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Development of Next Generation Multiphase Pipe Flow Prediction Tools

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Disclaimer

Abstract

The developments of oil and gas fields in deep waters (5000 ft and more) will become more common in the future. It is inevitable that production systems will operate under multiphase flow conditions (simultaneous flow of gas-oil-and water possibly along with sand, hydrates, and waxes). Multiphase flow prediction tools are essential for every phase of hydrocarbon recovery from design to operation. Recovery from deep-waters poses special challenges and requires accurate multiphase flow predictive tools for several applications, including the design and diagnostics of the production systems, separation of phases in horizontal wells, and multiphase separation (topside, seabed or bottom-hole). It is crucial for any multiphase separation technique, either at topside, seabed or bottom-hole, to know inlet conditions such as flow rates, flow patterns, and volume fractions of gas, oil and water coming into the separation devices. Therefore, the development of a new generation of multiphase flow predictive tools is needed.

The overall objective of the proposed study is to develop a unified model for gas-oil-water three-phase flow in wells, flow lines, and pipelines to predict flow characteristics such as flow patterns, phase distributions, and pressure gradient encountered during petroleum production at different flow conditions (pipe diameter and inclination, fluid properties and flow rates).

In the current multiphase modeling approach, flow pattern and flow behavior (pressure gradient and phase fractions) prediction modeling are separated. Thus, different models based on different physics are employed, causing inaccuracies and discontinuities. Moreover, oil and water are treated as a pseudo single phase, ignoring the distinct characteristics of both oil and water, and often resulting in inaccurate design that leads to operational problems. In this study, a new model is being developed through a theoretical and experimental study employing a revolutionary approach. The basic continuity and momentum equations is established for each phase, and used for both flow pattern and flow behavior predictions. The required closure relationships are being developed, and will be verified with experimental results. Gas-oil-water experimental studies are currently underway for the horizontal pipes.

Industry-driven consortia provide a cost-efficient vehicle for developing, transferring, and deploying new technologies into the private sector. The Tulsa University Fluid Flow Projects (TUFFP) is one of the earliest cooperative industry-university research consortia. TUFFP's mission is to conduct basic and applied multiphase flow research addressing the current and future needs of hydrocarbon production and transportation. TUFFP participants and The University of Tulsa are supporting this study through 55% cost sharing.

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Executive Summary

The developments of fields in deep waters (5000 ft and more) will become more common in the future. It is inevitable that production systems will operate under multiphase flow conditions (simultaneous flow of gas-oil-and water possibly along with sand, hydrates, and waxes). Multiphase flow prediction tools are essential for every phase of the hydrocarbon recovery from design to operation. The recovery from deep-waters poses special challenges and requires accurate multiphase flow predictive tools for several applications including the design and diagnostics of the production systems, separation of phases in horizontal wells, and multiphase separation (topside, seabed or bottom-hole). It is very crucial to any multiphase separation technique that is employed either at topside, seabed or bottom-hole to know inlet conditions such as the flow rates, flow patterns, and volume fractions of gas, oil and water coming into the separation devices.

The overall objective is to develop a unified model for gas-oil-water three-phase flow in wells, flow lines, and pipelines to predict the flow characteristics such as flow patterns, phase distributions, and pressure gradient encountered during petroleum production at different flow conditions (pipe diameter and inclination, fluid properties and flow rates).

The project is divided into two periods. In Period 1 (four years), gas-oil-water flow in pipes will be investigated to understand the fundamental physical mechanisms describing the interaction between the gas-oil-water phases under flowing conditions, and a unified model will be developed utilizing a novel modeling approach. A gas-oil-water pipe flow database including field and laboratory data will be formed in Period 2 (one year). The database and additional tests will be utilized in model performance demonstration.

Period 1 primarily consists of the development of a unified model and software to predict the gas-oil-water flow, and experimental studies of the gas-oil-water project, including flow behavior description and closure relation development for different flow conditions. The experimental results will be incorporated into the unified model as they become available, and model results will be used to better focus and tailor the experimental study.

Modeling studies are performed in two parts, Technology Assessment and Model Development and Enhancement. Technology assessment study has been completed and the results of the technology assessment study indicated that the performance of the current state of the art two-phase flow models was poor especially for three-phase pipeline flow when compared with the existing data. The basic equations for the three-phase unified model have already been derived.

As reported in the previous semi-annual technical reports, a frame work of a three-phase flow model was already developed and the model was tested against available data. The results show that the proposed model outperforms the existing two-phase flow models. The new model requires closure relationships pertaining to oil-water flow. Therefore, a new project titled "Characterization of Oil-Water Two-Phase Flow in Horizontal and Near Horizontal Pipes" was started.

During this reporting period, the testing for two-phase oil-water flow in horizontal pipes was completed. Currently, the analysis of the acquired data is underway. The preliminary results of the data analysis show the distinct characteristics of oil-water flows with respect to distribution and mixing of phases, pressure drop and holdup behavior. In particular, droplet size analyses are performed indicating log-normal distribution. In parallel, a detailed literature search is conducted for oil-water flow in inclined pipes. The experimental work will start during Spring 2007.

A detail progress report is provided in the following sections of this report.

Experimental Studies

Gas-Oil-Water Flow in Horizontal Pipes

The experimental work was conducted using the TUFFP facility for gas-oil-water flow. The details of the experimental facility and the tests conducted provided in the previous Technical Report, (Sarica & Zhang (2006)). Currently, experimental efforts are focused on oil-water studies.

Oil-Water Flow in Horizontal Pipes and Slightly Inclined Pipes

Objectives

The main objective of this study is to acquire detailed experimental data on oil-water flow including droplet sizes and phase distributions in horizontal pipes for different operating conditions to better understand the physics of oil-water flow. This will help develop better closure relationships that can be utilized in the three-phase gas-oil-water flow model developed.

Introduction

Two-phase liquid pipe flow is defined as the simultaneous flow of two immiscible liquids. It can be encountered in a wide range of industries and processes such as oil production and transportation.

Despite the importance of accurate prediction of oil-water characteristics, liquid-liquid flows have not been explored as much as gas-liquid flows. Oil-water tests have been conducted for horizontal pipe at various flow rates and water cuts. Information related to droplet size and phase distribution was collected using pertinent instrumentation and the results are discussed.

Experimental Study

The experimental part of this study was conducted using TUFFP gas-oil-water flow facility. Although this facility can be used to simulate oil-water-gas flows, in this work only oil-water flows will be investigated. For oil water flows, this facility has been used by Alkaya (2000), Flores (1997) and Trallero (1995) for horizontal and slightly inclined pipes and for vertical and deviated wells.

Experimental Facility and Flow Loop

The facility shown in Fig. 1 consists of a closed flow loop. There are 2 storage tanks equipped with valves at the outlet of each tank to control the flow rates. These tanks are followed by two progressive cavity pumps to maintain the liquid flow rates. After the pumps, there are manual bypass valves to obtain low flow rates, and pressure relief valves for excessive pressure control. Following the valves two copper-tube type heat exchangers control the temperature of the fluid during the tests. After the heat exchangers, manual bypass valves allow the fluids to be pumped back to the respective tanks.

Two separate metering sections are equipped with Micro Motion Corriolis flow meters to measure mass flow rates and densities of the fluids and with temperature transducers for monitoring the temperatures of the fluids. Oil and water flow through filters after the metering section.

Oil and water is mixed at the inlet of the test section. The current test section (See Fig. 2) consists of two 69.33-ft long straight transparent pipes, connected by a 4.0-ft diameter PVC bend. The upward branch of the test section consist of a 45.30-ft long flow developing section (L/D=272). This is followed by two short pressure drop measurement sections of 17.0-ft and 11.0-ft in length. These sections can be combined to obtain a long pressure drop section. The test section was designed to provide a 18.0-ft long trapping section (L/D=108) and a 6.0-ft long measurement section. The downward branch of the test section was constructed similar to the upward branch. Finally, the fluids are directed to a separator where a pressure is set at 20 psig.

Instrumentation and Data Acquisition

The test section is instrumented for continuous monitoring of temperature, pressure, differential pressure, holdup and spatial distribution of the phases.

Quick closing valves were used to measure the average holdup in Oil-Water flows for each flowing condition.

A new conductivity probe was developed; it consists of 10 probes across the pipe from top to bottom for determining the oil and water phases at 10 different points. The probe is located in a section that was modified in order to rotate the pipe. This rotating section consists of two swivel joints that allow the rotation of the pipe at different angles so the position of the probes inside the pipe will be changing as the pipe rotates. The objective of this configuration is to obtain different data points in the cross sectional area of the pipe and to determine the phase distribution for each flowing condition. Once the data is obtained, it is plotted in a model using DIAdem INSIGHT software from National Instruments; this software allows representing the data for the phase distribution in colors, depending on the voltage value of each probe at different times.

Flow pattern identification and droplet size measurements were performed by using a high speed video system. The videos were taken near the pipe wall. The images were logged into a computer and its analysis was performed by using Image-Pro Plus 5.1, an image processing software that allows image enhancement and droplet size measurements.

Lab View ™ 7.1 was used for the data acquisition. The program has been modified and adapted for oil-water studies.

Test Fluids

The fluids that are used in the experiments consist of a refined mineral oil and tap water. The characterization of the oil has been performed by ChevronTexaco laboratories. The physical properties of the oil are given below:

- 32.2 °API gravity.
- Density: 858.75 kg/m^3 @ 15.6 ºC.
- Viscosity: 13.5 cp @ 40ºC.
- Surface tension: 29.14 dynes/cm @ 25.1ºC.
- Interfacial tension with water: 16.38 dynes/cm @ 25.1ºC.
- Pour Point Temperature: -12.2 ºC.
- Flash Point Temperature: 185 ºC.

Testing Range

A large number of data points were acquired at various conditions. Superficial oil and water velocities ranged from 0.025 – 1.75 m/sec. The oil and water flow rates were chosen such that the flow pattern transition boundaries could be identified clearly. Moreover, large amount of data was taken for the dispersed flow patterns to characterize the droplet size.

Dispersion Droplet Size Data

The size distribution of droplets is one of the most important parameters in characterizing any dispersion. Two dispersions may have the same average droplet diameter and yet exhibit quite different behavior because of differences in distributions of diameters. The statistical description of droplet size data is the representation of the properties of raw data by a probabilistic model and to reproduce it with statistical parameters for further treatment. Distributional models used for the description of continuous data in oil-water flows include the Normal, Log-Normal and Rossim-Rammler distributions.

Before carrying out statistical parameterization, the following criteria must be fulfilled:

1. The determination of unimodality. The distribution must be unimodal.
2. The level of information content and reduction of the noise-to-information ratio during particle size analysis should be optimized.
3. Optimization of the raw data by the PDF should use the best mathematical procedures available.

A rigorous goodness-of-fit examination must be performed before deciding which PDF would best represent the raw data.

Mean Diameters

The widely used mean diameter for characterizing droplet size is the Sauter Mean Diameter (SMD or D_{32}). The D_{32} is the diameter of a drop having the same volume to surface area ratio as the total distribution. SMD can be considered as the ratio of the particle volume to surface area in a distribution, and given with the following expression:

$$D_{32} = \sum_{i=1}^{N} f_n(D) D^3 \Big/ \sum_{i=1}^{N} f_n(D) D^2 \ . \qquad (1)$$

Where $f_n(D)$ is defined as the probability distribution function, and D is the centroid of the bin size corresponding to that particular range of diameters.

The particle size distribution is either mono-disperse or poly-disperse. A mono-disperse distribution is one in which the particles are close to a single size whereas poly-dispersed suggests a wide range of particles sizes.

In general, it has been shown that the drop size distribution in a liquid-liquid stirred vessel can be characterized by a normal distribution function or a log-normal distribution function.

Normal Distribution

The Normal (Gaussian) distribution is a continuous, symmetric distribution with various uses in all aspects of statistics.

The Normal distribution is completely specified by two parameters: the mean (μ) and the variance σ^2. The mean of a Normal distribution locates at the center of the density, and can be any real number. The variance of a Normal distribution measures the variability of the density distribution and can be any positive real number. The standard deviation σ is the square root of the variance, and is used more often for its interpretability.

For a Normal random variable, PDF is

$$f(X) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2} * \left(\frac{X-\mu}{\sigma} \right)^2 \right] . \qquad (2)$$

The cumulative distribution function, CDF, is obtained by integrating (2):

$$F(D) = \frac{1}{\sqrt{2\pi}\sigma} \int_0^D \exp\left[-\frac{1}{2} * \left(\frac{x-\mu}{\sigma} \right)^2 \right] \frac{dD}{D} . \qquad (3)$$

In general, the normal distribution provides a good model for a random variable, when:

1. There is a strong tendency for the variable to take a central value;
2. Positive and negative deviations from this central value are equally likely;
3. The frequency of deviations falls off rapidly as the deviations become larger.

In practice the normal distribution relationship is unlikely to be applicable to dispersion size data for the simple reason that actual distributions are rarely symmetric; they tend to be skewed.

Log-Normal Distribution

The Log-Normal Distribution is frequently used to represent the size of solid particles. The Log-Normal Distribution derives from the Normal by replacing the independent variable with the logarithm of the particle diameter.

