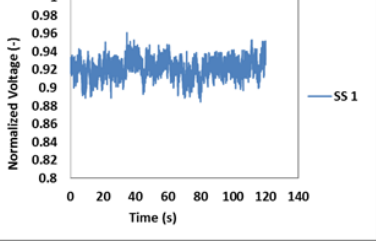
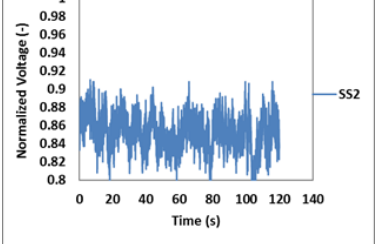
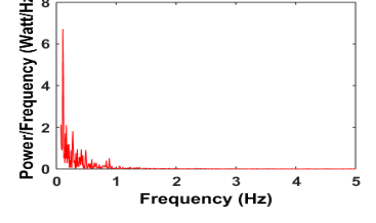
500micron, 200lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Suspension	0.35			0.98	± 0.0031	0.32	0.10	
Streak	0.25			0.96	± 0.0034	0.35	0.50	
Saltation	0.18			0.89	± 0.0095	1.07	0.51	

Table A- 2 Continued

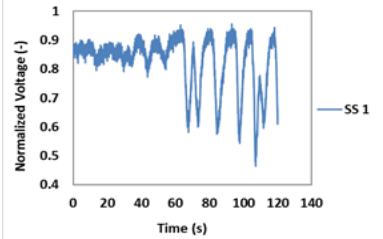
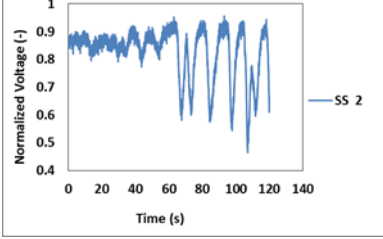
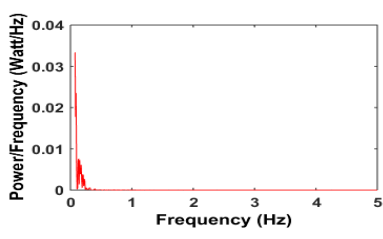
500micron, 200lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Moving Dune	0.15			0.86	± 0.064	7.44	0.52	

Table A- 3: Summary of sand-water flow regimes from sand sensor

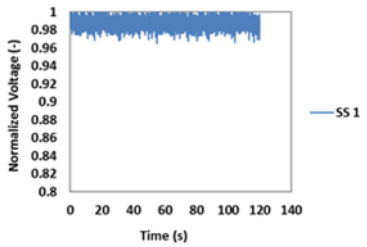
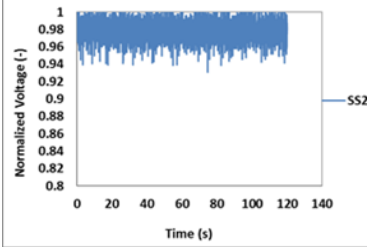
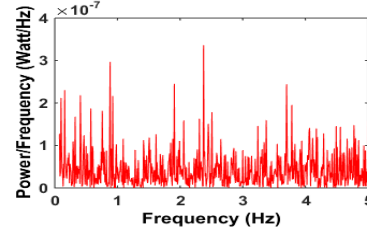
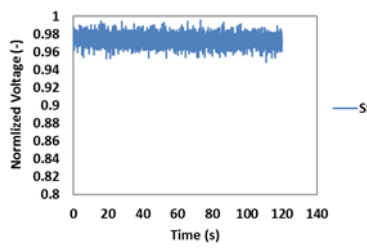
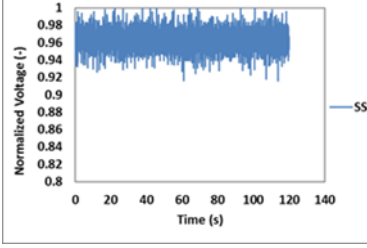
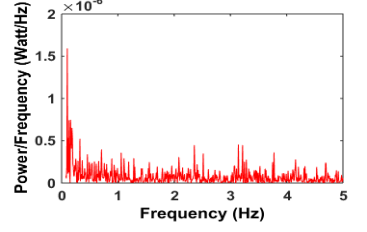
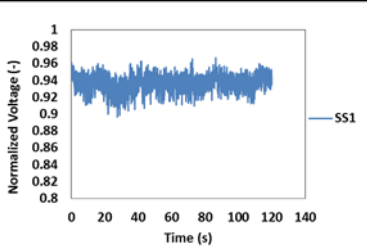
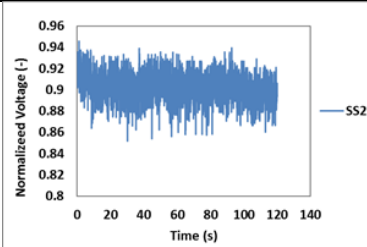
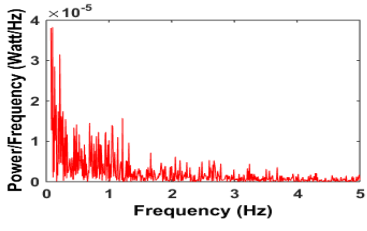
500micron, 500lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Suspension	0.35			0.98	± 0.0031	0.32	0.10	
Streak	0.25			0.95	± 0.0075	0.79	0.52	
Saltation	0.18			0.88	± 0.010	1.14	0.53	

