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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.

During this reporting period, the testing for three-phase flow in horizontal pipes was completed. Currently, the analysis of the acquired data to improve the existing and/or develop the new closure relationships is underway. 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.

High speed video and other instruments are tested to gather detailed information such as drop size distribution as a function of flow patterns. An image analysis software was identified and is currently being tested.

A detailed literature search is conducted for gas-oil-water flow in inclined pipes. After completion of oil-water studies, the three-phase inclined flow experimental studies will begin.

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

Experimental Studies

Gas-Oil-Water Flow in Horizontal Pipes

Objectives

The ultimate objective of TUFFP for gas-oil-water studies is to develop a unified model based on theoretical analysis and experimental results for the prediction of flow behavior during production and transportation of gas-oil-water in pipelines. This study is the first of a series of gas-oil-water studies. The general objective of this study is to investigate three-phase flow of gas-oil-water in horizontal pipes.

Introduction

Three-phase gas-oil-water flow is a common occurrence in the petroleum industry. Perhaps, the most relevant practice is the transportation of natural gas-oil-water mixtures through pipelines. Three-phase flow may also be encountered in pumping systems, especially in surface gathering lines, and in wellbores and surface gathering systems of many flowing and gas lift wells which produce water along with oil and gas.

There is a limited amount of published work on this subject, maybe due to the uncertainty in predicting the nature of both the gas-liquid and oil-water interfaces and the coupling among them. A summary of pertinent literature was given in the Advisory Board meeting brochure of April 2002 (Keskin, 2002).

Gas-oil-water tests were conducted for horizontal pipe at various flow rates and water cuts. Experimental data was analyzed and the results were discussed. A unified model of gas-oil-water three-phase flow was developed based on the theoretical analysis and experimental results. Required closure relationships for the model were presented.

Experimental Program

Experimental Facility and Flow Loop

The experimental work was conducted using the TUFFP facility for gas-oil-water flow located at The University of Tulsa North Campus Research Complex. This facility was used previously for oil-water flow experiments by Trallero (1995) and Alkaya (2000) in horizontal and slightly inclined pipes and by Flores (1997) for vertical and deviated wells.

The facility consists of a closed circuit loop with the following components: pumps, heat exchangers, metering sections, filters, test section, separator and storage tanks. The test section is attached to an inclinable boom. A schematic diagram of the flow loop is given in Fig. 1.

Instrumentation and Data Acquisition

The current test section is composed of two 21.1-m (69.3-ft) long straight transparent pipes, connected by a 1.2-m (4.0-ft) long PVC bend to reduce the disturbance to the flow pattern due to a sharp turn. The pipeline has a 0.0508-m (2.0-in.) internal diameter. The upward branch of the test section consists of: a 13.8-m (45.3-ft) long flow developing section (L/D = 272.0), two short pressure drop sections 5.2-m (17.0-ft) and 3.3-m (11.0-ft) long, one long pressure drop section combining the two short sections, one 5.5-m (18.1-ft) long fluid trapping section (L/D = 108), and a 1.8-m (6.0-ft) long measurement section. The downward branch of the test section is designed and built similar to the upward branch. The transparent pipes are instrumented to permit continuous monitoring of temperature, pressure, differential pressure, holdup, inclination angle and spatial distribution of the phases.

Quick-closing valves, conductance probes and capacitance sensors are used to measure phase fractions and flow characteristics.

Conductance probes were developed mainly to determine the liquid phase at a point in a gas-oil-water flow. They were also used to determine the continuous phase. Three on the upward branch and one on the downward branch of the test section were installed.

The capacitance sensors were mainly used to obtain slug characteristics such as, slug length and translational velocity. A schematic diagram of the test section is given in Fig. 2.

The TUFFP high speed video system was used in identifying the flow patterns and determining the oil-water mixing status.

For data acquisition, Lab VIEW™ 7.0 software is used. A new data acquisition program was developed for the new system. New hardware, including a computer, a multiplexer and a multifunction I/O board, were installed.

Test Fluids

The fluids used in the experiments consist of a refined mineral oil, fresh water, and air. Due to its good separability, Tulco Tech 80 oil is used as the oil phase in the tests. The physical properties of the oil are given below:

- 33.2 API gravity
- Density: 858.75 kg/m^3 @ 15.6 ^{o}C
- Viscosity: 13.5 cp @ 40 ^{o}C
- Surface tension: 29.14 dynes/cm @ 25.1 ^{o}C
- Interfacial tension with water: 16.38 dynes/cm @ 25.1 ^{o}C
- Pour point temperature: -12.2 ^{o}C
- Flash point temperature: 185 ^{o}C

Gas-Oil-Water Test Program

A typical test for gas-oil-water flow starts with varying the gas flow rate, keeping the oil and water flow rates and water fraction constant. Then, tests are repeated for several oil and water flow rates at constant water fraction, and continue with varying water fraction.

Gas-Oil-Water Tests

The testing ranges for the gas-oil-water tests conducted are as follows:

- Superficial gas velocity: 0.1 – 7.0 m/s
- Superficial oil velocity: 0.02 – 1.5 m/s
- Superficial water velocity: 0.01 – 1.0 m/s
- Water fraction: 20, 40, 50, 60 and 80 %

Three-Phase Flow Patterns

Three-phase gas-oil-water flow patterns are actually a combination of gas-liquid and oil-water flow patterns. Gas-liquid flow patterns observed during three-phase tests in horizontal pipe are: stratified smooth (SS), stratified wavy (SW), elongated bubble (EB), and slug flow (SL). There are also annular (AN) and dispersed bubble flows (DB). Oil-water flow patterns in horizontal pipes identified by Trallero (1995) are used in this study. The name of those flow patterns are: stratified (ST), stratified flow with mixing at the interface (ST & MI), dual type of dispersions (Dw/o & Do/w), dispersion of oil in water over a water layer (Do/w & w), water in oil dispersion (w/o), and oil in water dispersion (o/w).

The combination of those gas-liquid and oil-water flow patterns gives us several different three-phase flow patterns which are not practical in use. Therefore, a new classification of gas-oil-water three-phase flow patterns is needed.

Starting with the gas-liquid flow patterns, stratified smooth and stratified wavy flow patterns can be combined under the name “stratified” to reduce the number of three-phase flow patterns. Similarly, “intermittent flow” can be used for both elongated bubble and slug flows.

There are more oil-water flow patterns than gas-liquid flow patterns, and they are more complex. Six oil-water flow patterns observed during three-phase tests were mentioned above. This number can be reduced by grouping them into three. When oil and water flow separately in the pipe with even few droplets only at the interface, the flow pattern is called “stratified” oil-water flow. Stratified (ST) and stratified flow with mixing at the interface (ST & MI) flow patterns fall into this group. In an oil-water pipe flow, if there is an oil-water interface, and if oil droplets are observed in water and/or water droplets are observed in oil away from the interface, that means there are two continuous phases. This flow is called “dual continuous”. Trallero’s (1995) dual type of dispersions (Dw/o & Do/w) and dispersion of water in oil over a water layer (Dw/o & w) flow patterns fall into this group. When there is no oil-water interface and when one liquid phase is completely dispersed in the other liquid phase, we have mono continuous flow. The continuous phase is either oil or water. Dispersion of oil in water over a water layer (Do/w & w), water in oil dispersion (w/o) and oil in water dispersion (o/w) flow patterns are examples of this kind of flow.

Based on the above classifications, 12 individual three-phase gas-oil-water flow patterns in horizontal pipes have been identified and listed below. The names of the gas-oil-water flow patterns consist of two words. First word stands for gas-liquid flow pattern and the second word indicates oil-water flow pattern. The sketches of the gas-oil-water flow patterns and the gas-oil-water flow pattern maps for 20, 40, 50, 60 and 80 % water cut tests are given in Figs. 3 to 8 and Figs. 9 to 13, respectively.

- Stratified-Stratified (ST-ST)
- Stratified-Dual Continuous (ST-DC)
- Stratified-Oil Continuous (ST-OC)
- Stratified-Water Continuous (ST-WC)
- Intermittent-Stratified (IN-ST)
- Intermittent-Dual Continuous (IN-DC)
- Intermittent-Oil Continuous (IN-OC)
- Intermittent-Water Continuous (IN-WC)
- Annular-Oil Continuous (AN-OC)
- Annular-Water Continuous (AN-WC)
- Dispersed Bubble-Oil Continuous (DB-OC)
- Dispersed Bubble-Water Continuous (DB-WC)

Pressure Gradient

The pressure gradients increase with increasing gas and liquid flow rates. From a flow pattern point of view, the pressure gradients increase slightly for stratified and partially mixed oil-water flows where both gas and liquid flow rates are relatively low. At superficial gas velocities higher than 1.0 m/s where slug and fully mixed oil-water flows are observed, the increase in the pressure gradients is quite sharp. This might be due to the rise in effective viscosity as the water-in-oil dispersion occurs, or just because of the increase in gas flow rate. Another observation is that, the pressure gradients for water in oil dispersions are relatively higher than the pressure gradients for oil in water dispersions at similar gas and liquid flow rates most probably due to the change of the continuous phase. The pressure gradient change with water cut at various superficial gas velocities for constant 0.05 m/s superficial liquid velocity is given in Fig. 14 where the flow patterns are mostly ST-ST. In Fig. 15, the same graph is plotted for constant 1.25 m/s superficial liquid velocity where the flow patterns are IN-OC for 20 % and 40 % water cuts and IN-WC for 60 % and 80 % water cuts.

Holdup Measurements

Local holdup measurements were performed using the quick closing ball valves located on the downward branch of the test section by lifting the test section to vertical or close to the vertical position. One particular problem encountered during the measurements for intermittent flows was the variation of the trapped volume of liquid depending on whether or not a liquid slug was trapped, due to the ratio of the length of the trapping section (5.56 m) to the length and frequency of slugs.

Wetted Perimeter Measurements

Wetted perimeter, which is the pipe periphery wetted by the liquid phases, is measured by a measurement tape attached to the outer surface of the pipe. The oil and water wetted perimeters are measured separately when one of the liquid phases is not dispersed in the other liquid phase. For intermittent flows, the wetted perimeter measurements are performed only for the liquid film unless the liquid phases in slug body are separated.