For a Log-Normal random variable;

$$f(X) = \frac{1}{\sqrt{2\pi}\sigma_O} \exp\left[-\frac{1}{2} * \left(\frac{\ln X-\mu_O}{\sigma_O} \right)^2 \right] . \qquad (4)$$

CDF of a Log-Normal random variable is obtained by integrating (4):

$$F(D) = \frac{1}{\sqrt{2\pi}\sigma_O} \int_0^D \exp\left[-\frac{1}{2} * \left(\frac{\ln X-\mu_O}{\sigma_O} \right)^2 \right] \frac{dD}{D} . \qquad (5)$$

Where, σ_O and μ_O are the standard deviation and the mean of the Log-Normal distribution.

Uncertainty Analysis

In general, errors can be divided into two parts, systematic and random errors. Systematic error is an error that shifts the measurements in a systematic way, so that their mean value is displaced. Systematic error includes incorrect calibration and improper use of equipment or failure to account for certain effects present in the device. It is important to try to eliminate as much as possible the effect of the systematic error. The random error is directly related to the scatter of the data around its average value, which can be defined as a displaced measurement in any direction, as opposed to the systematic error that displaces the measurement in one direction.

Random Uncertainty

A sample of the data is used to determine the random uncertainty, as opposed to the whole population. Using the whole population is almost always impossible due to the nature of the data. For the case of the droplet size, a sample of glass beads with known sizes (0.6-1 mm) was measured and the random uncertainty from its measurement was taken for the uncertainty analysis of the droplet size measurement.

A number of points in the population are obtained when a parameter is measured N times. The sample standard deviation of this population is calculated as follows:

$$S_X = \sqrt{\sum_{i=1}^{N} \left(X_i - \bar{X} \right)^2 \Big/ (N-1)} . \qquad (6)$$

The standard deviation S_X is known as the scatter in the N data points. It is more desirable to find the scatter of the mean values. Therefore, the standard deviation of population average is calculated with the following equation,

$$S_{\overline{X}} = S_X / \sqrt{N} \ . \quad (7)$$

Systematic Uncertainty

Systematic error uncertainty can come from various sources such as imperfections in the equipment, improper or biased observation, or by the presence of additional physical effects. For this study, the instrument calibration is considered as the only source of the systematic error. Each source of the elemental systematic uncertainty, b_i, needs to be combined by using the following equation,

$$B_R = \left[\sum_{i=1}^{N} (b_i)^2 \right]^{1/2} \ . \quad (8)$$

Where, B_R is the combined systematic uncertainty.

Because of their nature, systematic errors tend to remain consistent from measurement to measurement. Experimental data can not be used for systematic uncertainty.

Combination of Random and Systematic Uncertainties

Random and systematic uncertainties are combined in experimental studies to describe the quality of data. The combined uncertainty can be calculated by:

$$U_{95} = \pm t_{95} \left[(B/2)^2 + \left(S_{\overline{X}}\right)^2 \right]^{1/2} . \quad (9)$$

Combined uncertainty is stated at a 95% confidence level as a reasonable value for the desired accuracy being sought. Random uncertainty ($S_{\overline{X}}$) has a confidence level of 68%. First, the systematic uncertainty is divided by 2, which is the Student's *t* value with infinite degree of freedom. Then, the t_{95} is used to bring the combined uncertainty equation to the 95% confidence level.

Uncertainty Propagation

When a parameter is not directly measured, but calculated from two or more directly measured parameters, the uncertainty in the derived parameter must be determined from the uncertainties in the measured parameters from which it is calculated. If *y* is a function of independent variables *a*, *b*, *c*…., the uncertainty of *y* will be described as a function of independent uncertainties of *a, b, c*…., as follows:

$$U_y = \sqrt{\left[\left(\frac{\partial y}{\partial a}\right)^2 (U_a)^2 + \left(\frac{\partial y}{\partial b}\right)^2 (U_b)^2 + \left(\frac{\partial y}{\partial c}\right)^2 (U_c)^2 + ... \right]} \ . \quad (10)$$

The results of the uncertainty analysis are given in Table 1.

Table 1 - Uncertainty Analysis

Instrument	Random Uncertainty	Systematic Uncertainty	Degrees of Freedom	Students't	Overall Uncertainty
DP1 (In H2O)	0.0001	0.0100	∞	2	0.010
DP4 (In H2O)	0.0001	0.0111	∞	2	0.011
WFM (gpm)	0.0000	0.0000	∞	2	0.000
OFM (gpm)	0.0000	0.0000	∞	2	0.000
Tape (mm)	0.5000	2	∞	2	2.236
Droplet Size (mm)	0.0123	0.01	∞	2	0.027
Total DP Propagation (In H20)	0.0291	0.1163	∞	2	0.130
U_{ws} Propagation (m/s)	0.00091	0.0036	∞	2	0.0040
U_{os} Propagation (m/s)	2.81748E-05	0.000112667	∞	2	0.0001
Holdup Propagation (-)	0.0025	0.0101	∞	2	0.0113

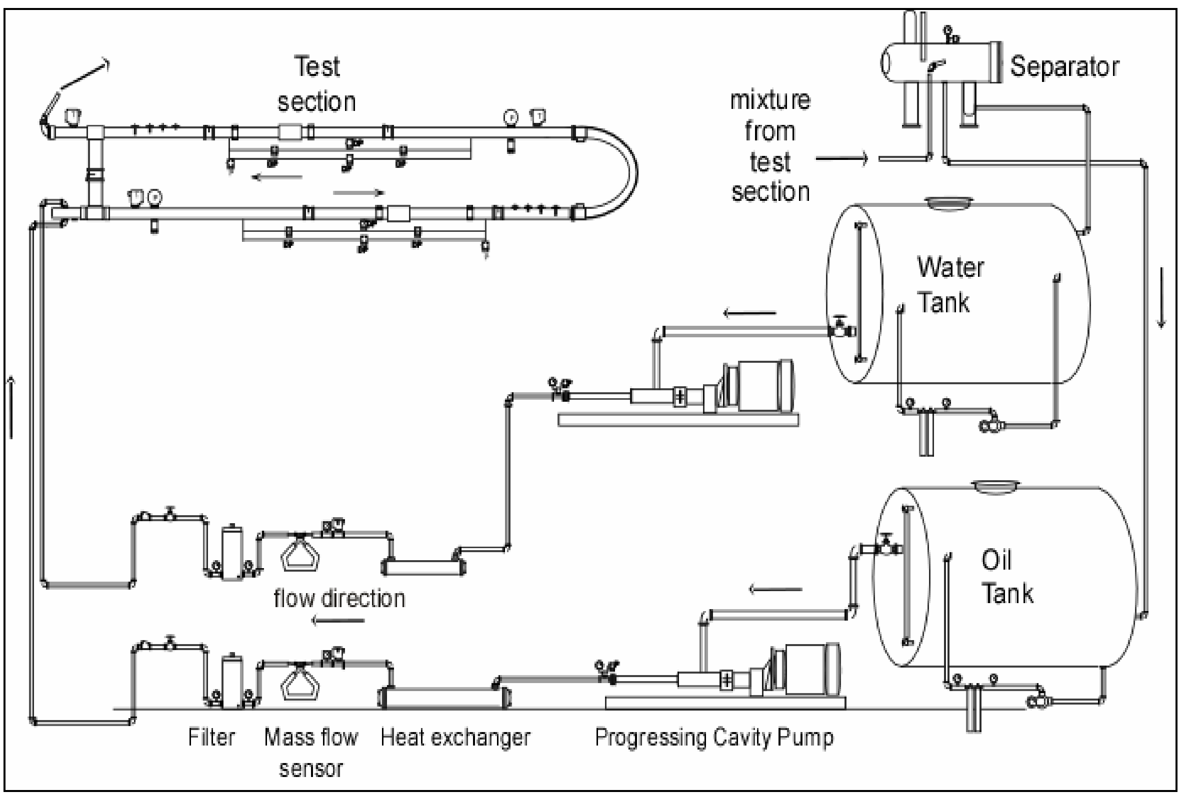

Figure 1 - Facility Schematic

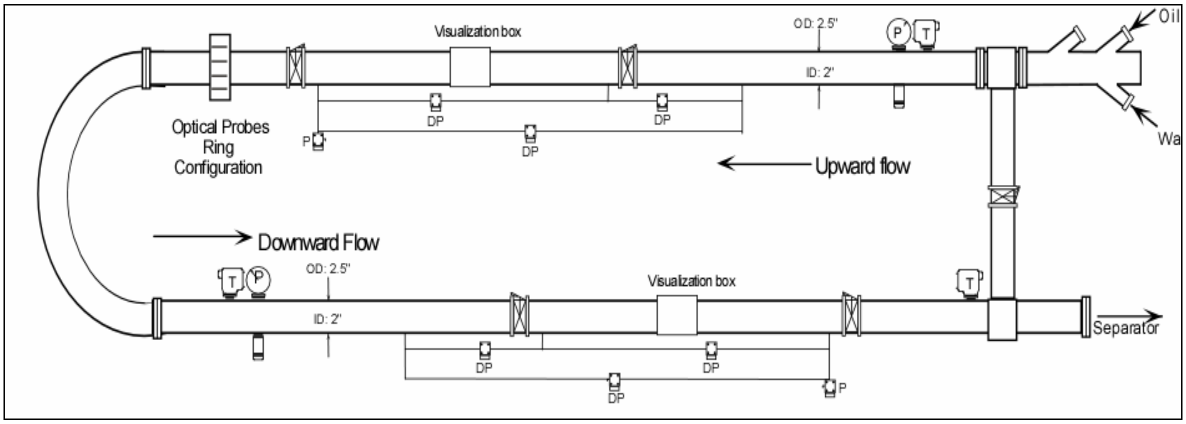

Figure 2 - Test Section Schematic

Oil-Water Flow in Horizontal Pipes and Slightly Inclined Pipes

Objectives

The main objective of this study is to investigate the oil-water flow behavior in inclined pipes and collect experimental data on oil-water flow including droplet sizes and velocity fields to understand the physics and phenomena of oil-water flow. The existing models will be tested against the data, and attempts will be made to improve the existing models or develop new ones if necessary.

Introduction

Two-phase liquid pipe flow is defined as the simultaneous flow of two immiscible liquids in pipes. One of the common occurrences in the petroleum industry during transportation and production is oil-water flow in pipes. Moreover, two-phase liquid-liquid flow is common in process and petrochemical industry. Perhaps the most relevant and important application is transportation of oil-water through pipelines. Although the accurate prediction of oil-water flow is essential, oil-water flow in pipes have not been explored as much as gas-liquid flow.

Trallero (1995) studied oil-water flow pattern transitions in horizontal pipes at the TUFFP Oil-Water Flow Facility. In his study, a new classification for oil-water flow patterns based on published and acquired data was made. Six flow patterns were identified. These six flow patterns were subdivided into two categories; segregated and dispersed flows. A new mechanistic model was developed based on a rigorous two-fluid model for stratified flows, and a force balance between gravity and turbulent fluctuations normal to the axial flow directions for dispersed flows. Comparisons of the model with data from his research and from several other studies showed that the Trallero flow pattern model performed well for oil-water flow in horizontal pipelines.

Alkaya (2000) experimentally studied the inclined oil-water flow using the same TUFFP facility used in Trallero (1995) to obtain experimental data at various flow conditions and inclination angles using mineral oil and water. In her study, flow patterns, holdup, pressure gradients were measured for horizontal, ±0.5º, ±1º, ±2º, ±5º inclinations. The pressure gradient data were compared against existing pressure gradient prediction correlations, two-fluid model and homogenous model. Among these, two-fluid model performed well for almost all data sets. The droplet size, droplet size distributions, velocity distributions and phase distributions were not studied by Alkaya (2000).

Flores (1997) investigated oil-water flows theoretically and experimentally in vertical and deviated pipes to identify and characterize the flow patterns, and to model the flow pattern transitions, holdup and pressure drop occurring for conditions pertinent to oil-water producing wells. 90º, 75º, 60º, 45º inclination angles were covered.

Brauner (2002) identified the flow patterns based on the visual observations which were taken by photographic and video techniques.

Soleimani et al. (1999) used high frequency impedance probes (HFP) and gamma densitometer systems (GDS) to determine phase distributions.

They analyzed and compared HFP and GDS results for different cases. At a lower mixture velocity (1.25 m/s), HFP and GDS measurements were adequately similar, within the bounds of experimental error. The agreement between GDS and HFP was fairly satisfactory and sufficient at an intermediate mixture velocity (2.12 m/s) within the bounds of experimental error. At a high mixture velocity (3 m/s), the agreement between HFP and GDS was not so good. That was believed to be associated with the existence of small droplets in these flows, which were not detected by HFP.

Malinowsky (1975) conducted an experimental study of oil and water mixtures. The oil-water data were compared against the predictions from several oil-water flow models. A stratified oil-water model was presented which gave good accuracy in the prediction of pressure gradients observed by this study and others for segregated oil-water flows.

Arirachakaran et al. (1989) collected extensive experimental data for oil-water flows in horizontal pipes for a wide range of oil viscosity. Six different flow patterns were used in their study. A new correlation is proposed for the prediction of the inversion point of oil-water dispersion. It was claimed that the input water fraction required for inverting the dispersion decreases with increasing oil viscosity. Moreover, two pressure gradient prediction method were presented; one for stratified and the other for homogeneously dispersed oil-water flows. Experimental oil-water flow pattern maps were developed.