Table A- 3 Continued

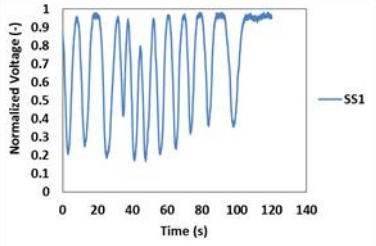
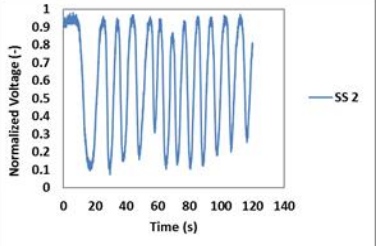
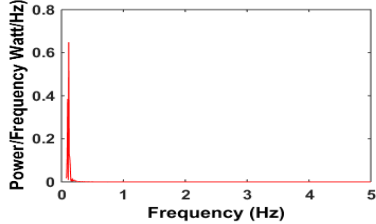
500micron, 500lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Moving Dune	0.15			0.65	± 0.19	13.85	0.50	

Table A- 4: Summary of sand-water flow regimes from sand sensor

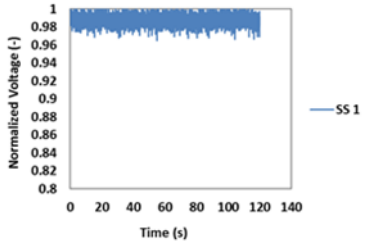
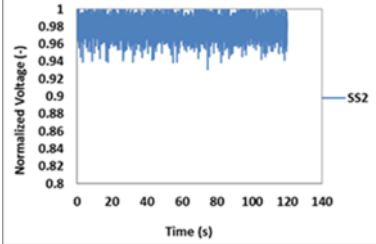
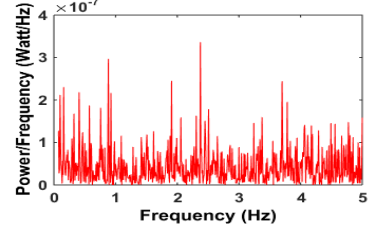
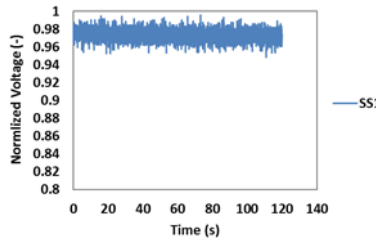
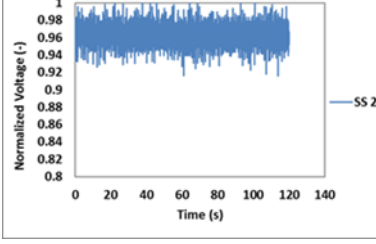
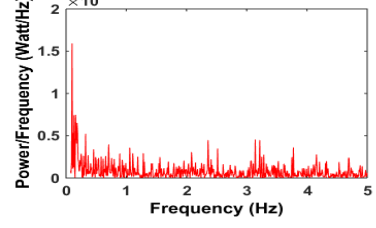
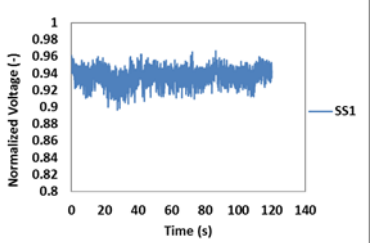
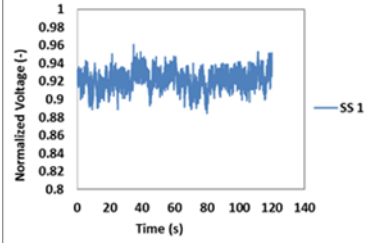
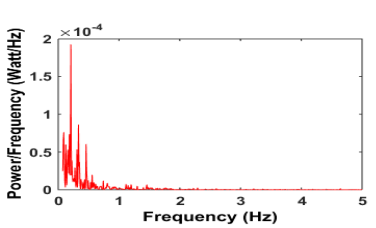
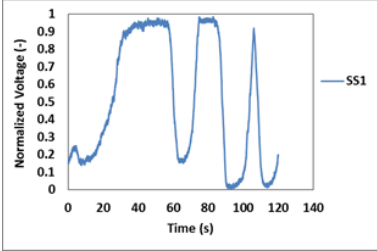
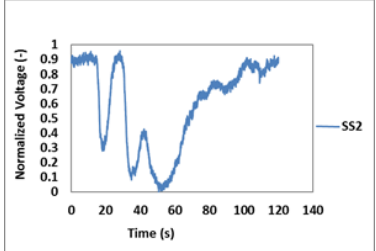
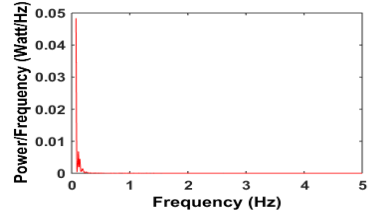
800micron, 500lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Suspension	0.35			0.97	± 0.0031	0.32	0.10	
Streak	0.25			0.94	± 0.01	1.06	0.81	
Saltation	0.18			0.84	± 0.03	3.57	0.82	