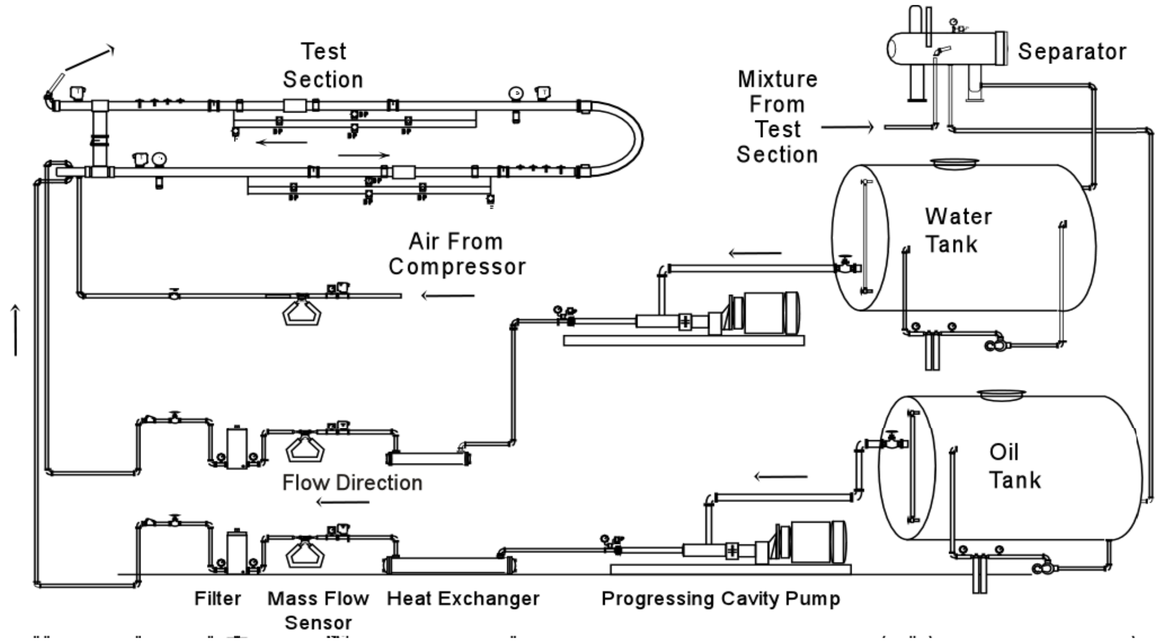

Figure 1 – Schematic Representation of Experimental Flow Loop

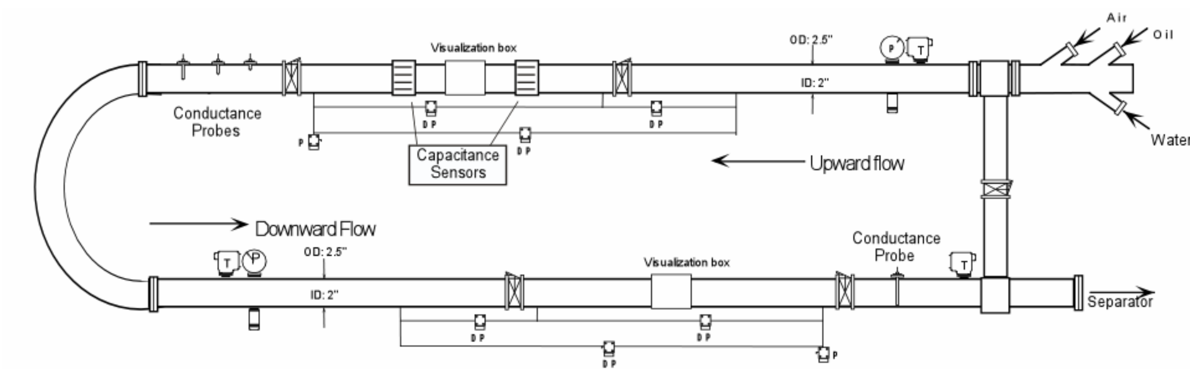

Figure 2 – Test Section

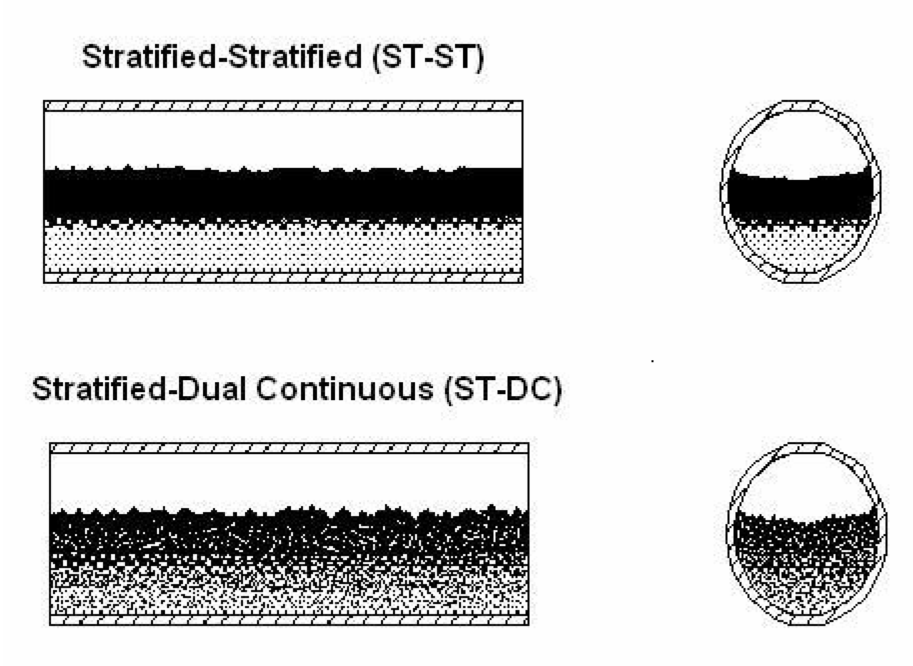

Figure 3 – Stratified-Stratified (ST-ST) and Stratified-Dual Continuous (ST-DC) Gas-Oil-Water Flow Patterns

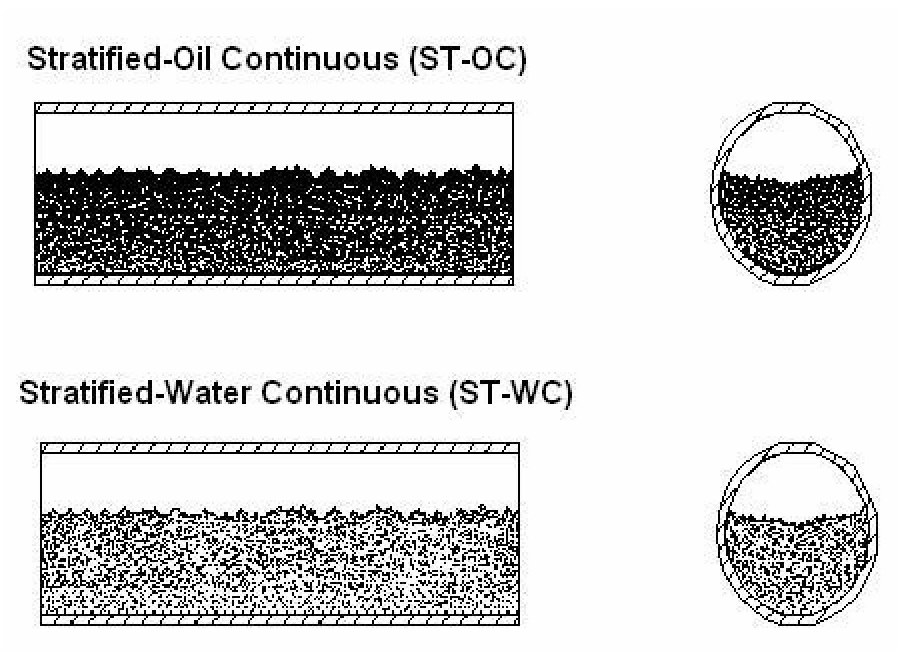

Figure 4 – Stratified-Oil Continuous (ST-OC) and Stratified-Water Continuous (ST-WC) Gas-Oil-Water Flow Patterns

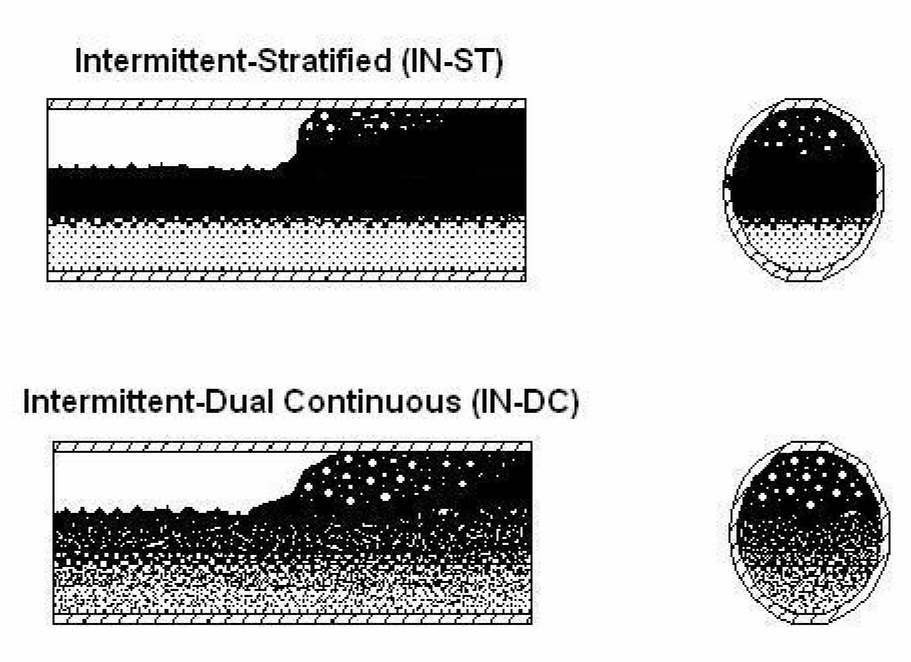

Figure 5 – Intermittent-Stratified (IN-ST) and Intermittent-Dual Continuous (IN-DC) Gas-Oil-Water Flow Patterns

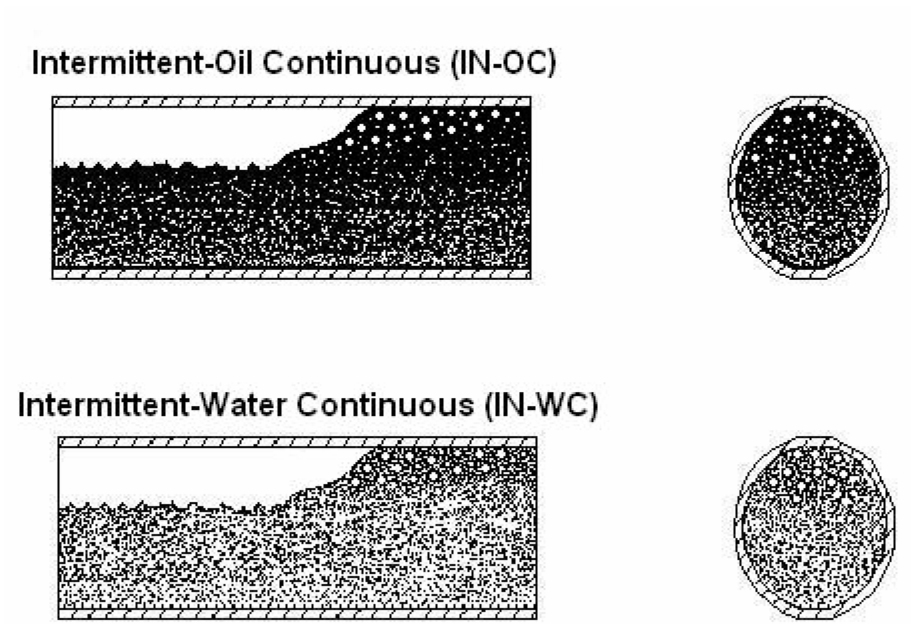

Figure 6 – Intermittent-Oil Continuous (ST-OC) and Intermittent-Water Continuous (ST-WC) Gas-Oil-Water Flow Patterns