Lovick et al. (2000, 2004) claimed that stratified flow in particular has received most attention among the other flow patterns, since the low flow velocities and well defined interface from both experimental and theoretical investigations. For fully dispersed systems information is available mainly from the studies in stirred vessels. Due to the different system configurations this studies can not be directly applied to the pipe flow. The available information is even more limited for the intermediate flow patterns between the stratified and the fully dispersed flow patterns. Their study was aimed at the investigation of the flow behavior, particularly, pressure drop, phase distribution and holdup of liquid-liquid flows with an emphasis on medium and high flow velocities. Moreover, in their study, it was claimed that average drop size data mostly exist for the low dispersed phase concentration of oil-water flow in pipes. Actually, only in some studies, mostly related to surfactant-stabilized emulsions, high concentration was examined. The reason of having limited data on average drop size and distribution in unstable dispersion at high dispersed phase volume fractions is mainly due to difficulty in performing such measurements. Photography/video recording enables to get the information on the actual shape of the droplets. If used outside the pipe, these methods are non-intrusive but allow measurements away from the wall only in dilute dispersions. The recent use of endoscopes has allowed recording at different locations within the flow overcoming the problem of dense dispersions but in an intrusive way. Moreover, Lovick et al. postulated that the knowledge of drop size and distribution would improve understanding of dispersed systems and contribute to better design and modeling. However, there is only limited amount of data for drop size distributions for oil-water pipe flow.

Nädler et al. (1997) claimed that flow pattern and consequently the distribution of oil-water in the pipe are the main factors that affecting pressure drop in the pipes. The pressure gradient increases as the turbulent forces create emulsions and dispersions. Volume fraction and the droplet distribution of the dispersed phase are the main factors that determine the flow behavior of emulsions of oil and water.

In the Lum et al. (2006) study, the effect of upward (5° and 10°) and downward (-5°) pipe inclinations on the flow patterns, holdup and pressure gradient during oil-water phase flows was investigated experimentally for varying mixture velocities and phase fractions. High-speed video recording and local impedance and conductivity probes were used to precisely identify the different flow patterns. The dispersed oil-in-water flow pattern extended to lower mixture velocities and higher oil fractions when compared to horizontal flow.

Rodriguez et al. (2005) conducted oil–water two-phase flow experiments by using mineral oil and brine. Steady-state data of flow patterns, two-phase pressure gradient and holdup were obtained over the entire range of flow rates at inclinations of -5°, -2°, -1.5°, 0°, 1°, 2° and 5°. The characterization of flow patterns and identification of their boundaries were achieved via observation of recorded movies and by analysis of the relative deviation from the homogeneous behavior. A stratified wavy flow pattern with no mixing at the interface was identified in downward and upward flow. Extensive results of holdup and two-phase pressure gradient as a function of the superficial velocities, flow pattern and inclinations are reported.

Angeli et al. (2000) studied the drop size distributions using a video recording technique which employed an endoscope. The experiments were performed with either water or oil as the continuous phases. The experimental drop size distributions were satisfactorily represented by the Rosin-Rammler distribution. The results showed that the drop size distributions were strongly influenced by the pipe material, with the drops being smaller in the steel pipe than in the acrylic pipe for the same flow conditions. They were also influenced by the nature and the velocity of the continuous phase. None of the theoretical correlations for the maximum drop size could represent accurately the experimental data, while the often used Hinze (1955) equation under-predicted the experimental results in all cases.

Vielma (2006) is currently conducting horizontal oil-water flow experiments to get the droplet size, droplet size distributions and phase distributions during flow. TUFFP high speed video camera is being used to capture the images during different flow patterns and different oil-water ratios through visualization box. Conductance probes are being used to determine the phase distributions.

Future Research Directions

There is limited work done by the researchers on two-phase oil-water flow drop size and distribution especially for unstable dispersions at high dispersed phase volume fractions in inclined pipes. This is mostly because of the difficulty in performing such measurements.

In this study the following areas will be investigated:

- Explore better methods and ways to describe droplet size distributions and phase distributions of oil-water flow in pipes
- Assess performance of current models by checking against experimental data
- Improve current models through development of better closure relationships

The experimental part of this study will be conducted using TUFFP's gas-oil-water flow facility currently being used by Vielma (2006). For this study, the facility will be used for the inclined oil-water pipe flow.

Modeling Studies

Gas-Oil-Water Flow in Horizontal and Inclined Pipes

Introduction

In general, three-phase flows can be examined between two extremes. One of the extremes is to treat the three-phase flow as a three-layer stratified flow with gas on the top, oil in the middle and water at the bottom. This is possible for immiscible liquids flowing in horizontal or slightly inclined pipe with low flow rates. Hall (1992), Taitel *et al.* (1995) and Khor (1998) modeled stratified three-phase flow in pipes using momentum equations for the three layers.

The other extreme is to treat the three-phase flow as gas-liquid two-phase flow with the two liquids assumed to be fully mixed. This may occur during vertical and steeply inclined flows, and high rate slug and annular flows. Then, the physical properties of the liquid mixture can be calculated based on the fractions and the individual physical properties of the two liquids.

However, the majority of three-phase flows occur between the above two extremes: partially mixed with slippage between the two liquid phases. Slug flow, for instance, may have different states in different regions, such as stratified in the film region and mixed in the slug body.

Modeling Approaches

A modeling approach similar to TUFFP's unified hydrodynamic model (Zhang *et al.*, 2003) for gas-liquid pipe flow can be used for the gas-liquid-liquid three-phase modeling. The TUFFP unified model is based on the dynamics of slug flow. Because slug flow has transition boundaries with all other flow patterns, the equations of slug flow can be used not only to calculate the slug characteristics, but also to predict transitions from slug flow to other flow patterns. Therefore, flow pattern transitions and other hydrodynamic behaviors are all calculated within a single model.

Oil and water can be found as a fully mixed pseudo-single-phase in a slug body and in bubbly, dispersed-bubble and annular flow. On the other hand, they may not be fully mixed, and the local holdups may not be the same as the input fractions. Presumably, the continuous phase is slower than the dispersed phase due to its contact with the pipe wall. The relative velocity between the continuous phase and the dispersed phase needs to be modeled under different flow conditions.

As mentioned above, if the oil and water are fully separated, like in stratified flow or in the film region of slug flow, then the flow can be modeled with the three-layer approach. The model for predicting the transition from stratified to dispersed liquid-liquid flow can be developed based on the local turbulent intensity and the physical properties of the liquid phases.

Basic equations and approaches of a unified modeling of gas-oil-water pipe flow were proposed and presented by Dr. Hong-Quan (Holden) Zhang at the TUFFP ABM in March 2004. The proposed model is applicable for horizontal and inclined pipes.

Results and Discussions

Oil-Water Flow in Horizontal Pipes and Slightly Inclined Pipes

Two-phase oil-water experiments were performed for horizontal pipe. Results for oil superficial velocities of 0.025m/s, 0.035 m/s, 0.05 m/s and 0.075 m/s are presented in this report.

Flow Pattern

The flow patterns that were observed for oil-water flows in horizontal pipes at oil superficial velocities between 0.025-0.075 m/s are shown in Fig. 3. Stratified flow, stratified with some mixing at the interface, dispersion of oil in water over a water layer and dispersion of oil in water were observed.

Three data points could not be defined according to Trallero's flow pattern classification; they were called Transition between stratified with some mixing at the interface and dispersion of oil in water over a water layer. The reason for that is that there was no continuity of either of the two flow patterns along the pipe.

Pressure Gradient

Figure 4 shows the measured pressure gradient for Uos=0.025 m/s and its comparison with Trallero and Alkaya experimental data for the same condition. It can be seen that, as expected, the pressure gradients increase with increasing water superficial velocity and that its value also depends on the viscosity of the oil phase.

Figure 5 shows the repeatability of the data for Uos=0.025 m/s. The agreement between the two curves is good. The differences are mainly due to not being able to have exact same flow conditions; the uncertainties for pressure drop measurements are small.

Figure 6 shows the result for oil superficial velocities between 0.025 m/s and 0.075 m/s. The behavior of the curves is similar: the pressure drop increases with increasing the water and oil superficial velocities. At low water superficial velocities the pressure drop is similar, however, it increases rapidly as the water superficial velocity increases after 0.1 m/s. This phenomenon can be related to flow pattern effect.

For low water superficial velocities the predominant flow patterns are stratified flow and stratified with some mixing at the interface; in those types of flow, the amount of droplets is non existent or almost null having negligible effect on the frictional pressure gradient which is the most important component of the total pressure gradient for horizontal flows. By increasing the water superficial velocity, droplet entrainment phenomenon starts to occur affecting directly and in great proportion the mixture viscosity and moreover the frictional pressure gradient.

Water Holdup

Quick closing valves were used to measure the water holdup. The measurements were performed twice for each test in order to increase the accuracy of the result. The results for the water holdup ratio for oil superficial velocities between 0.025 m/s and 0.075 m/s are shown in Fig. 7. The slippage between the phases tends to decrease with increasing oil superficial velocities and it approaches to 1 at high water superficial velocities meaning negligible slippage between the phases. The shape of the curves varies mainly due to uncertainty of the measurement technique.

For Uos=0.025 m/s there is a gap between two points because the average holdup could not be measured; this was due to the transitional flow pattern observed. Without any continuity, it was very difficult to catch with the quick closing valves, a representative section for water holdup measurement

Droplet Size

The determination of droplet sizes by using image analysis is a time consuming process, due to that only the results for oil superficial velocities of 0.025 and 0.035 m/s are presented in this report. The procedure for taking the images is as follows:

1. For dispersed flow patterns (namely all the flow patterns with droplet entrainment), different pictures were taken only at the pipe wall.
2. For fully dispersed flow patterns, the pictures where taken at the center of the pipe.
3. For dispersions of oil in water over a water layer, pictures where taken at the bottom, center and top of the pipe.

The procedure for analyzing the images is as follows:

1. Once the images were obtained (25-100 frames for each condition), a sample of 3 pictures was chosen.

2. Each picture was then calibrated and the droplets were counted by hand using Image Pro-Plus.
3. Once the results where obtained, the three results where combined to obtain the droplet size distribution and SMD.

Figures 8, 10, 12 and 14 show the droplet size distributions (Normal and Log-Normal) for the fully dispersed flow patterns. In this type of flow pattern, the dispersion reaches to the entire pipe diameter so the measurement was done in the whole pipe area.

After the statistical representation of the droplet sizes, a test of goodness of fit (GOF) was performed in order to determine which distribution fitted better the results (See Figs. 9, 11, 13 and 15). The results for the GOF are shown in Table 2 where it can be seen that for all the sets the distribution that fits the better is Log-Normal Distribution.

When the water flow rate is decreased, the size of oil droplets increases due to the decrease of the turbulent forces that creates the droplets. When the oil droplet size increases, the mean of the distribution is moved to the right, and its tendency is to take a central value.

For Uws=1 m/s and 0.75 m/s the flow pattern changed from o/w to Do/w&w where the determination of the droplet size distribution was no longer performed. Instead of calculating the distribution that best fitted the data, the variation of SMD with the pipe diameter was calculated; the droplets are no longer covering the entire pipe diameter, and coalescence of oil droplets has started to take place reducing the area of droplet existence. Figures 16 - 19 show the variation of the SMD with the pipe section. As expected, SMD increases from bottom to top. With further reduction of water flow rate, the coalescence does not allow to count the droplets at the top.

An average SMD was calculated from all the sections analyzed. The variation of SMD with Uws was then plotted for Uos=0.025 m/s and Uos=0.035 m/s (See Fig. 20). The curves shift for this case at Usw=1m/s when it seems that coalescence starts to take place. It does not seem reasonable to compare SMD between different flow patterns because the droplet sizes are generated from different mechanisms namely coalescence and breakup. The existence of only one of them or a combination of both will affect the final value randomly.

The repeatability of the droplet size measurement is acceptable; measuring droplets sizes by hand introduce certain error (See Fig. 21).

Phase Distribution

The conductivity probes can determine which phase is the continuous phase. The feasibility of using conductivity probes for analyzing the phase distribution in oil-water flows was tested. The probe worked fine for stratified flow patterns but sometimes it became dirty and gave wrong values. The data is taken by rotating the pipe for 4 different angles yielding 40 data points. These data points are plotted using DIAdem Insight to get the phase distribution as color difference between 0 volts for oil (blue) and 10.4 volts for water (red). Some of the results for Uos=0.025 m/s are shown in Figs. 22-25. It can be seen that with increasing the water flow rate, the area that represents the water holdup increases. In some cases this difference can not be seen mainly due to the need of more data around those points. More data points were taken for Uos=0.075 m/s and Uws=0.075 m/s and its results can be seen in Fig. 23 where the phase distribution map was improved significantly. There is also a problem with the dirt on the probe that can give wrong signals as shown in Fig. 24.