Table A- 4 Continued

800micron, 500lb/1000bbl								
Flow Regime	V_{sl} (ms^{-1})	Sand Sensor 1	Sand Sensor 2	Mean Normalized Voltage	Standard Deviation of Normalised Voltage	Coefficient of Variation	Equivalent Sand Thickness (mm)	Power Spectral Density
Moving Dune	0.15			0.55	± 0.2	36.36	0.84	

Appendix B: Description of Sand Property Measurement

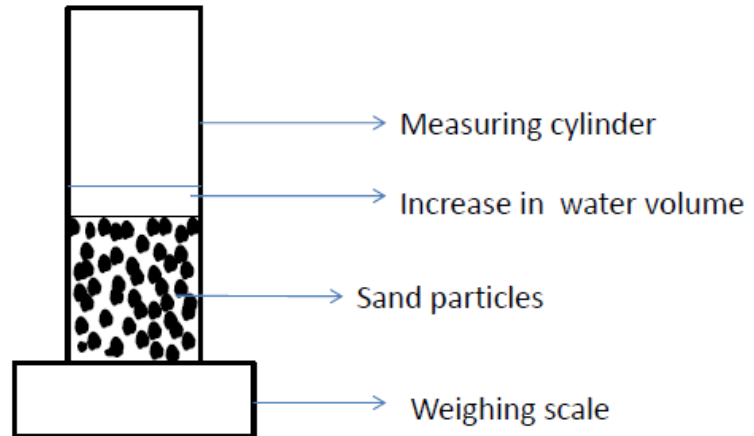


Figure B- 1: Schematic measurement for sand properties

Procedures for measurement of sand properties

1. Weigh an empty measuring cylinder and record the mass and label it as cylinder A.
2. Measure and determine the apparent volume of a known quantity of sand (50g, 100g etc.) in a separate measuring cylinder of the same size and height as the measuring cylinder A, and label it as measuring cylinder B.
3. Put about 50ml of water into the measuring cylinder A and determine the weight of the cylinder A and water.
4. Add all the sand particles, in which the quantity and apparent volume are known from measuring cylinder B, to the weighed water and measuring cylinder A and determine the total mass (Sand + Water + Cylinder A).
5. Record the increase in the total volume of the contents in the measuring cylinder when sand is added to the water in measuring cylinder A.
6. Calculate the void volume of the sand and actual volume using the equations below:

$$\text{Void volume} = [(V_{S.app} + V_w) - V_m]$$

$$V_{S.act} = V_{S.app} - \text{Void volume}$$

where $V_{S.act}$ is the actual volume of sand, V_m is the mixture volume, $V_{S.app}$ connotes the apparent volume of sand, and V_w is the volume of water.

7. Calculate the density and porosity of the sand by using the equations below:

$$\text{Density of sand} = \frac{\text{Mass of the sand}}{\text{volume of the sand}}$$

$$\text{Porosity} = \left(1 - \frac{\text{Actual volume}}{\text{Apparent volume}}\right) * 100\%$$

8. Repeat the above steps for the same sand size particles twice more, thus obtaining three measurements of the density and porosity, and record the results.