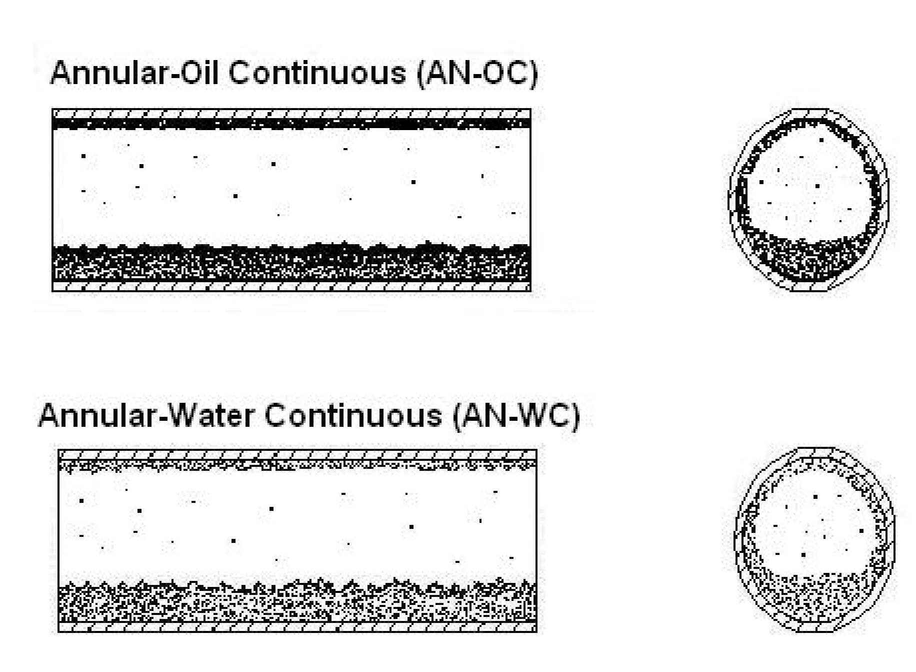

Figure 7 – Annular-Oil Continuous (AN-OC) and Annular -Water Continuous (AN-WC) Gas-Oil-Water Flow Patterns

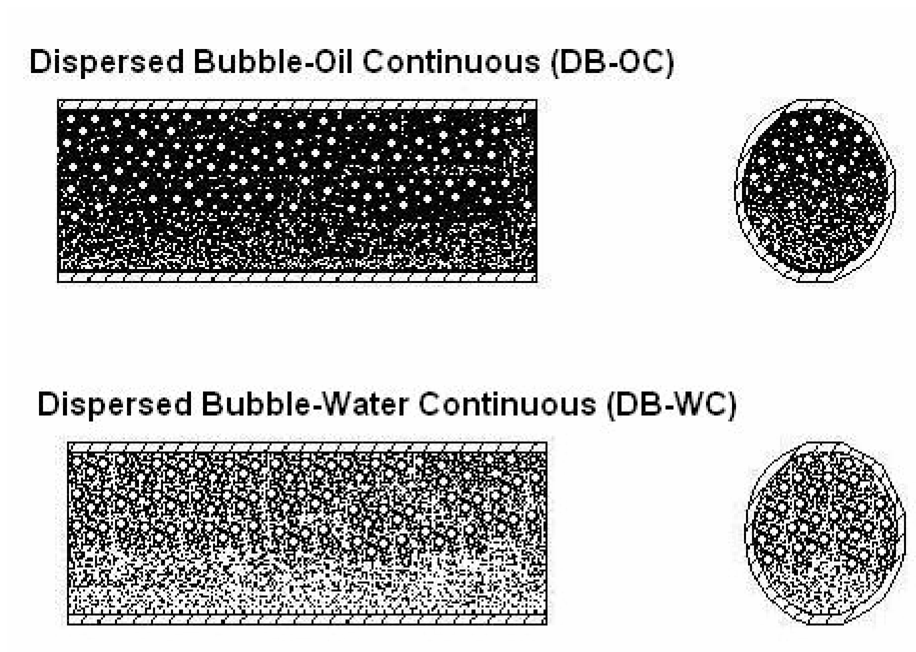

Figure 8 – Dispersed Bubble-Oil Continuous (DB-OC) and Dispersed Bubble-Water Continuous (DB-WC) Gas-Oil-Water Flow Patterns