Table 2 - Goodness of Fit Test for Fully Dispersed Flow Patterns

Test of Goodness of Fit			
Uos (m/s)	Uws (m/s)	Normal	Log-Normal
0.025	1.75		X
0.025	1.5		X
0.035	1.75		X
0.035	1.5		X

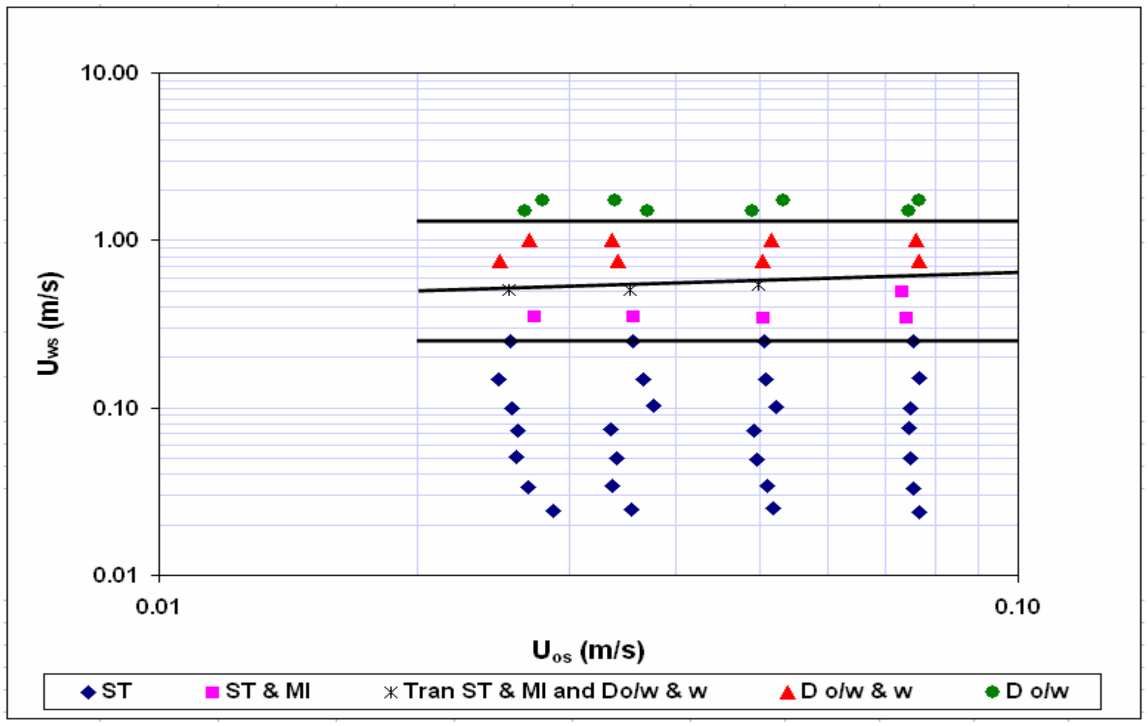

Figure 3 - Experimental Flow Pattern Map

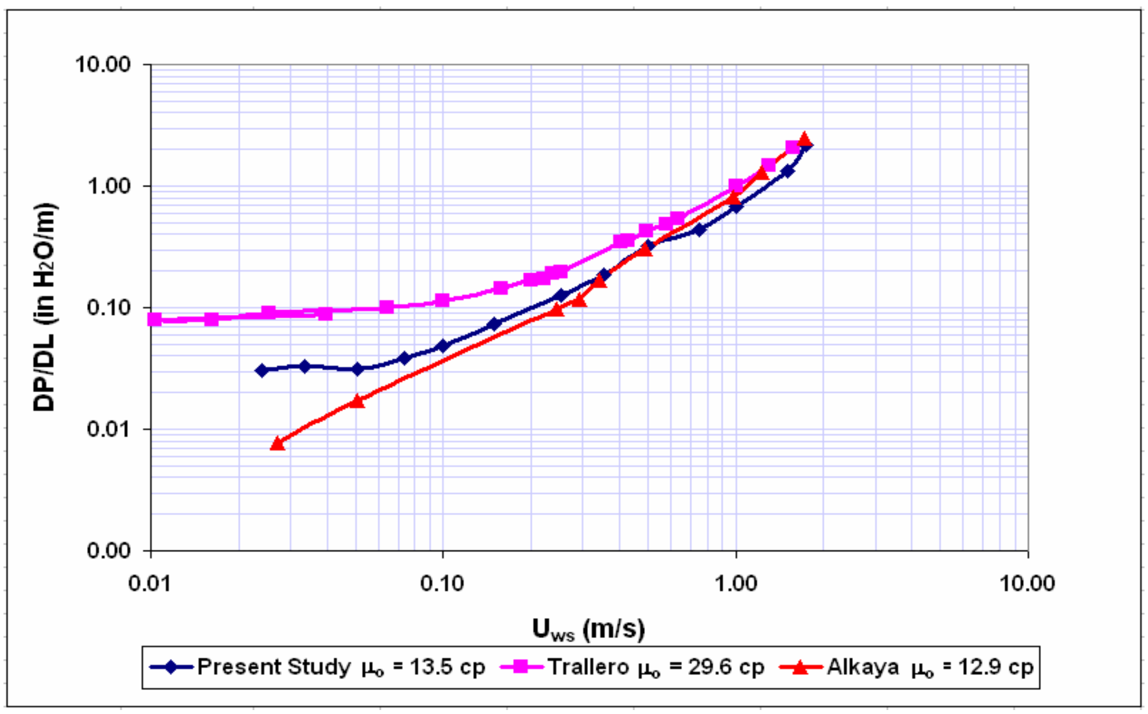

Figure 4 - Pressure Drop Comparisons for Uos = 0.025 m/s

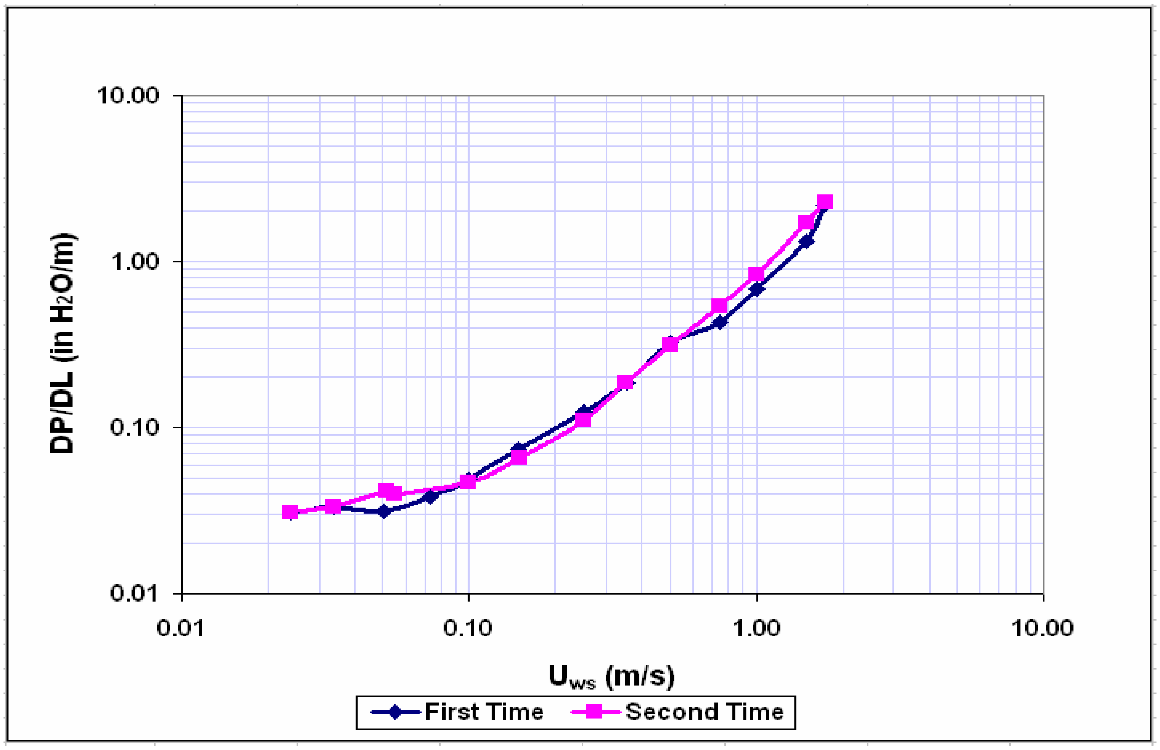

Figure 5 - Repeatability of the data for Uos = 0.025 m/s

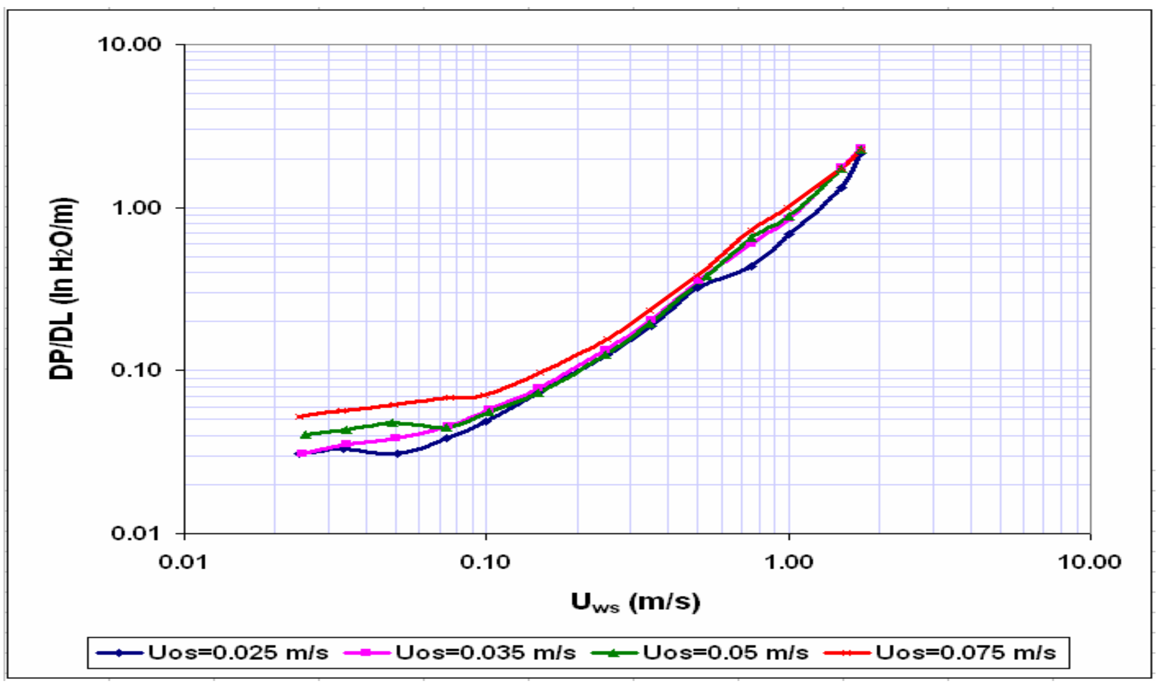