Appendix C: Particle Size Effect on MTC for 500lb/1000bbl

Table C-1 summarises the effect of particle size on MTC for 500lb per 1000bbl,

Table C-1 Effect of particle size on MTC

500lb/1000bbl			
Particle Diameter (microns)	Vsl (ms ⁻¹)	Vsg (ms ⁻¹)	Actual liquid velocity at MTC (ms ⁻¹)
212	0.06	4.29	0.24
500	0.06	4.70	0.25
800	0.06	5.40	0.27
212	0.07	4.19	0.33
500	0.07	4.40	0.35
800	0.07	5.10	0.37
212	0.08	4.00	0.36
500	0.08	4.20	0.36
800	0.08	4.85	0.38
212	0.09	3.62	0.39
500	0.09	3.98	0.45
800	0.09	4.69	0.45

Appendix D: Pressure Transducer Calibration

Two PMP 4070 pressure transducers were calibrated before they were installed on the Perspex pipe for experimental runs. The pressure calibration instrumentation consists of a hand-held pneumatic pressure pump with digital pressure gauge. The model of the hand-held pneumatic pressure pump is ADT 914 which ranges from 0.96 to 25 bar with an adjustment resolution of 10 Pa, while the digital pressure gauge is model ADT 681 and has a range of 0 to 20 bar.

Procedures for pressure transducer calibration are as follow:

1. Connect the digital pressure gauge and the pressure transducer to the connector on the hand-held pneumatic pump.
2. Connect the pressure transducer cable to the voltmeter.
3. Set the pressure gauge to zero bar by adjusting the vent valve at the side of the hand-held pneumatic pump and read and record the output equivalent voltage on the voltmeter.
4. Introduce a pressure of 1 bar to the system using the hand-held pump and record the output voltage.
5. Add pressure consecutively (2, 3, 4, and 5 bar) and record the equivalent output voltage for each pressure introduced through the hand-held pump.
6. Decrease the pressure from the maximum value to the next minimum value consecutively using the vent valve (e.g. 5 bar to 4 bar) and record the corresponding voltage. This is to check the accuracy of the calibration.
7. Plot the pressures against the equivalent voltages and determine the slope and offset.

Appendix E: Two Fluid Model

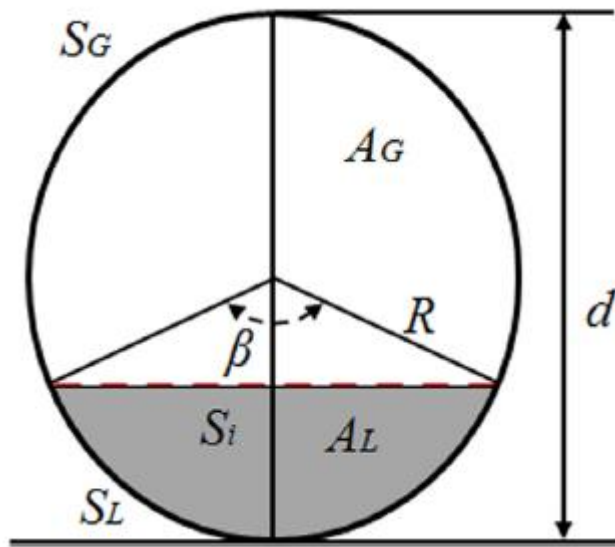


Figure E-1: Cross section view of horizontal pipe

Assumption

Considering gas and liquid flow together in horizontal pipe without mixture. The momentum conservation of both phases for steady state assuming no acceleration yields

$$-A_L \frac{dp}{dx} - \tau_{WL} S_L + \tau_i S_i = 0 \quad (\text{E-1})$$

$$-A_G \frac{dp}{dx} - \tau_{WG} S_G - \tau_i S_i = 0 \quad (\text{E-2})$$

Resolve equation 1 and 2 by adding them together to give equation E-3

$$-\frac{dp}{dx} = \frac{1}{A} [\tau_{WL} S_L + \tau_{WG} S_G] = 0 \quad (\text{E-3})$$

Since sand particles are transported in the liquid phase, assuming the wavy interface is less chaotic and the wall shear stress contributed by gas is far less than that contributed by the liquid. $\tau_{WG} S_G = 0$ or negligible equation E-3 becomes equation E-4

$$-\frac{dp}{dx} = \frac{1}{A} \tau_{WL} S_L = 0 \quad (\text{E-4})$$

where $\frac{dp}{dx}$ is the total pressure gradient within the pipe

Make τ_{WL} subject of formula

$$\tau_{WL} = \left[-\frac{dp}{dx} \right] \cdot \frac{A}{S_L} \quad (\text{E-5})$$

where $S_L = R\beta$, liquid perimeter

$$A_L = \frac{1}{2} R^2 \beta - R^2 \sin\left(\frac{\beta}{2}\right) \cos\left(\frac{\beta}{2}\right) \quad (\text{E-6})$$

where A_L is area occupied by liquid

$$H_L = \frac{A_L}{A} \quad (\text{E-7})$$

Equating 7 and 8 and simplifying gives

$$f_L = \frac{2\tau_{WL}}{\rho_l v_L^2} \quad (\text{E-8})$$

where v_L is average velocity for liquid and f_L

$$v_L = \frac{v_{sl}}{H_L} \quad (\text{E-9})$$