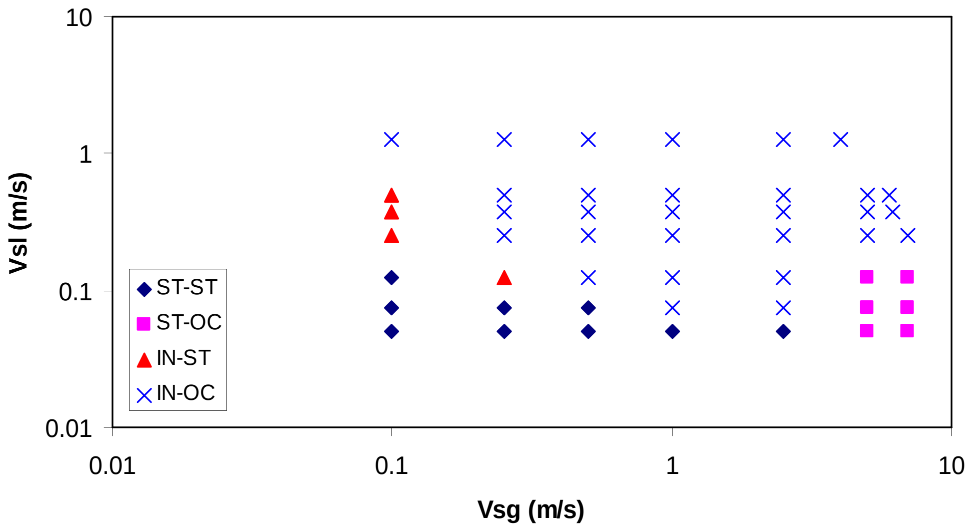

Figure 9 – Gas-Oil-Water Flow Pattern Map for 20 % Water Fraction

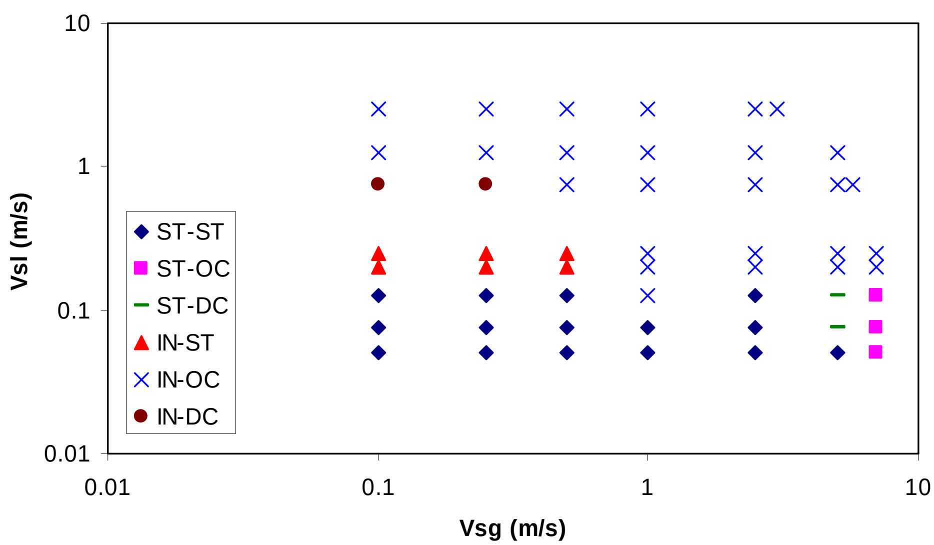

Figure 10 – Gas-Oil-Water Flow Pattern Map for 40 % Water Fraction

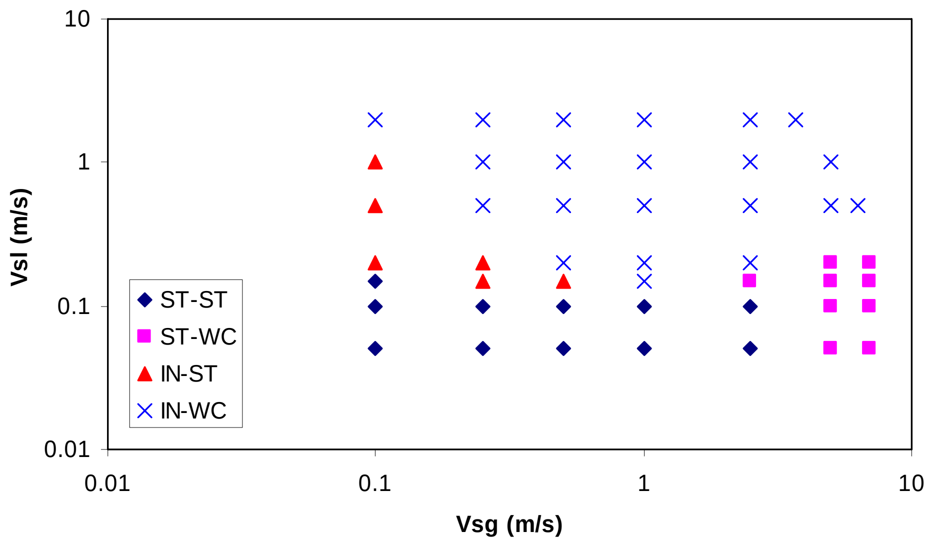

Figure 11 – Gas-Oil-Water Flow Pattern Map for 50 % Water Fraction

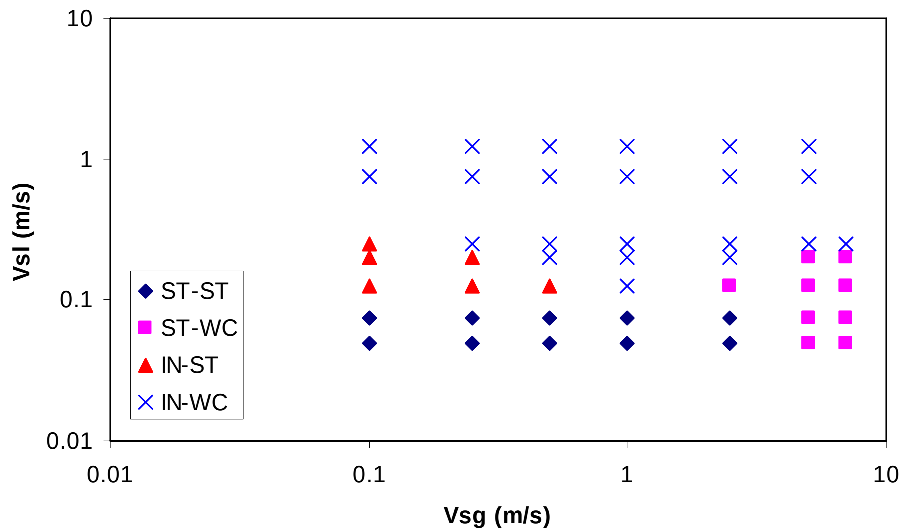

Figure 12 – Gas-Oil-Water Flow Pattern Map for 60 % Water Fraction

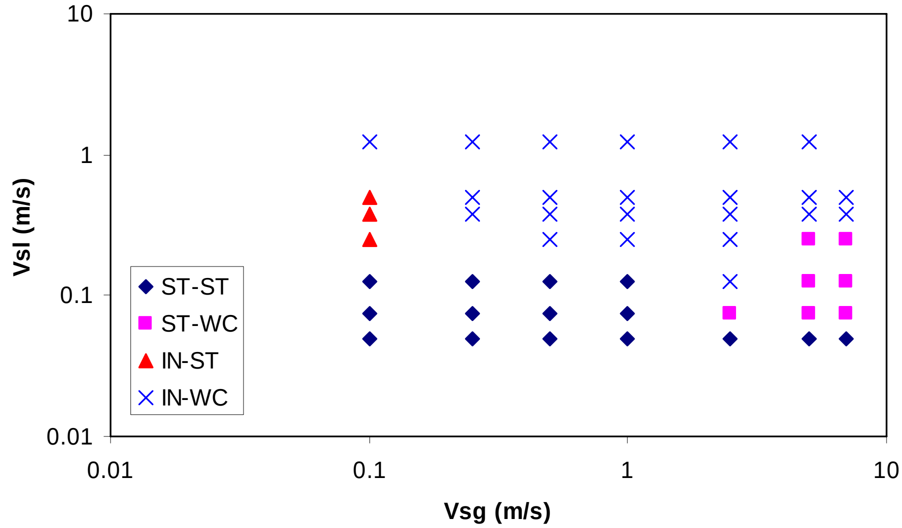

Figure 13 – Gas-Oil-Water Flow Pattern Map for 80 % Water Fraction

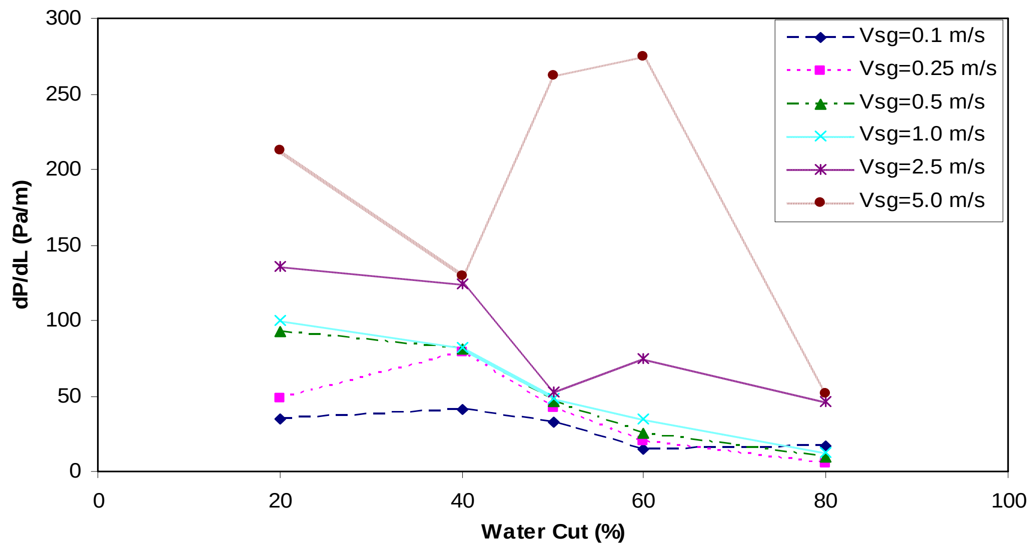

Figure 14 – Pressure Gradient vs Water Cut (Vsl = 0.05 m/s)

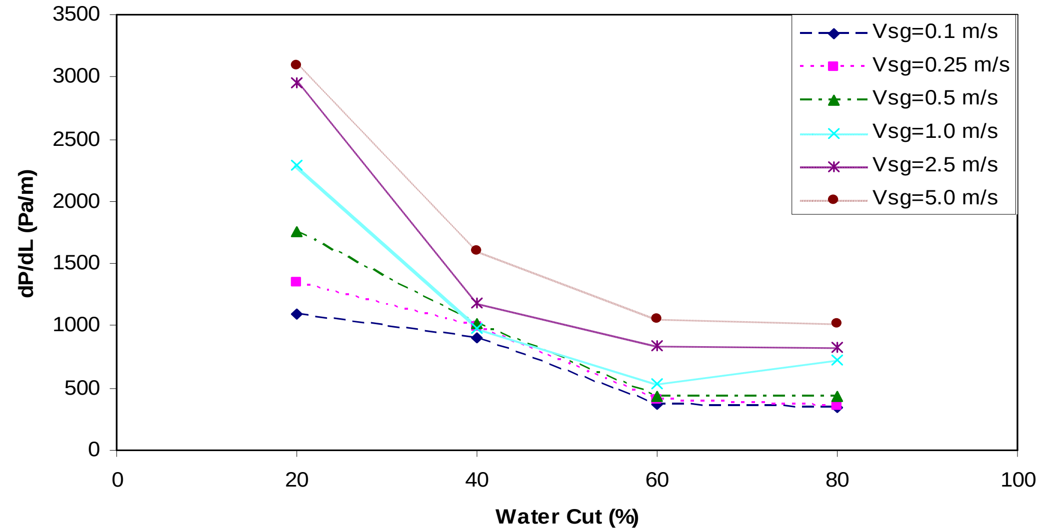

Figure 15 – Pressure Gradient vs Water Cut (Vsl = 1.25 m/s)

Oil-Water Flow in Horizontal Pipes and Slightly Inclined Pipes

Objectives

The main objectives of this study are:

- Acquire detailed experimental data on oil-water flow including droplet sizes and velocity fields in horizontal and slightly inclined pipes (-1° and +1°) for different operating conditions to better understand the physics of oil-water flow.

- Improve the existing oil-water flow models or develop new ones if necessary.

Literature Review

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.

Experiments

During the simultaneous flow of oil and water, a number of flow patterns can appear which range from fully separated to fully dispersed ones (Lovick & Angeli, 2005). In most of the reported studies, identification of the flow pattern is based on visual observations, photographic/video techniques, or abrupt changes in the average system pressure drop (Brauner, 2002). Only recent studies have used tools such as conductivity probes or sampling probes (Soleimani et al., 1999); some others include isokinetic probes, impedance probes and gamma densitometers.

From the different existing flow patterns in oil-water flows, stratified flow in particular has received most attention, since the low flow velocities and well defined interface favor both experimental and theoretical investigations. For fully dispersed systems, information is available mainly from studies in stirred vessels. The available information is even more limited for the intermediate flow patterns between the stratified and the fully dispersed ones (Lovick et al., 2005).

Pressure drop of two-phase pipe flows strongly depends on the flow regime and hence the distribution of the two liquids in the cross sectional area of the pipe. Turbulent mixing in the pipe can be sufficient to disperse the initially separated phases, so that dispersions and emulsions are formed, resulting in higher pressure drops. The flow behavior of emulsions of oil and water depends on the volume fraction and the droplet distribution of the dispersed phase (Nädler & Mewes, 1997). Drop size depends on the competing phenomena of breakup and coalescence. Knowledge of drop size and distribution would improve understanding of dispersed systems and contribute to their better design and modeling. However, there is only limited amount of data for drop size distributions in pipe flow (Lovick & Angeli, 2004).

Experimental data on average drop size mainly exist for low dispersed phase concentrations, where a variety of measuring techniques can be used. Few studies have looked at high concentrations and most of them were surfactant-stabilized emulsions. The limited available data on average drop size and distribution, especially in unstable dispersions at high dispersed phase volume fractions, are partly due to the difficulty in performing such measurements. Photography/video recording provide information on the actual shape of the drops. If used outside the vessel, 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 container overcoming the problem of dense dispersions but in an intrusive way (Lovick et al., 2005).

Modeling

A central problem in the analysis of two-phase flow is the determination of the flow pattern. Much of the past work has concentrated on the analysis of flow-regime transitions in gas-liquid two phase flow. However, the flow pattern prediction methods developed for gas-liquid flow cannot be readily extended to liquid-liquid systems. Some flow configurations of liquid-liquid two-phase flow mixtures in pipes are different from those of gas liquid mixtures. Moreover, there is no agreement in the published literature on the classification of flow patterns in liquid-liquid flow (Fairuzov, 2000).

Flow pattern characterization and transitions are usually related to the common parameters, which include the phase flow rates and physical properties. However, in dealing with liquid-liquid systems, the wide range of physical properties encountered generates a sort of ambiguity as how to characterized liquid-liquid systems (Brauner, 2002).

Only a few published studies deal with the modeling of oil-water flow pattern transitions (Torres, 2005). In these studies, the two main techniques used for the prediction of oil-water flow pattern transitions are linear stability analysis for stratified – non-stratified transition and turbulent dispersion mechanism for the transition to dispersed flow (Trallero, 1995).

Stratified – Non-Stratified Flow Transition

The starting point for the stratified / non-stratified transition is the so called “two-fluid model”. The two-fluid model treats the two fluids separately as if each flows in its own channel within the pipe. This transition has been described by most of the researchers in terms of stability analysis. Brauner and Moalem (1992) investigated the linear-stability analysis of two stratified immiscible liquids and the well-posedness analysis of the hyperbolic system of equations for the two-fluid model. Based on the analysis, they formulated two criteria for predicting the stratified to non-stratified flow transition: 1) the so-called Zero-Neutral-Stability (ZNS) condition, and 2) the Zero-Real-Characteristics (ZRC) condition.

Similar criteria can be obtained via the classical Kelvin-Helmholtz (KH) linear-stability analysis of the interface for one-dimensional two-phase flow. Two types of Kelvin-Helmholtz analysis have been used: 1) Viscous Kelvin-Helmholtz (VKH) analysis, which uses the full two-fluid model and takes into account the shear stress, and 2) Inviscid Kelvin-Helmholtz (IKH) theory, in which the shear stresses are neglected (Torres, 2005).

Trallero (1995) examined the oil-water interface stability with these two types of linear-stability analyses, namely VKH, and IKH. ZNS theory is equivalent to VKH analysis for long interfacial waves when the effects of the surface tension are negligible. However, Trallero (1995) questioned the use of well-posedness analysis for predicting flow-pattern transitions. Ramshaw and Trapp (1978) showed that the two-fluid formulation in which surface tension is not ignored is always well-posed. Ill-posedness means, instability at the limit of the short wavelength, but it is believed that the transition is associated with instability of long interfacial waves.

Transition to Dispersed Flow

Prediction of the transition boundaries to dispersed flow for gas-liquid and liquid-liquid systems has been carried out in most of the published studies based on the modeling of the turbulent dispersion forces balanced against the forces due to surface tension and buoyancy.

For horizontal and slightly inclined gas-liquid pipe flow, Taitel and Dukler (1976) modeled the dispersed-bubble transition boundary by equating the turbulent breakage forces with the buoyant forces tending to keep the gas at the top of the pipe. For vertical and off-vertical inclined gas-liquid systems, Taitel *et al.* (1980) and Barnea *et al.* (1982a, 1982b) suggested the transition mechanism to dispersed-bubble flow occurs when the turbulence intensity in the liquid-phase is sufficiently high: 1) to overcome the surface tension forces, which resist deformation and breakup of droplets (Hinze, 1955, and Sevik and Park, 1973), and 2) to disperse the gas-phase as small and stable spherical bubbles.

Brodkey (1969) and Barnea (1987) included the effect of buoyant forces in horizontal and shallow inclinations in the analysis and presented a unified transition boundary including both the surface tension and buoyant forces vs. turbulence forces. Calderbank (1958), investigating dispersion phenomena in gas-liquid systems, found that the bubble size increases proportionally to the gas void fraction of the system. Chen *et al*. (1997) proposed a model which considers the balance between the liquid turbulent kinetic energy and surface energy of the bubbles as a criterion for transition to dispersed bubble flow.

Brauner and Moalem (1992a, 1992b) and Trallero (1995) presented preliminary models for the prediction of the transition boundary to dispersed flow in liquid-liquid systems. Recently, Brauner (2001) presented a general approach for the prediction of dispersed flow boundaries in gas-liquid and liquid-liquid flows. She applied Hinze (1955) model for both dilute and dense dispersed flows.