Figure 6 - Experimental Pressure Drop

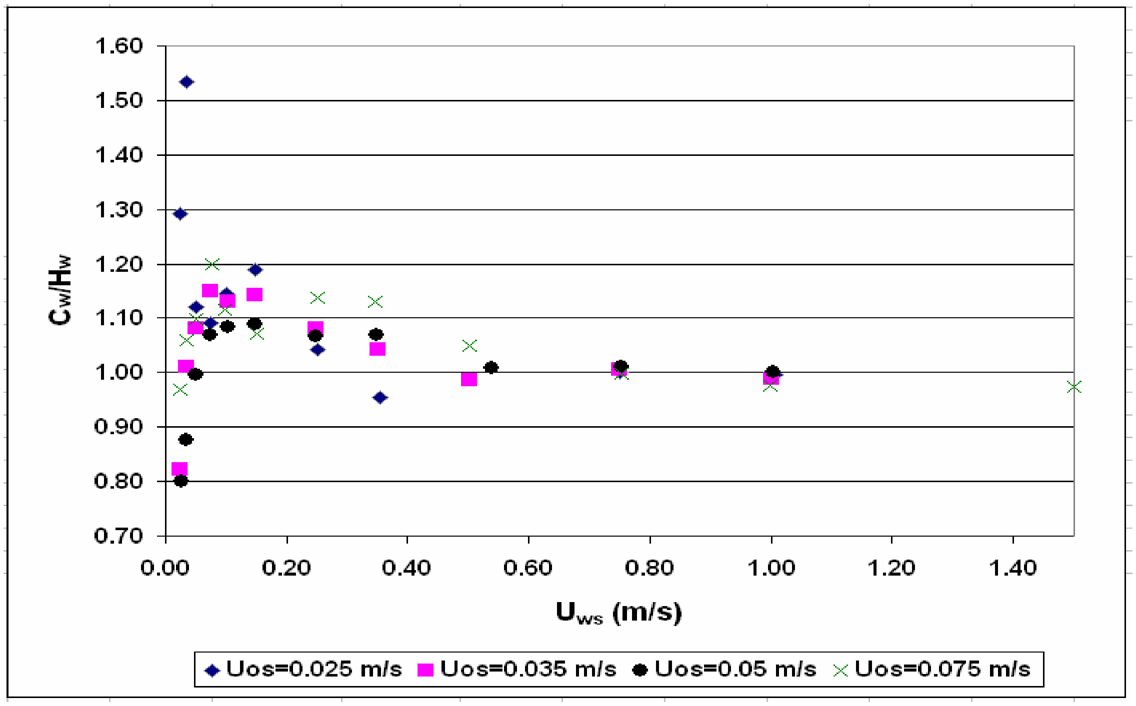

Figure 7 - Experimental Water Holdup Ratio

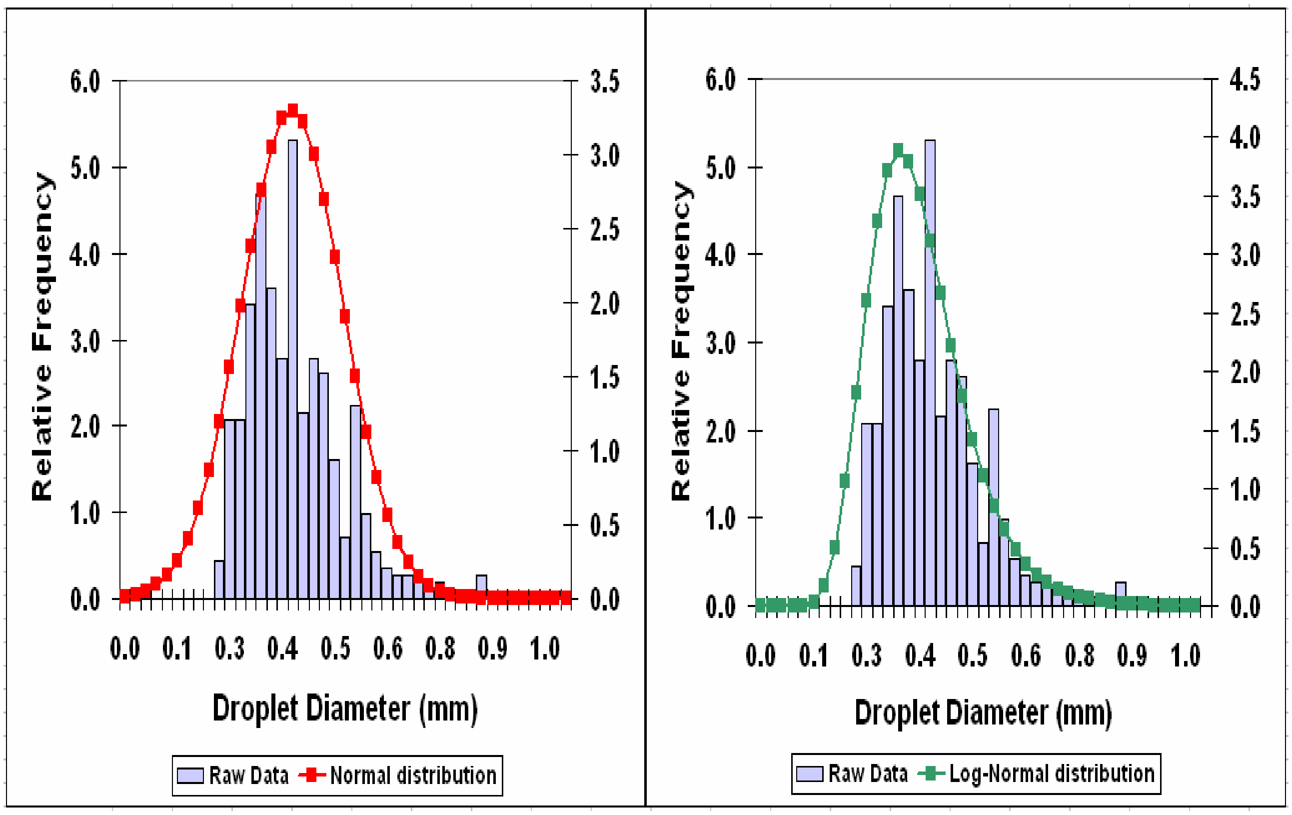

Figure 8 - Droplet Size Distributions for Uos = 0.025 m/s and Uws = 1.75 m/s

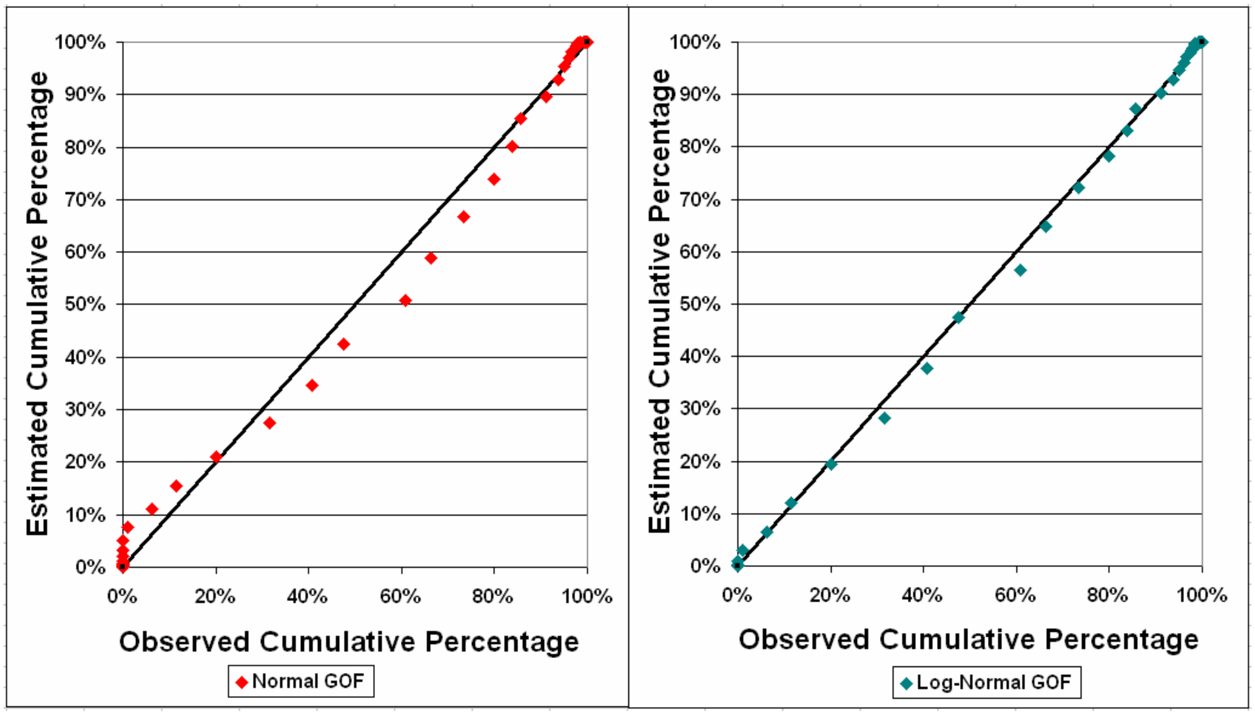

Figure 9 - GOF for Uos = 0.025 m/s and Uws = 1.75 m/s

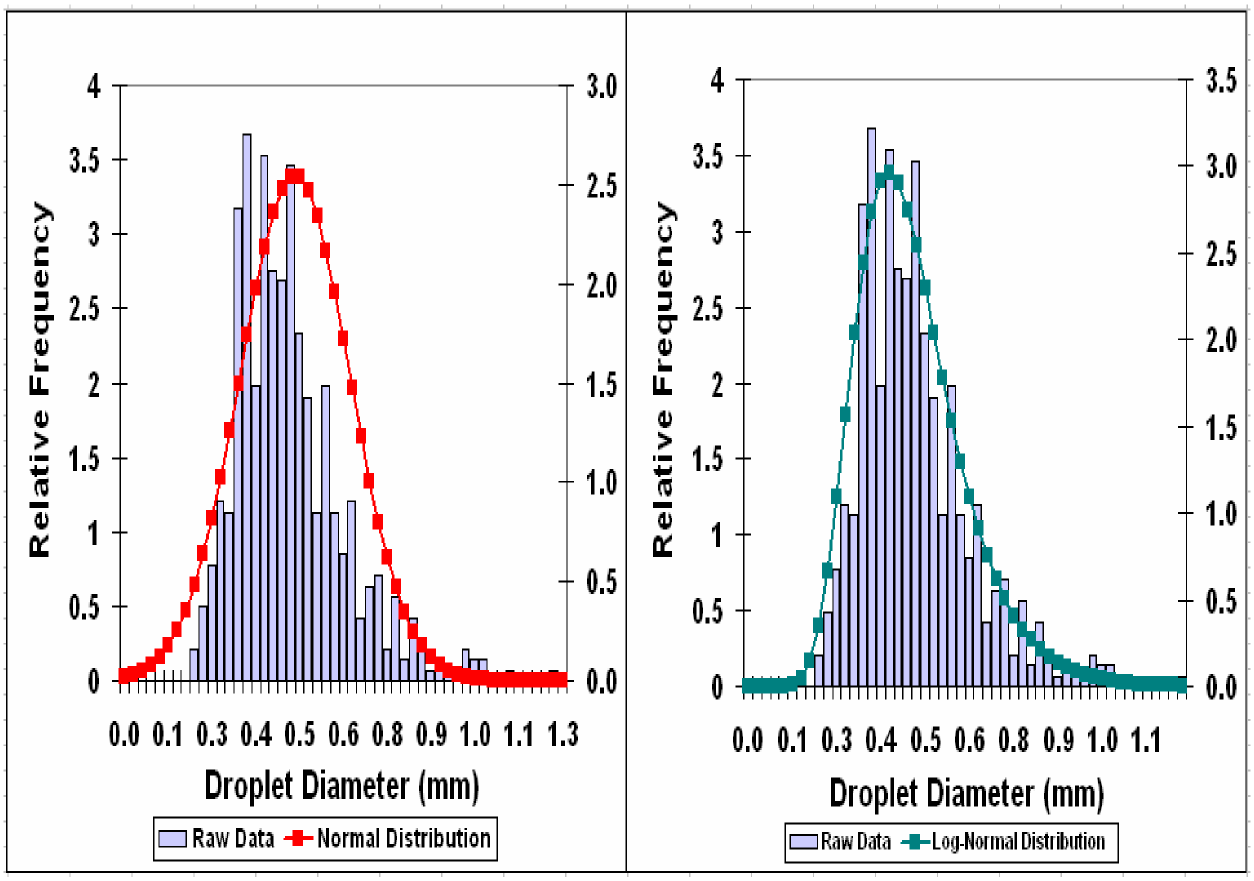

Figure 10 - Droplet Size Distributions for Uos = 0.025 m/s and Uws = 1.5 m/s

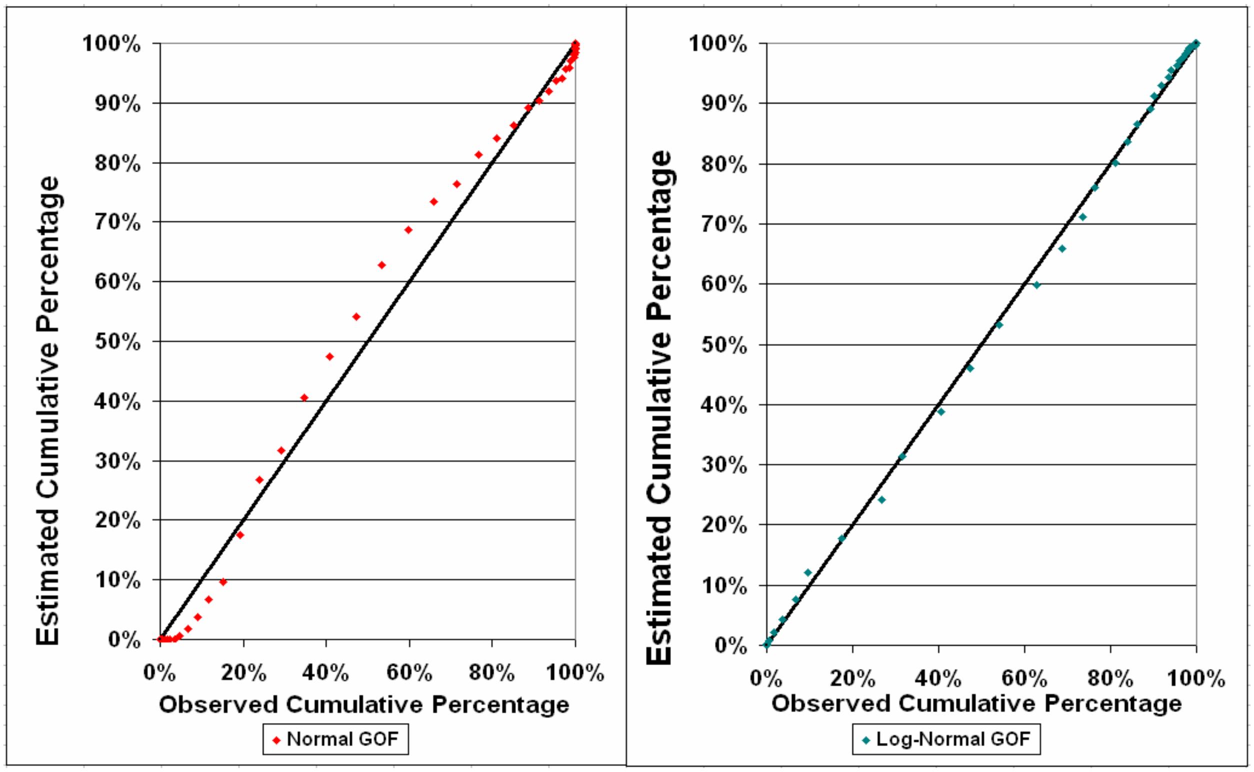

Figure 11 - GOF for Uos = 0.025 m/s and Uws = 1.5 m/s

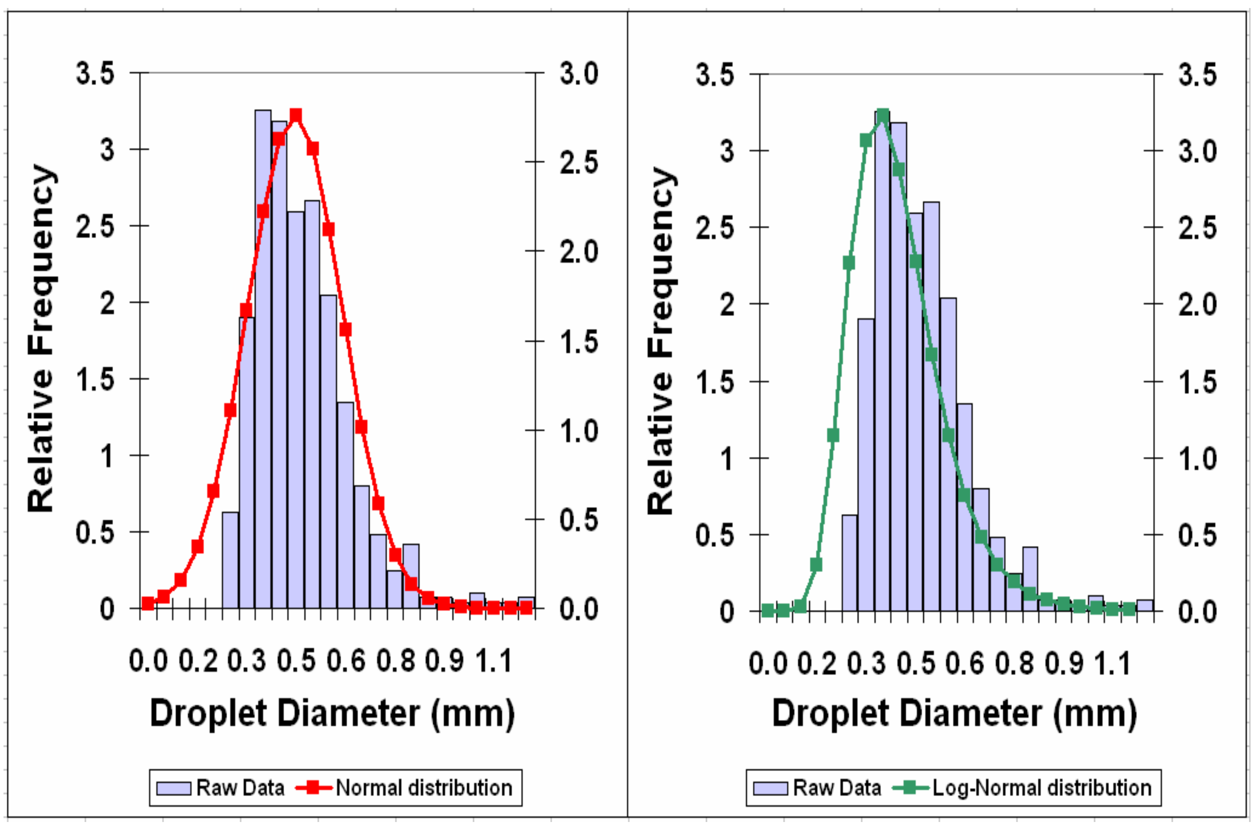

Figure 12 - Droplet Size Distributions for Uos = 0.035 m/s and Uws = 1.75 m/s

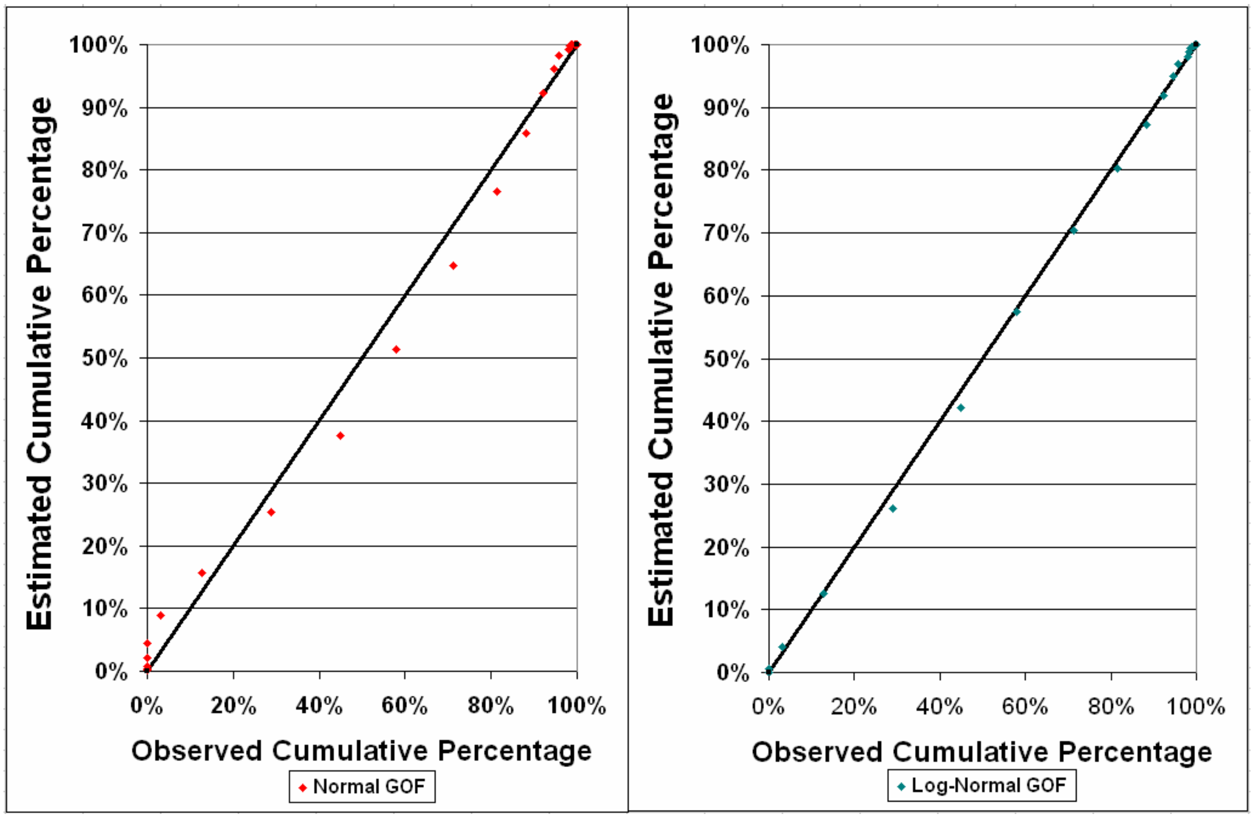

Figure 13 - GOF for Uos = 0.035 m/s and Uws = 1.75 m/s

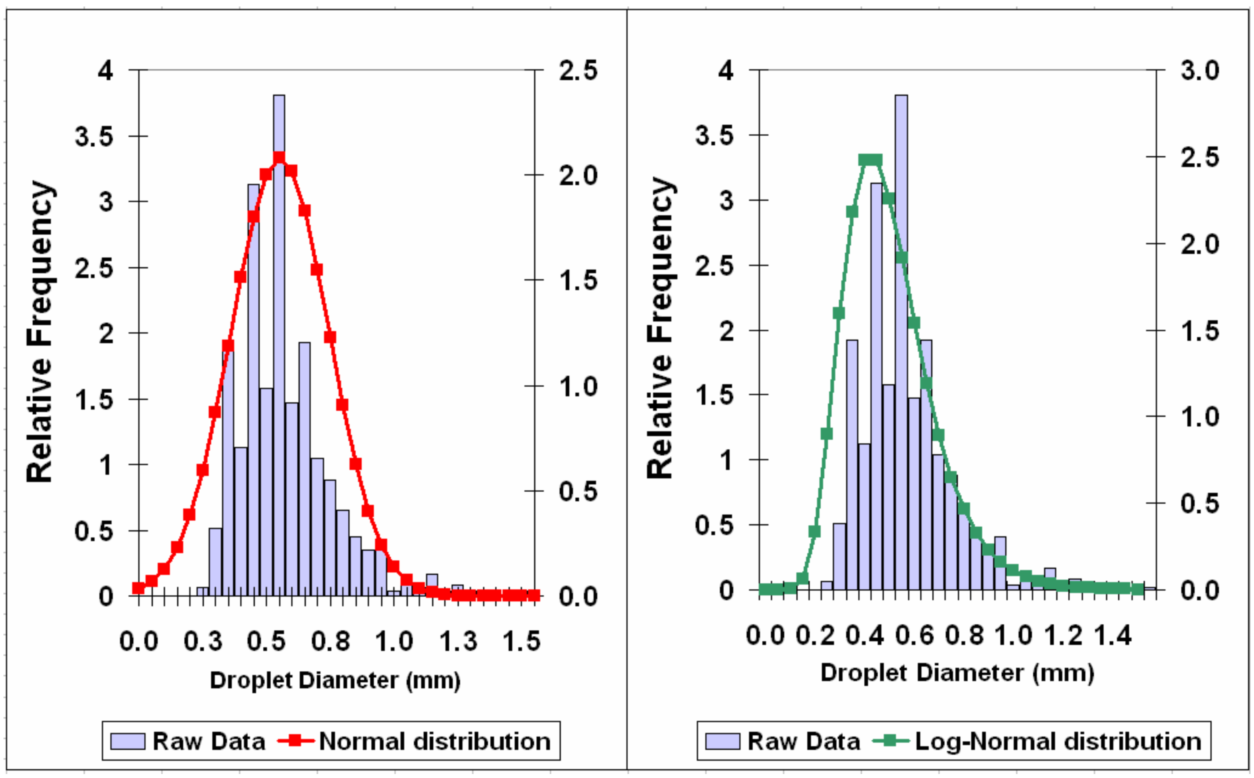

Figure 14 - Droplet Size Distributions for Uos = 0.035 m/s and Uws = 1.5 m/s

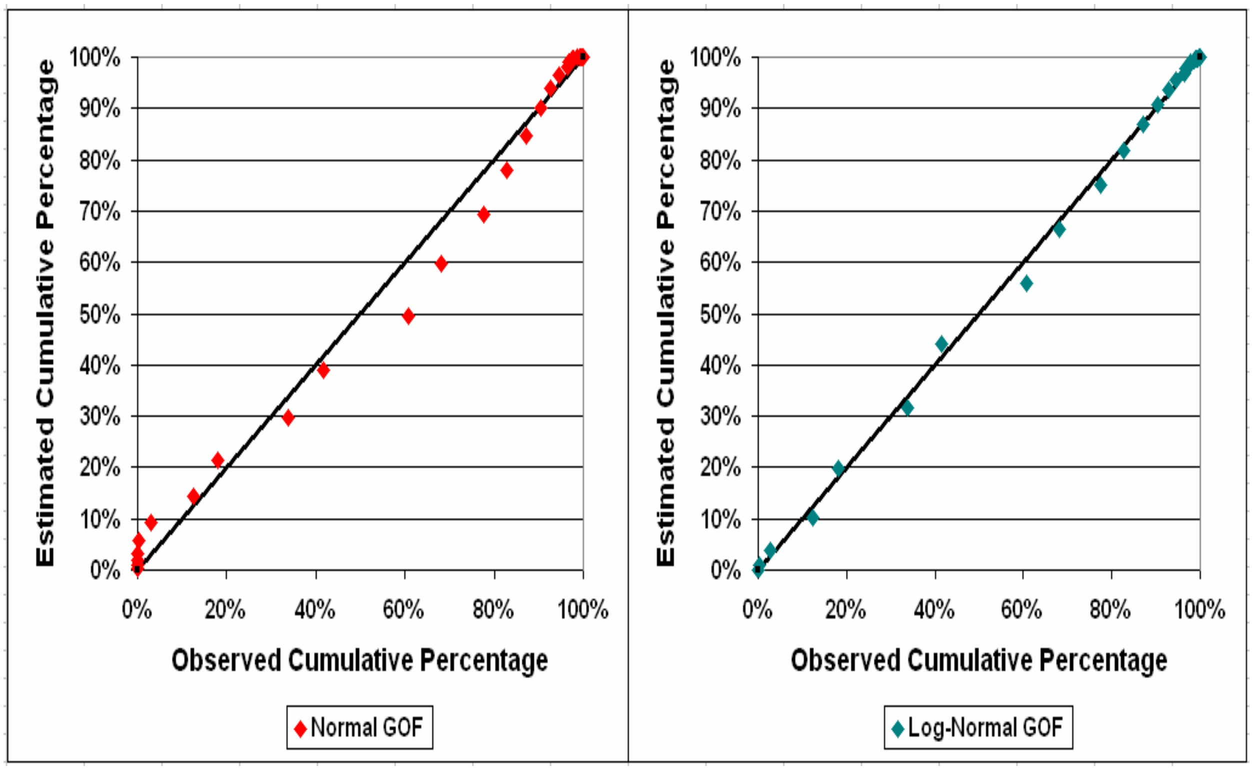

Figure 15 - GOF for Uos = 0.035 m/s and Uws = 1.5 m/s