Preliminary Experimental Study

Previous authors have stated that image analysis for determining droplet size distributions mostly works for dilute dispersions; however, different fractions of the dispersed phase would be obtained in the present study. Since there is uncertainty about the highest percentage of dispersed phase and the range of sizes the image processing software can analyze, it is proposed to conduct a study of the oil-water dispersed system in a controlled environment by stirring the dispersion in a beaker.

The experimental setup is shown in Fig. 16. It consists of a transparent square container in which different dispersions are prepared. The proposed arrangement will allow taking images without any distortion due to curvature if the dispersion were generated in a cylindrical vessel or in a pipe. The system will remain dispersed by the use of an impeller that rotates at a fixed rotational speed (300RPM) by a driving motor. The driving motor is a RW 20 DZM.n from IKA Labortechnik which can operate from 60 to 2000 rpm with a high shear radial flow impeller.

The testing procedure includes mixing water and oil at different fractions ranging from 2% to 90% of the total volume. Photographic measurements are made and droplet size distributions are obtained for each measurement.

The objective of these experiments is to simulate the behavior of oil-water non-stabilized dispersions, and obtain their droplet size distribution by recording videos and analyzing them; the digital image analysis technique is tested to determine the maximum limits for obtaining droplet size distribution.

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.

Mean Diameters

The widely used mean diameter for characterizing droplet size is the Sauter mean diameter (SMD). The Sauter Mean Diameter (D_{32}) is the diameter of a drop having the same volume to surface area ratio as the total distribution. The Sauter mean diameter can be thought of as the ratio of the particle volume to surface area in a distribution.

$$D_{32} = \frac{\sum_{i=1}^{N} f_n(D) D^3}{\sum_{i=1}^{N} f_n(D) D^2} \tag{1}$$

where $\boldsymbol{f_n(D)}$ 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 monodisperse or polydisperse. A monodisperse distribution is one in which the particles are close to a single size whereas polydispersed 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 distribution (sometimes referred as the 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 the probability density function (p.d.f.) 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 (c.d.f.) of a Normal random variable 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 or Gaussian distribution by replacing the independent variable with the logarithm of the particle diameter.

For a Log-Normal random variable the probability density function (p.d.f.) is

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

The cumulative distribution function (c.d.f.) 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, now, σ_O and μ_O are the standard deviation and the mean of the Log-Normal distribution.

Experimental Study

The experimental part of this study will be 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). These studies were conducted for horizontal and slightly inclined pipes and for vertical and deviated wells.

Experimental Facility and Flow Loop

The facility (Fig. 17) 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 there are 2 copper-tube type heat exchangers to 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 density of the fluids and with temperature transducers for monitoring the temperature of the fluids. Oil and water flow through filters after the metering section.

After the metering section, oil and water flow through the mixing tee at the inlet of the test section to form the oil-water two-phase flow. The current test section (See Fig. 18) consists of two 21.13-m (69.33-ft) long straight transparent pipes, connected by a 1.22-m (4.0-ft) diameter PVC bend. The upward branch of the test section consist of a 13.8-m (45.30-ft) long flow developing section (L/D = 272). This is followed by two short pressure drop measurement sections of 5.18-m (17.0-ft) and 3.35-m (11.0-ft) in length. These sections were combined to obtain a long pressure drop section. The test section was designed to provide a 5.49-m (18.0-ft) long trapping section (L/D = 108) and a 1.83-m (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.

The transparent pipes are instrumented to permit continuous monitoring of temperature, pressure, differential pressure and inclination angle. Quick closing valves and optical probes will be used to measure phase fractions and distributions.

Flow pattern identification and droplet size measurements will be performed by using a high speed video system. The video will be taken near the pipe wall. The images obtained will be logged into a computer and its analysis will be performed by using Image-Pro Plus 5.1 which is an image processing software allowing images enhancement and droplet size measurements.

The existing test section has been modified by replacing the temperature and pressure transducers from Validyne to Rosemount, and by adding an optical type multi-point probe to determine phase distribution and a conductivity type multi-point probe to obtain interface shape as well as phase distributions.

Use of hot film anemometry for measuring velocity distribution is still under investigation.

Data Acquisition

For data acquisition, Lab View ™ 7.1 will be used. The data acquisition program has been modified and adapted for Oil-Water studies.

Test Fluids

The fluids that will be used in the experiments consist of a refined mineral oil (Tulco Tech 80) and tap water. The same oil used by Keskin (2005) will be used in this study for maintaining the same fluid properties. The characterization of the oil has been performed in Chevron Lab. The physical properties of the oil are given below:

- 32.2 ºAPI 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 will be acquired at various conditions. Inclination angles used for the experiments will be 0°, and ±1.0º. Superficial oil and water velocities range from 0.025 – 1.8 m/sec. The oil and water flow rates will be chosen such that the flow pattern transition boundaries can be identified clearly. Moreover, large amount of data will be taken for the dispersed flow patterns to characterize the droplet size and phase distributions.

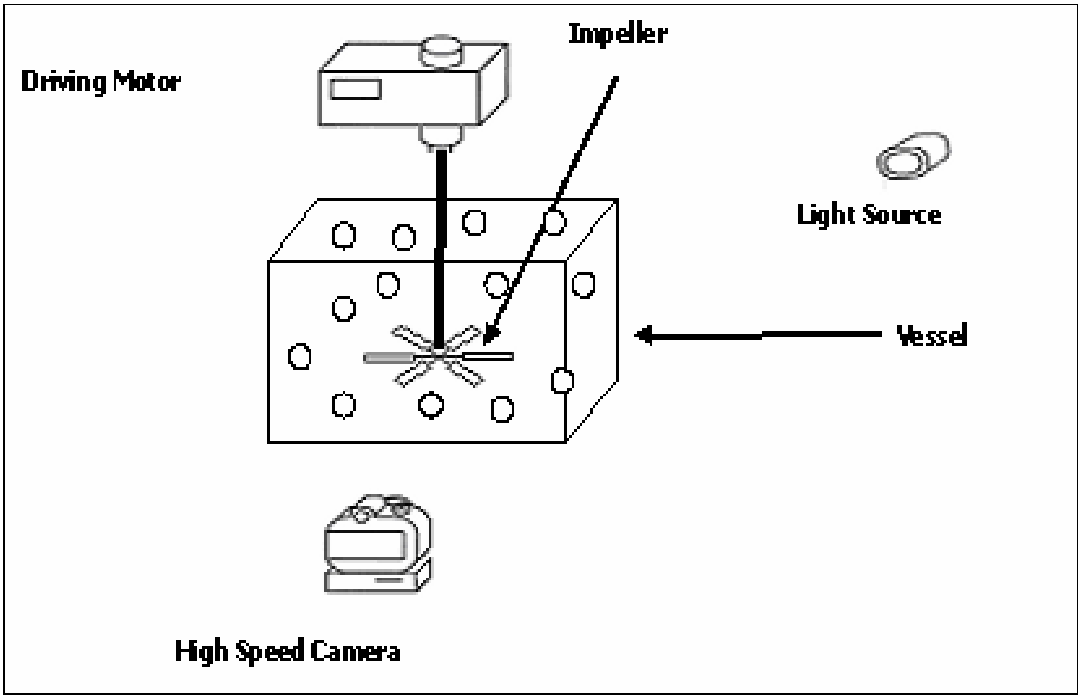

Figure 16 - Experimental Set-up for Measuring Droplets Dispersed in a Small Tank

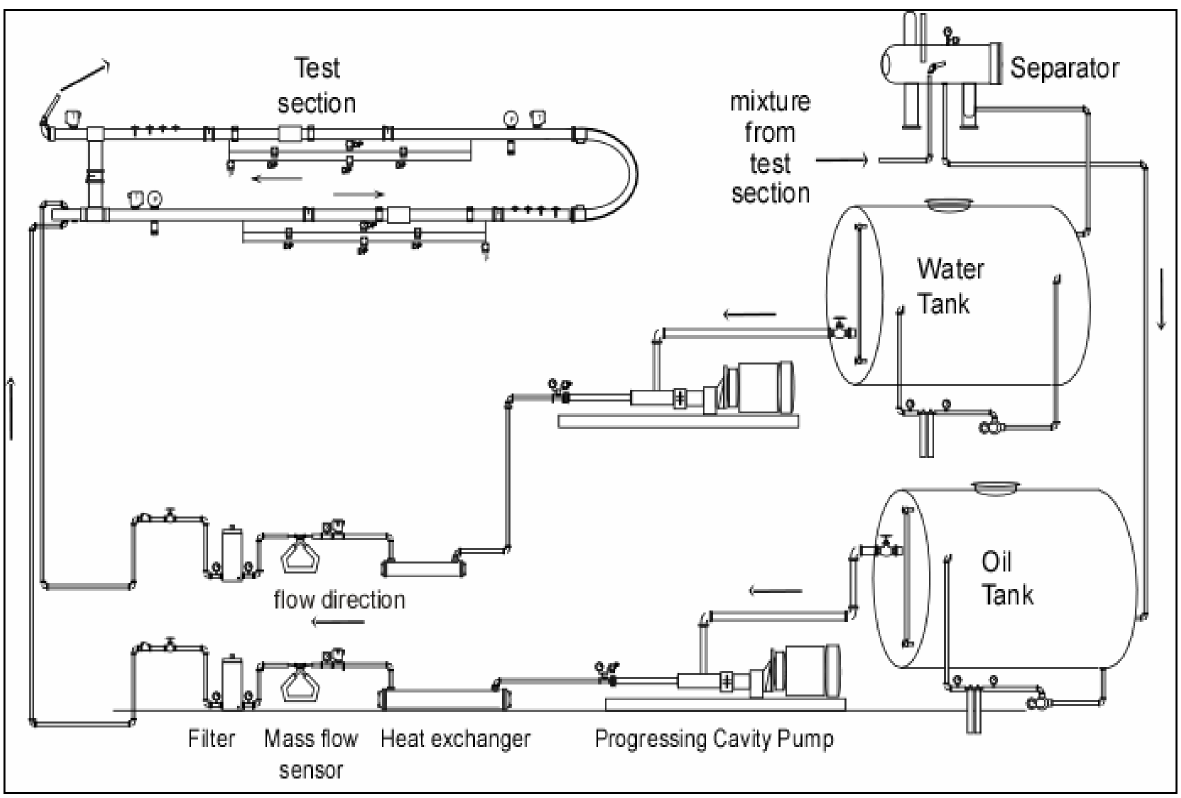

Figure 17 - Facility Schematic

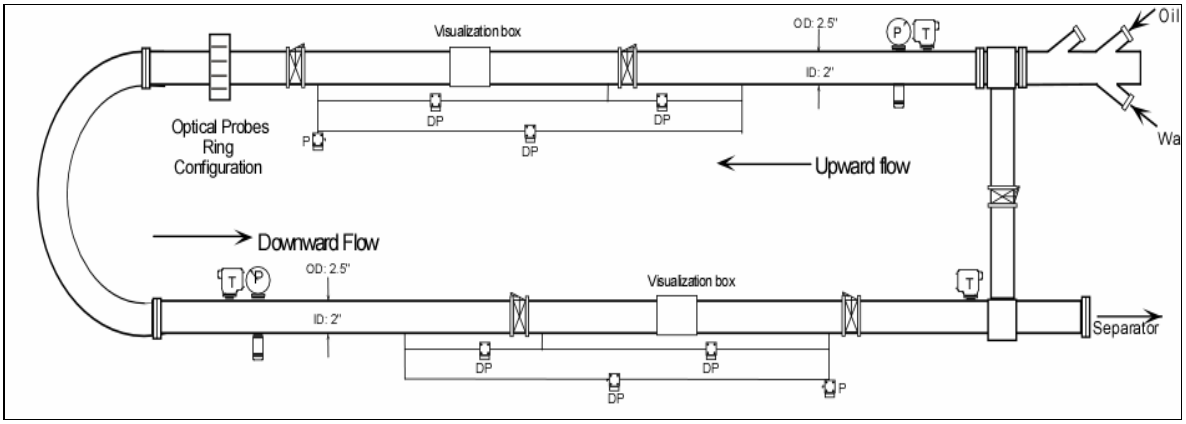

Figure 18 - Test Section Schematic

Modeling Studies

Gas-Oil-Water Flow in Horizontal 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.*, 2003b) 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.