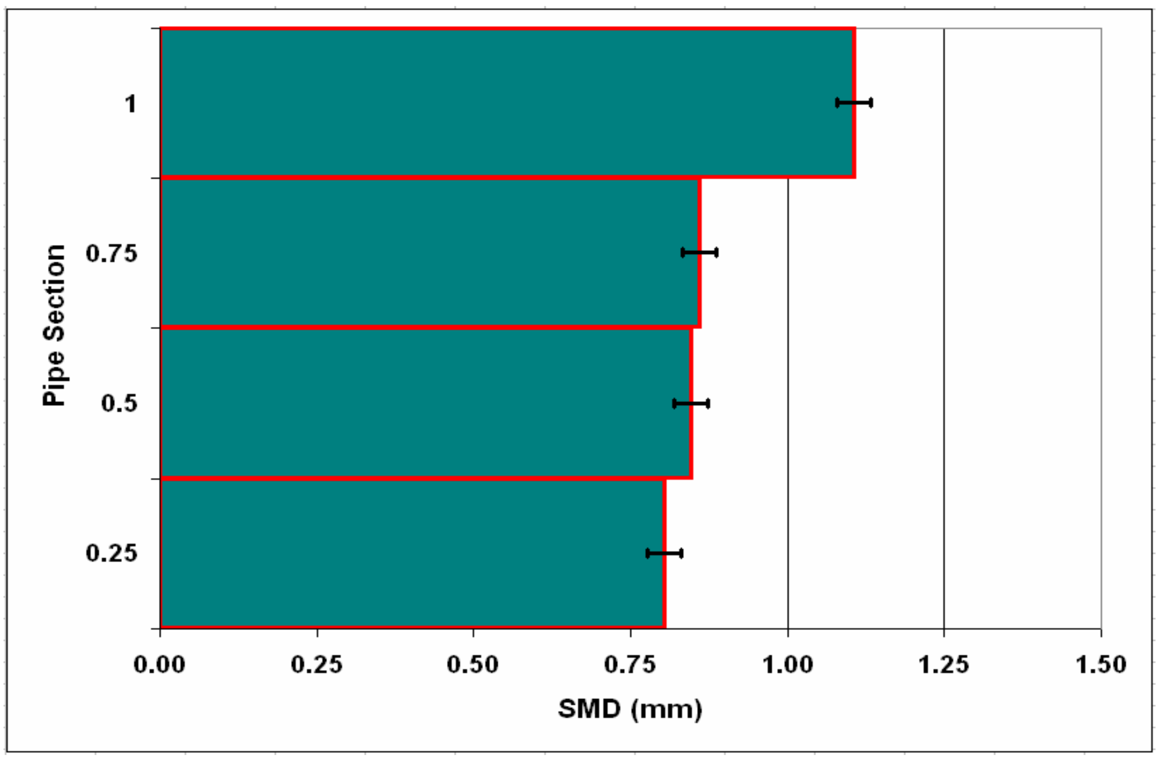

Figure 16 - Variation of SMD with Pipe Diameter (Uos = 0.025 m/s and Uws = 1 m/s)

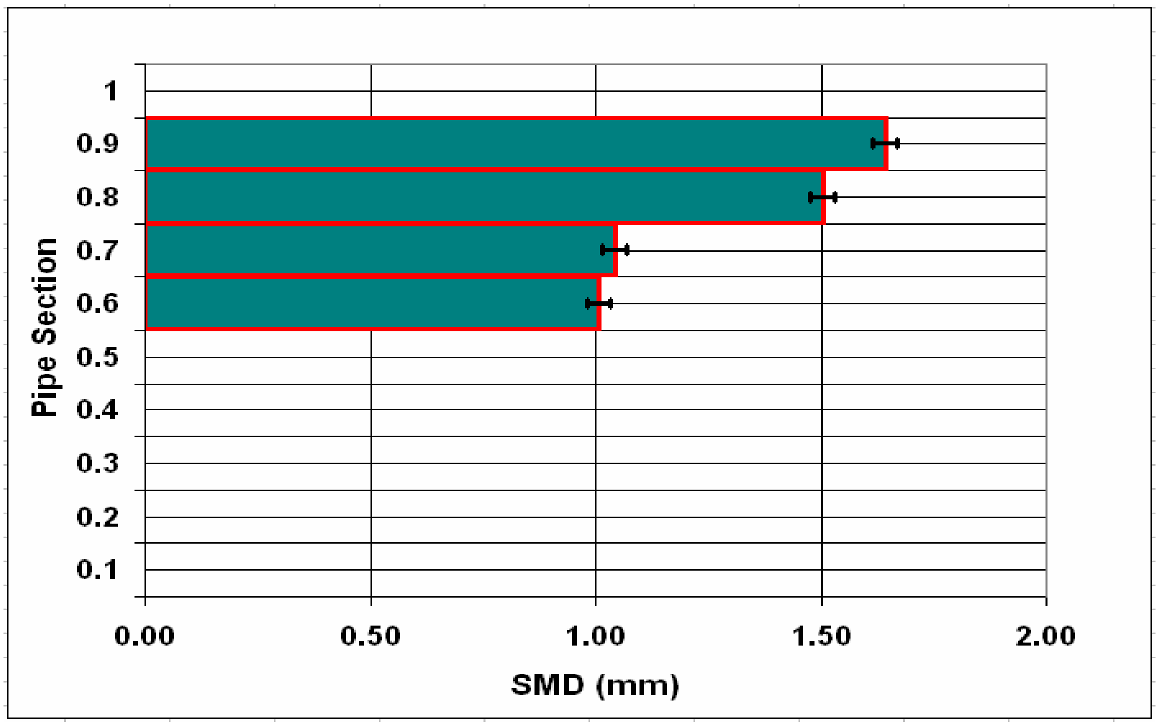

Figure 17 - Variation of SMD with Pipe Diameter (Uos = 0.025 m/s and Uws = 0.75 m/s)

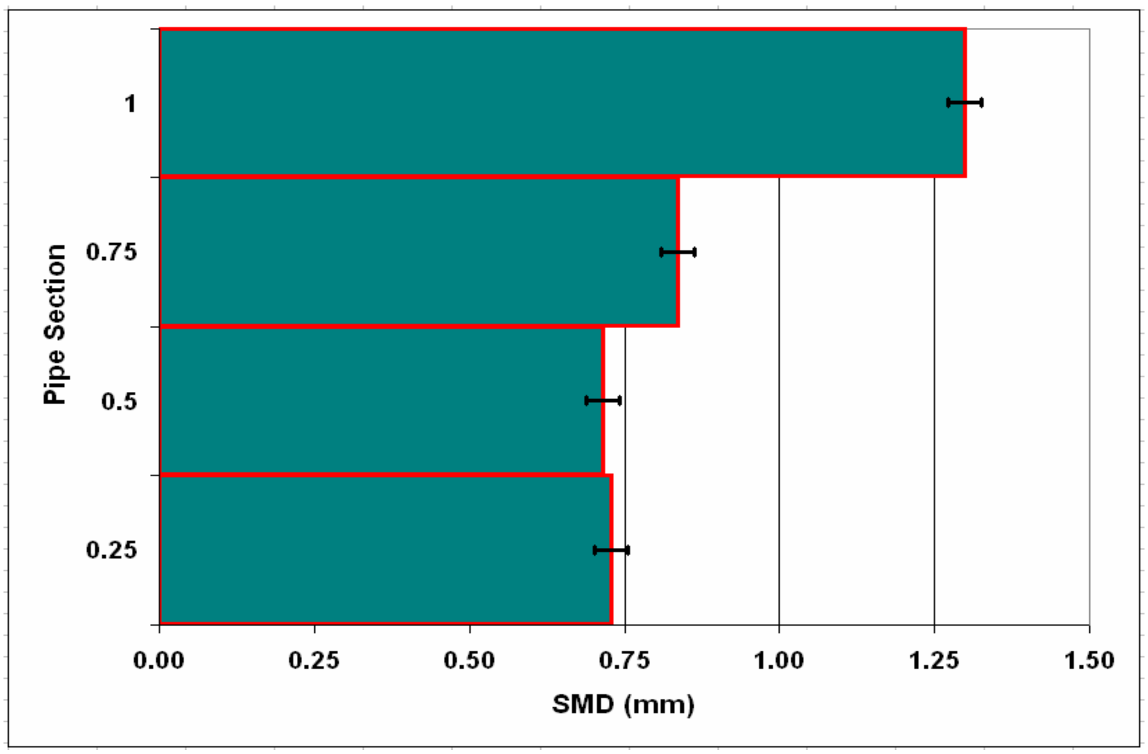

Figure 18 - Variation of SMD with Pipe Diameter (Uos = 0.035 m/s and Uws = 1 m/s)

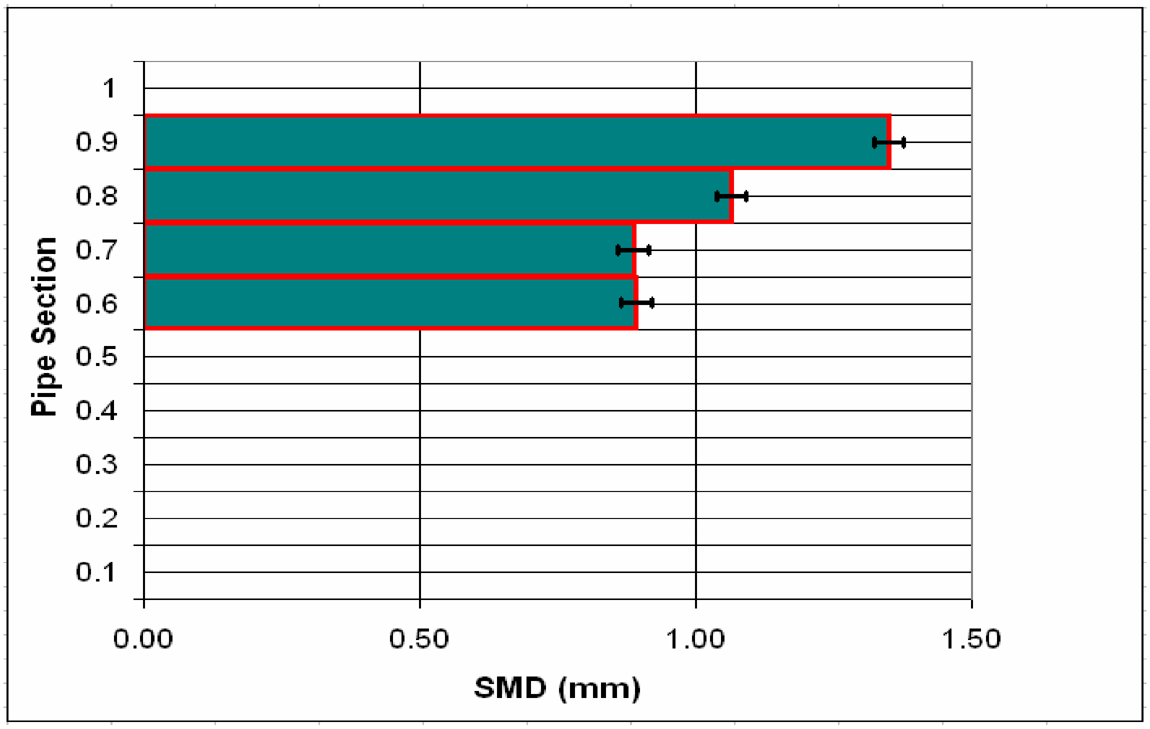

Figure 19 - Variation of SMD with Pipe Diameter (Uos = 0.035 m/s and Uws = 0.75 m/s)

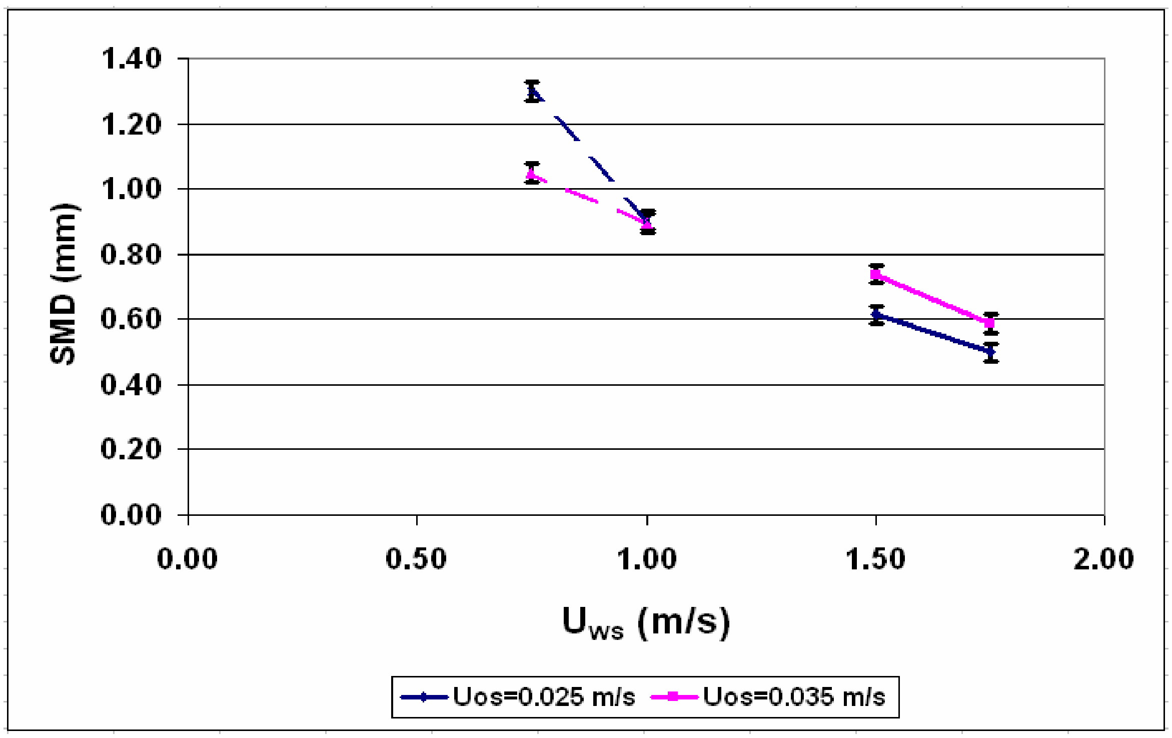

Figure 20 - Variation of SMD with Uws for Uos = 0.025m/s and Uos = 0.035 m/s

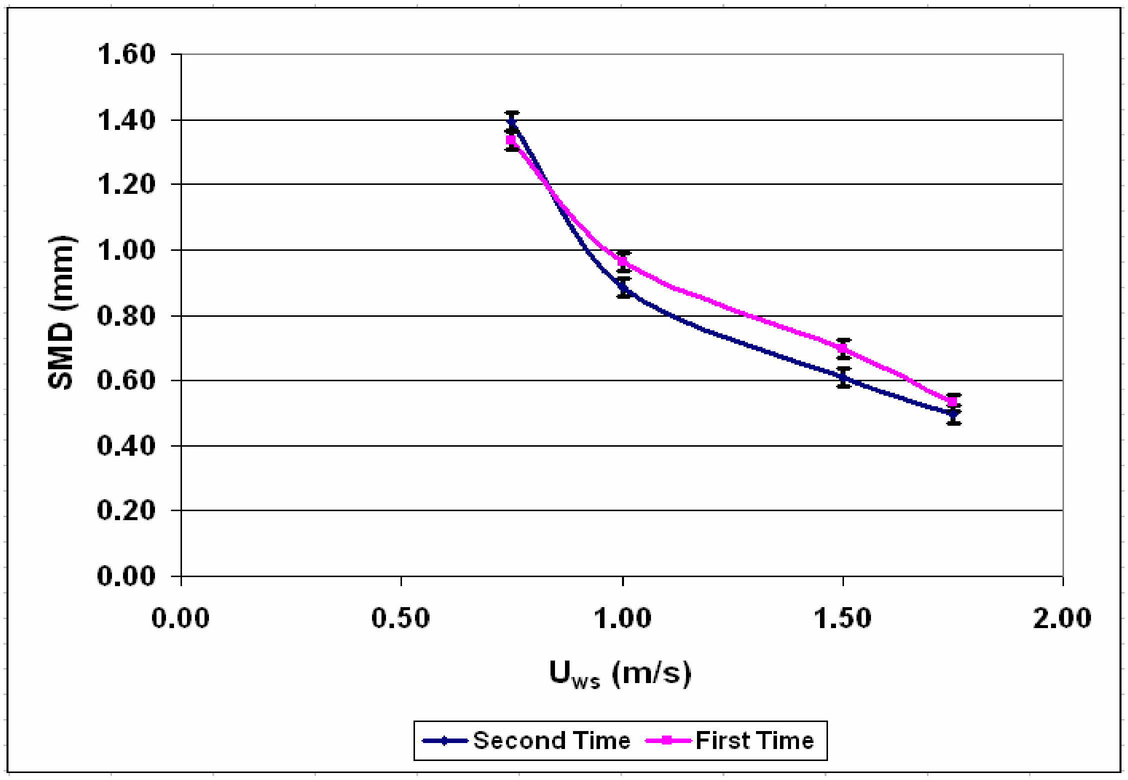

Figure 21 - SMD Measurement Repeatability

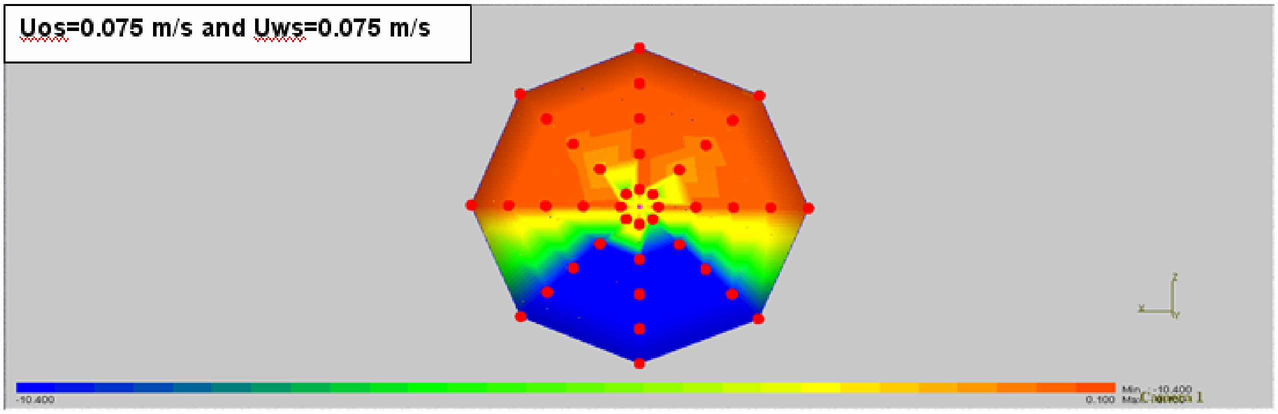

Figure 22 - Phase Distribution for Uos = 0.075m/s and Uws = 0.075 m/s

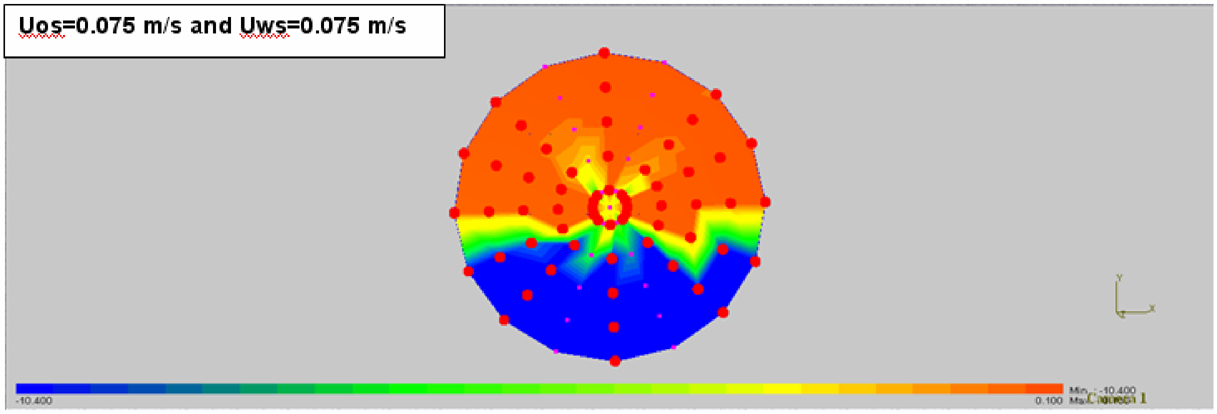

Figure 23 - Phase Distribution for Uos = 0.075m/s and Uws = 0.075 m/s. (More data points)

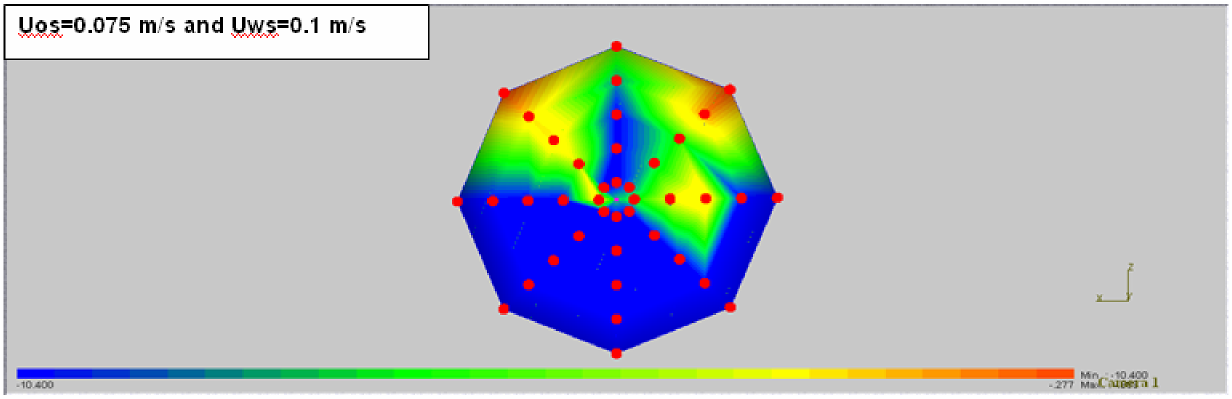

Figure 24 - Phase Distribution for Uos = 0.075m/s and Uws = 0.1m/s

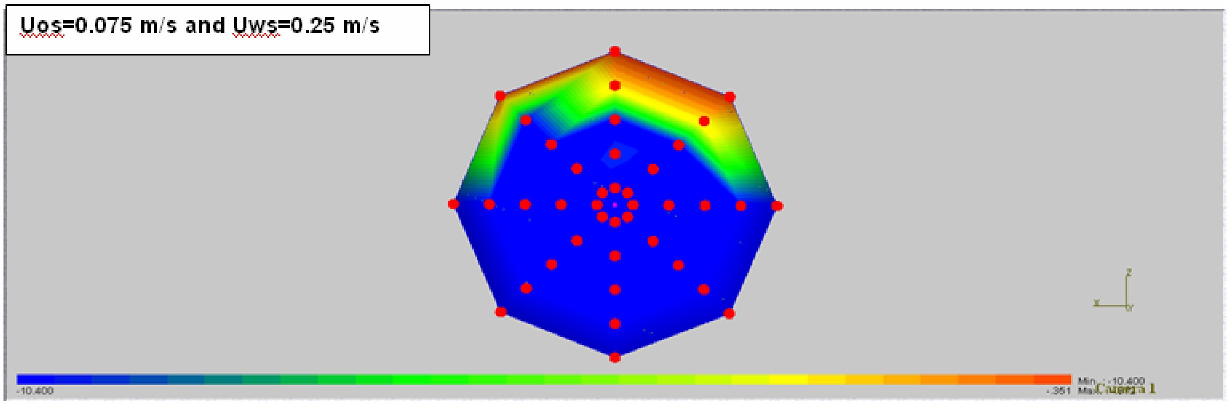

Figure 25 - Phase Distribution for Uos = 0.075m/s and Uws = 0.25 m/s

Conclusions

The first phase of the two-phase oil-water tests which covers the horizontal pipe configuration has been completed. Part of the data has been analyzed. Flow patterns, pressure and holdup behavior of oil-water were studied. Analysis of the droplet distribution for various flow patterns was started. The early findings indicate that droplets exhibit log-normal distribution. Moreover, cross-sectional variation of the droplet sizes were observed and quantified.

A parallel study to investigate the oil-water flow behavior in inclined pipes is initiated. A thorough literature search indicating the need for further work has been completed.

Nomenclature

English Letters

Symbol	Description	Unit
a, b, c	Example variables in uncertainty analysis	/
b_i	Elemental systematic uncertainty	/
Cw	Water cut	
B_R	Combined systematic uncertainty	/
d	Droplet diameter	mm
$\left(\frac{dp}{dL}\right)$	Total pressure gradient	Pa/m
D_{32}, SMD	Sauter Mean Diameter	mm
f_n	Probability Density Function	/
H_W	Water holdup	/
N	Number of elements in a population, Sample size	/
N_i	Number of droplets in a bin i.	/
P	Pressure	Pa
S_x	Standard deviation of a population	/
$S_{\bar{x}}$	Standard deviation of a population average	/
T	Temperature	K
U	Uncertainty	/
U_{95}	Combined uncertainty with 95% confidence	/
U_a, U_b, U_c	Combined uncertainties of parameters a, b, c	/
U_{os}	Oil superficial velocity	m/s
U_{ws}	Water superficial velocity	m/s
X_i	*i*th element in a population	/
$\overline{X}$	Population average	/

Symbol

μ	Mean	/
σ^2	Variance	/

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