Gas-Oil-Water Flow in Inclined Pipes

Objectives

The overall objective of TUFFP multi-phase flow studies is to develop a mechanistic model for gas-oil-water flow in pipes with different inclination angles. The objective of this study is to investigate the gas-oil-water flow behavior in inclined pipes and check experimental results against existing models.

Introduction

One of the common occurrences in the petroleum industry during transportation and production is gas-oil-water flow in pipes. Perhaps the most relevant and important application is transportation of gas-oil-water through pipelines. The other occurrences can be encountered in surface gathering lines, wellbore and gas lift wells. Actually, from many aspects three-phase flows are important in design of the pipelines and operation of the oil fields. Pressure gradient is directly related to the hold-up of each phase. Changes in pressure gradient will affect production rates. Flow assurance problems such as paraffin deposition and hydrate formation will directly be affected by the behavior of three-phase gas-oil-water flow. Moreover, erosion and corrosion will be influenced by the three-phase flow behavior.

Although three-phase gas-oil-water flow is really important, in past, there have been relatively limited experimental and theoretical modeling studies. This can be due to complexity of the flow phenomenon or uncertainty in predicting the behavior of gas-oil and oil-water interfaces.

Literature Review

Literature review and assessment study is currently underway. The following is a summary of the literature review to date. The literature review will be completed by June 2006.

Sobocinski (1995) conducted three-phase gas-oil-water flow experiments at atmospheric pressure. 114 three-phase flow experiments with pressure gradients and flow patterns were recorded. This set of experiment was one of the earliest studies on three-phase flows. It was proposed on his study to use smaller diameter pipe, longer test sections to see the flow behavior more clearly and collect more data.

One of the first researchers who were working on the three-phase gas-oil-water was Malinowski (1975). A total of 34 air-oil-water three phase experiments were conducted at pressure of 2 atm. The important note in his experiment was the percentage error in pressure loss predictions increased near the oil-water inversion points. The results measured were compared with the calculated ones by Beggs and Brill (1973) and Dukler et al (1964). The pressure drops were overestimated when water fraction was more than 0.5 and underestimated when water fraction was less than 0.5. The liquid viscosity was back calculated from measured pressure gradients. Then it was realized that the liquid viscosities were different from the calculated ones

After Malinowski (1975), Laflin and Oglesby (1976) conducted 79 air-oil-water three phase flow experiments and recorded the pressure gradients and flow rates. They plotted their data on flow pattern maps proposed by Beggs and Brill (1973) and Mandhane et al (1974). Then, it was realized that all the data they recorded was in the intermittent flow pattern. It was proposed that calculated flow patterns matched well with the previously stated flow pattern maps. On the other hand, not all the flow patterns were studied. Therefore, their recommendations were questionable.

Hall (1992) conducted three-phase gas-oil-water experiments by using the Water, Air, Sand and Petroleum (WASP) facility. The entire test conducted was in the slug region. Six different two-phase flow models and three different liquid mixture viscosity relations were used to estimate the pressure gradients. After some investigation the best match was achieved when Beggs and Brill’s (1973) two-phase model was used with Brinkman’s (1952) liquid viscosity relation. Hall (1992) solved set of equations numerically to obtain the liquid holdups. Some assumptions were made to solve the set of equations. As a result, good agreement with measured holdups was achieved for oil and water. On the other hand the pressure gradients did not agree well with prediction. It was claimed that this poor agreement in pressure gradient might be due to the instrumentation that was used. After conducting three-phase flow experiments, data were checked with Stapelberg’s (1990) data and reasonable agreement satisfied with the water and oil holdups. On the other hand more error occurred in the pressure gradient comparison. It was claimed that the reason for mismatching of the pressure gradient data might be due to distortion by the pipe walls in Stapelberg’s (1990) experiment.

Acikgoz et al. (1992) conducted an experimental study on three-phase gas-water-oil flows to determine the flow pattern. Based on the observations ten flow patterns were described for the horizontal flow and the flow regime map was constructed. The flow patterns can be summarized as follows:

- Oil-Based Dispersed Plug Flow
- Oil-Based Dispersed Slug Flow
- Oil-Based Dispersed Stratified/Wavy Flow
- Oil-Based Separated Stratified/Wavy Flow
- Oil-Based Separated Wavy Stratified Annular Flow
- Oil-Based Separated Stratifying-Annular Flow
- Water-Based Dispersed Slug Flow
- Water-Based Dispersed Stratified/Wavy Flow
- Water-Based Separated/Dispersed Incipient Stratifying-Annular Flow

- Water-Based Dispersed Stratifying Annular Flow

Neogi et al. (1994) proposed a mechanistic model for gas-oil-water stratified flow in order to calculate the liquid film heights. The same momentum balance equation was used as in Hall (1992). The hydraulic diameter concept and interfacial friction factor which was suggested by Brauner (1991) were used. As a result, two cases were proposed for friction factors for a certain v_{SG} value. Good agreement was found with the experimental data but no further comparison was done with the other set of data.

Stapelberg and Mewes (1994) worked on the three-phase gas-oil-water flow in two different facilities. Dukler and Hubbard (1975) and Aziz et al. (1978) two-phase flow prediction methods were used to estimate pressure gradients. Good agreement against predicted flow rate was reached for low air volume velocities but not for high air volume velocities.

Taitel et al. (1995) used the similar approach by Neogi et al. (1994) and reached similar solution. The difference in their study was the approach to friction factors (f_{GO} and f_{OW}). For the gas-oil friction factor Taitel et al. (1995) suggested using the f_G or a constant value that had been proposed by Cohen and Hanratty (1968). Also for the oil-water friction factor it was suggested using the f_O or a constant value. After solving set of equations numerically, based on the previous assumption, the liquid heights (h_L) were determined. There are multiple solutions for the liquid heights. They chose the smallest solution, as Barnea and Taitel (1922) suggested to maintain the stability of the multiple solutions.

Pan (1996) conducted more than 1000 three-phase flow experiments. The flow patterns, pressure gradients and phase holdups were determined. He suggested a three-part or two-part approach to determine the flow pattern. In the first part the flow was defined as dispersed and separated. If the flow was dispersed then it was continued with the second part which was oil continuous or water continuous. If the flow was separated it was continued directly to the third part which was gas-liquid relationships. Oil-water relationship, liquid-wall relationship and gas-liquid relationship can be counted as the three parts of the approach to determine the flow pattern. Theoretically, 15 different flow patterns can be achieved but from the experimental observation, he concluded 8 different flow patterns. These can be summarized as follows:

- Separated Slug Flow
- Dispersed Water Continuous Slug Flow
- Dispersed Oil Continuous Slug Flow
- Separated Stratified Flow
- Dispersed Oil Continuous Stratified Flow
- Dispersed Oil Continuous Annular Flow
- Dispersed Water Continuous Stratified Flow
- Dispersed Water Continuous Annular Flow

Khor (1998) conducted three-phase gas-oil-water flow experiments in WASP facility with horizontal and downward inclined flow. He determined new flow patterns for the stratified gas-oil-water flow. The flow patterns for stratified gas-oil-water flow were divided into 9 categories. These flow patterns can be summarized as follows:

- Stratified Smooth
- Air-Oil Stratified Wavy, Oil-Water Stratified Smooth
- Air-Oil Stratified Smooth, Oil-Water Stratified Wavy
- Air-Oil Stratified Wavy, Oil-Water Stratified Wavy
- Air-Oil Stratified Smooth, Oil-Water Partially Mixed
- Air-Oil Stratified Wavy, Oil-Water Partially Mixed
- Stratified Wavy with Oil-Water Upper Tube
- Oil-Water Fully Mixed, Oil Dispersed in Water Continuous Phase
- Oil-Water Fully Mixed, Oil Dispersed in Oil Continuous Phase

Khor (1998) developed a computer program (PRESBAL) to solve the momentum equations. Pressure gradient was solved by assuming a value for liquid height and different values for the water height. The water height should be in the range of $0.05h_L$-$0.95h_L$. This program has a good agreement on holdups with Taitel et al. (1995). On the other hand, this program was underestimating WASP data and overestimating the Sobocinski's data. This computer program has some advantages such as having reliable convergence, flexibility of using different shear stress relationships, adjusting the desired accuracy level and having flexibility to choose hydraulic parameters. By using these different shear stress relationships, he had good agreement for pressure gradients for horizontal data. Average percentage difference between measured and calculated results was around 4% for high pressure flow. On the other hand it was around 15% for low pressure flow. The model did not show very good agreement with inclined data in terms of hold-ups and pressure gradients. It was claimed that similar evaluation for the inclined stratified three-phase flow might give better results.

Zhang et al. (2003) proposed a unified model for gas-liquid two-phase flow. The model is based on the slug dynamics. It is proposed that similar methodology can be applied to gas-oil-water three-phase flow in Zhang et al. (2005). Gas-liquid flow pattern and oil-water mixing status are the most important parameters that determines the flow behavior in three-phase flow. The two-phase models can be applied to the three-phase gas-oil-water flow if only two liquids are fully mixed or there is three-layer-stratified flow at low flow rates. Usually most of the flow patterns for the three-phase flow are between these two extreme patterns. Zhang et al. (2005) applied two-phase unified model for describing the three-phase gas-oil-water flow. Additional closure relationships have been applied between the liquid phases.

Oil-Water Flow in Horizontal Pipes and Slightly Inclined Pipes

The idea conceived for this study is to try to simplify the classification of the flow patterns in oil-water flows. Three different flow patterns are proposed: (See Figure 19)

- Segregated Flow.
- Dual Continuous Flow.
- Fully Dispersed Flow.

Efforts will be made to develop a model to predict the average droplet diameter. New transition boundaries based on local fractions of the dispersed phase (water or oil) and superficial velocities for each phase will be proposed as a criterion for the determination of the oil-water mixing status in pipes.

An analysis of the turbulent energy as well as the free surface energy and gravitational potential will be the basis of this modeling approach. Data on droplet size, phase distribution and in situ velocities will be used to validate the models developed.

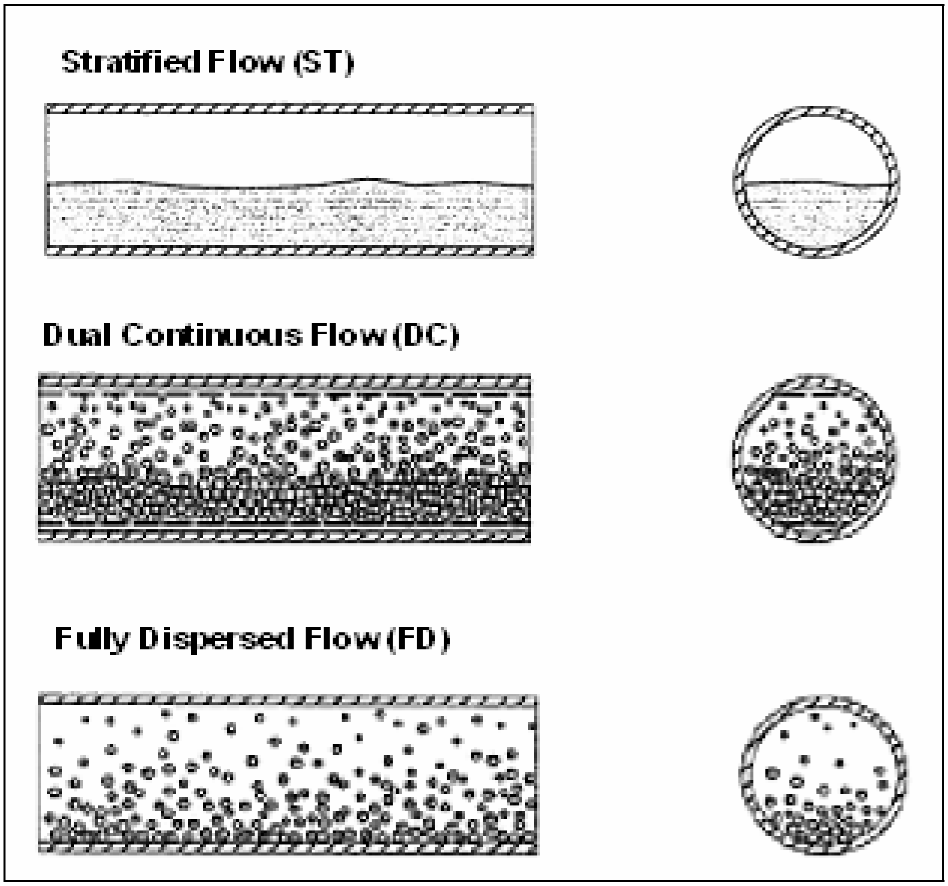

Figure 19 - New Flow Pattern Classification

Results and Discussions

Gas-Oil-Water Flow in Horizontal Pipes

Closure Relationships

Oil-Water Mixing

The mixing status of the two liquids must be predicted to determine whether the three-layer stratified model should be used or whether the two liquids should be treated as a single phase. The transition boundaries to dispersed liquid-liquid flows may be used. A criterion for the transition to dispersed flow in liquid-liquid systems was proposed and presented at the TUFFP ABM on March 2004 (Keskin, 2004). This transition criterion was applied to the gas-oil-water flow data acquired in this study. Results are given in Fig. 20.

Translational Velocity and Slug Length

The translational velocity of the liquid slugs for gas-liquid two-phase flow is expressed by Nicklin (1962) as a function of mixture velocity, v_S ,

$$v_T = C_S v_S + v_D \qquad (1)$$

Where v_D is the drift velocity and C_S is a coefficient approximately equal to the ratio of the maximum to the mean velocity of a fully developed velocity profile. A value of 2 for laminar flow and 1.2 for turbulent flow can be used for C_S. Nicklin's correlation is compared with the translational velocities obtained by analyzing the data from the capacitance sensors in Fig. 21. The total of gas, oil and water superficial velocities was used as mixture velocity in the correlation. Although the correlation was proposed for gas-liquid two-phase flows, the prediction of the translational velocities for gas-oil-water flow is quite good.

Based on the analyses of Taitel *et al.* (1980), an average slug length of 32d has been used for horizontal flows at relatively small pipe diameters. For this study 32d is equal to 1.626-m. The average slug length obtained from the analysis of capacitance sensors data is 1.675-m which is very close to 32d.

Physical Properties of Liquid Mixture

The liquid phases can be treated as a pseudo-single-phase when they are fully mixed. In that case, the physical properties of the mixture can be obtained based on the phase fractions and knowledge of the continuous phase.

For instance, the mixture density can be calculated as the volumetric average value of the densities of the two liquid phases,

$$\rho_m = \rho_w F_w + \rho_o (1 - F_w) \qquad (2)$$

where ρ_w, ρ_o and ρ_m are the densities of water, oil and the liquid mixture, respectively, and F_w is the water volume fraction in the liquid mixture. The surface tension of the continuous phase can be used as the surface tension of the mixture if the gas phase is only in contact with the continuous phase.

For the viscosity of the liquid mixture, many correlations, based on the continuous and dispersed phase viscosities and phase fractions, are available in the literature. One of those is Brinkman's (1952) correlation,

$$\frac{\mu_m}{\mu_c} = (1.0 - F_d)^{-2.5} \qquad (3)$$

where μ_m and μ_c are the viscosities of the mixture and the continuous phase, respectively and F_d is the volume fraction of the dispersed phase.

Wetted Wall Fractions and Interfacial Perimeters

The wall fractions wetted by oil and water must be predicted to solve the basic equations. The interfacial perimeters between gas and liquid, and between oil and water are needed as well. These parameters can be developed by modifying the gas-liquid two-phase closure relationships based on experimental observations.

An explicit expression is proposed to estimate the gas-liquid interfacial perimeters,

$$S_{I1} = \frac{(S_W + S_O)(A_{CD} - A_O - A_W) + S_{CD}(A_O + A_W)}{A_{CD}} \quad ....(4)$$

where S_O and S_W are wall perimeters wetted by oil and water, respectively. S_{CD} is the chord length corresponding to the wetted wall fraction, and A_{CD} is the cross-sectional area embraced by the wetted wall and its chord, as shown in Fig. 22. Similarly, the oil-water interfacial perimeter can be estimated based on the perimeter wetted by water and the water holdup.

Interfacial Shear Stress

A new unified approach for the modeling of interfacial shear stress between different phases based on the turbulent mixing-length theory was proposed by Zhang (2005) and presented at the Advisory Board meeting in October 2005. This model can be used at various inclination angles not only for stratified and annular flow interfacial shear stresses but also for multiphase flows without a clear interface such as oil-water flow with mixing at the interface.

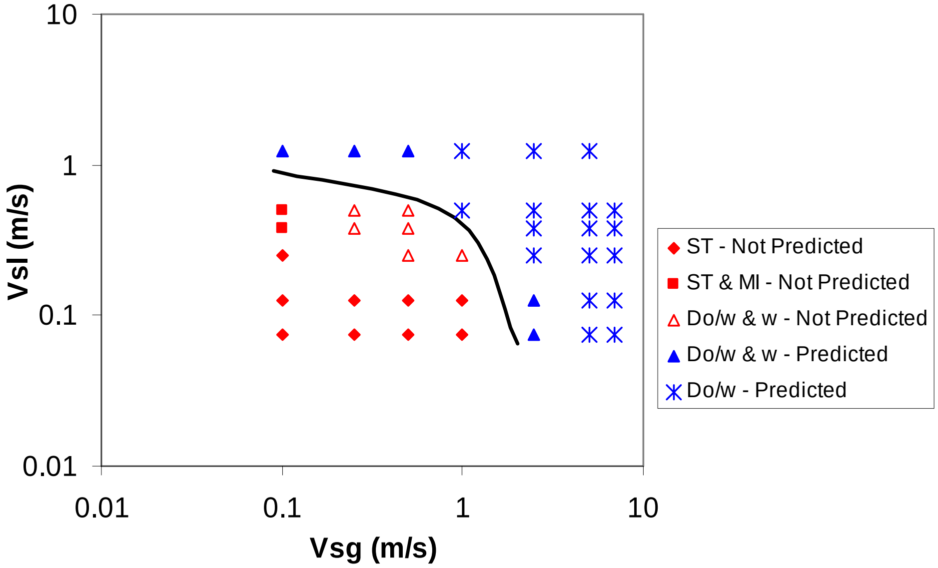

Figure 20 – Oil-Water Mixing Criterion Comparison with 80 % WC Data

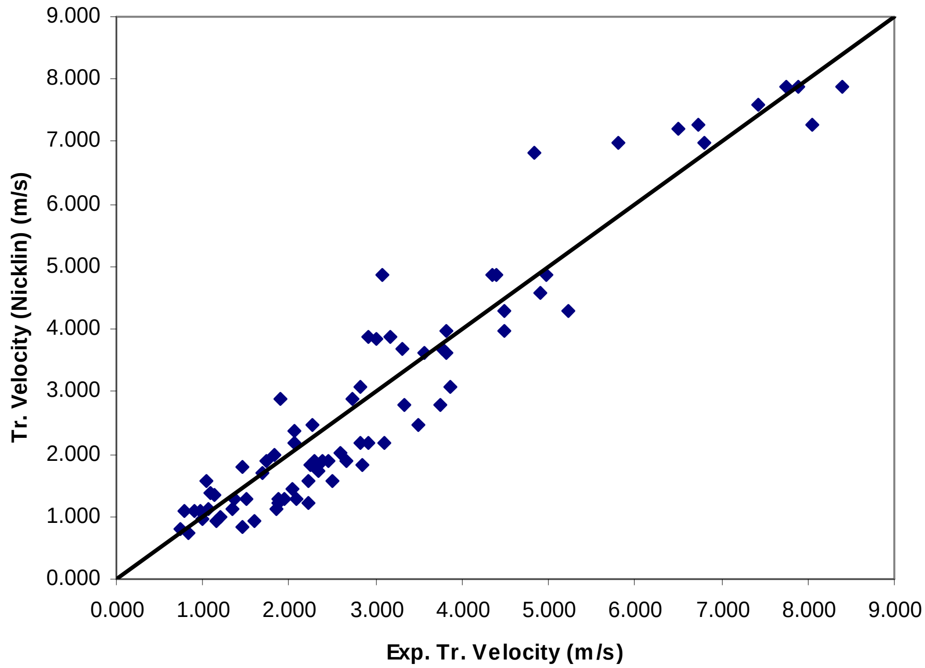

Figure 21 – Comparison of Translational Velocities from Nicklin's Correlation and Experimental Data

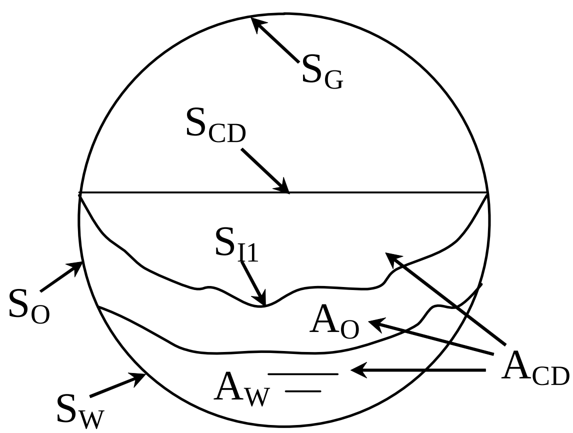

Figure 22 – Cross Section of a Stratified Three-phase Flow with Curved Interface

Photographic measurements were made for oil in water mixtures of 2%, 4%, 10%, 20% and 30% of oil volume content and for water in oil mixtures of 10%, 20% and 30% of water volume content.

The image for 10% of oil in water is shown in Fig. 23. The results for its droplet size analysis are demonstrated in Figs. 24a and 24b where the Normal Distribution p.d.f and c.d.f as well as the Log-Normal Distribution p.d.f and c.d.f are shown. Similar analyses were performed for the rest of the images up to 30% of oil in water.

From 30% to 70% of oil content, measurements were not reliable because the droplets in the dispersion (O/W or W/O) were too dense that they overlaped each other rendering the droplet images indistinguishable. Although video image analysis is a very effective and non-intrusive technique for measuring droplet sizes it has its limitation at high volume percentage of dispersed phase.

The image for 70% of oil content is shown in Fig. 25 and the results for its droplet size analysis are plotted in Figs. 26a and 26b where the Normal Distribution p.d.f and c.d.f as well as the Log-Normal Distribution p.d.f and c.d.f are shown. Similar analyses were performed for the rest of the images corresponding to water contents less than 30%.

The Sauter mean diameter values for the dispersions of oil in water and water in oil are shown in Table 1.

Table 1. Sauter Mean Diameters at Different Water Cuts

% O/W	D32 (mm)
2	1.06
4	0.92
10	1.82
20	2.42
30	1.53
% W/O	**D32 (mm)**
30	1.13
20	1.16
10	1.29

Figure 23 - Photographic Image for 10% of Oil in Water

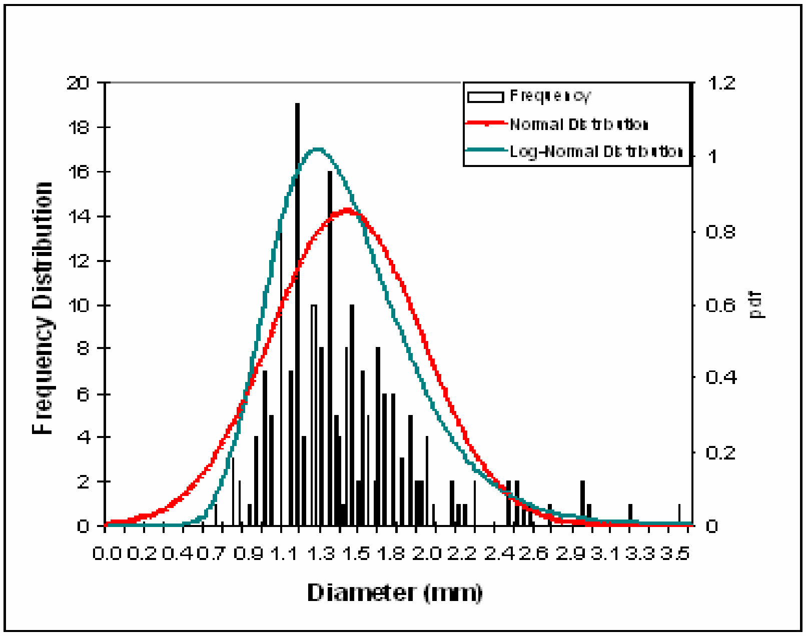

Figure 24a - Probability Distribution Function for Drop Diameter (10% O/W)

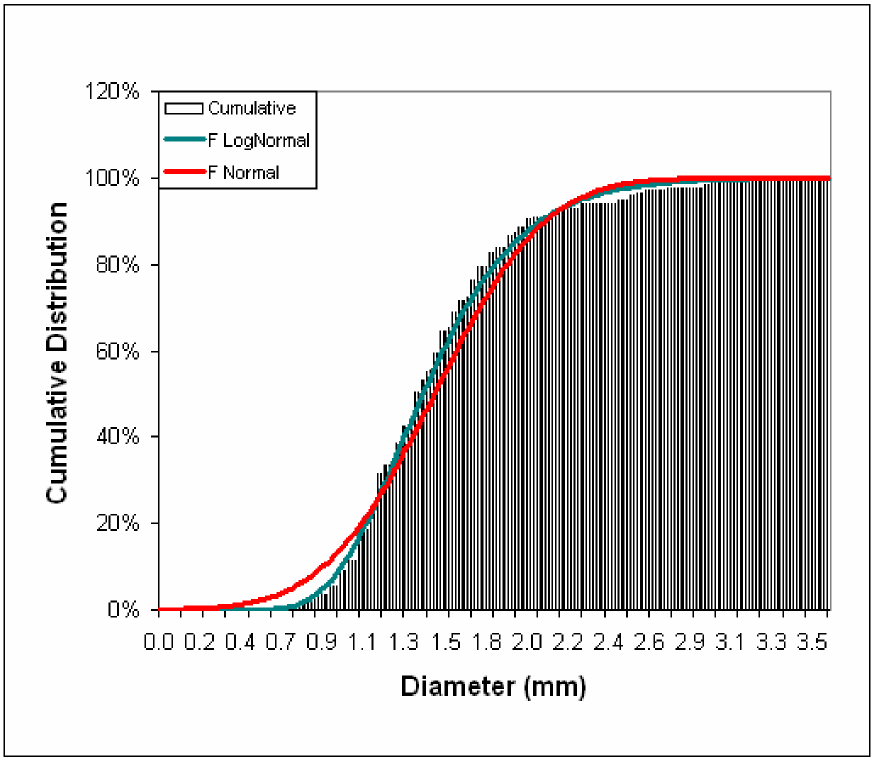

Figure 24b - Cumulative Distribution Function for Drop Diameter (10% O/W)

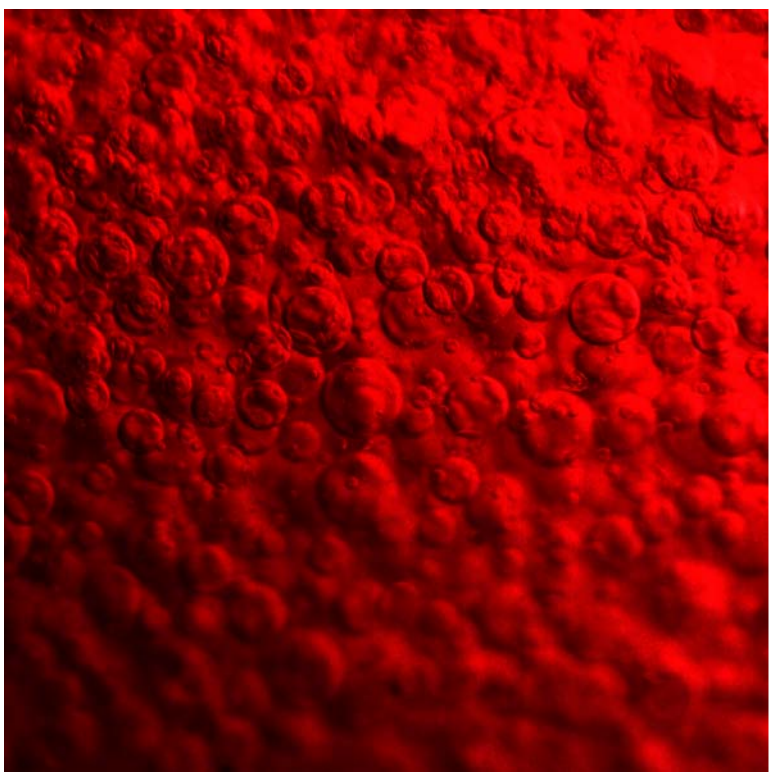

Figure 25 - Photographic Image for 70% of Oil in Water

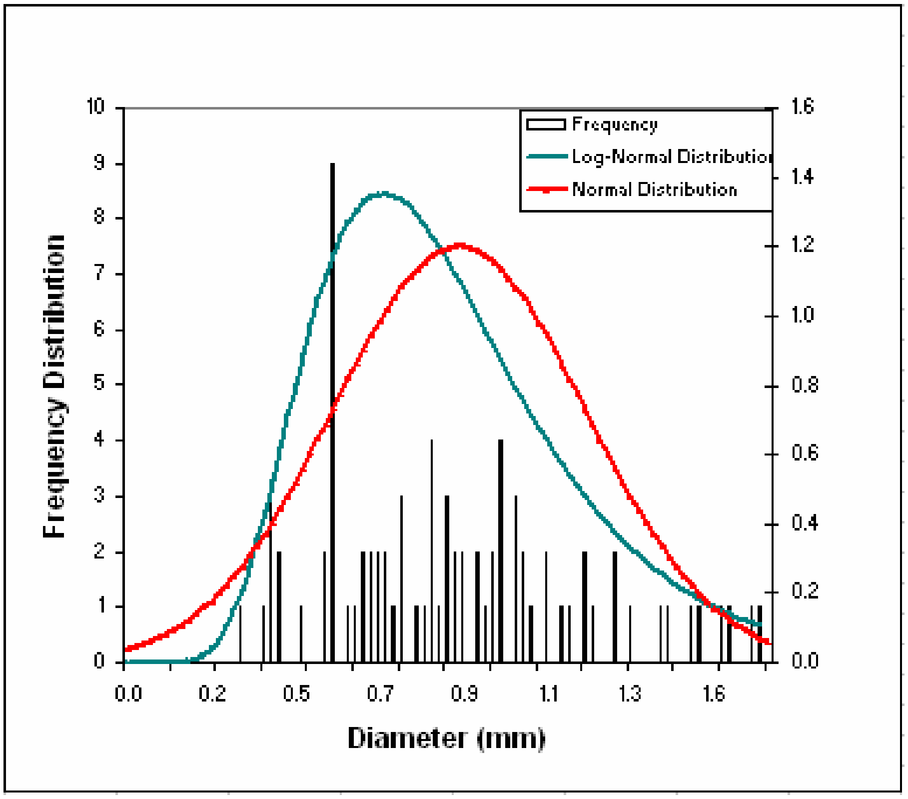

Figure 26a - Probability Distribution Function for Mean Drop Diameter (70% W/O)

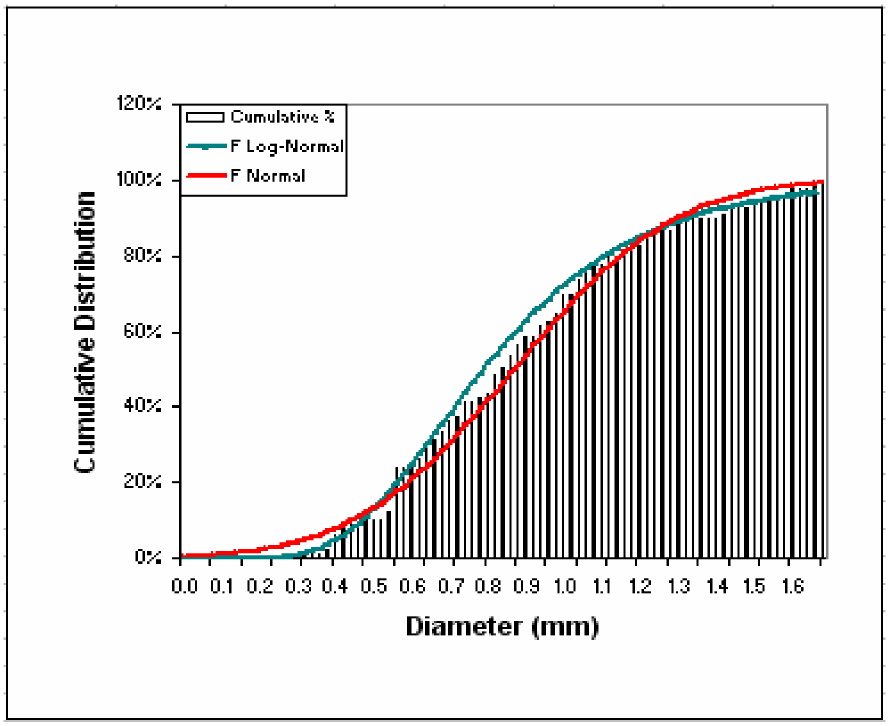

Figure 26b - Cumulative Distribution Function for Drop Diameter (70% W/O)

Conclusions

A unified model of gas-oil-water flow for all inclination angles was developed. The model requires several closure relationships.

Three-phase gas-oil-water studies for horizontal configuration is near completion. Experimental studies are completed. Flow patterns are identified and a new classification is proposed.

Most of the three-phase gas-oil-water flow closure relationships require the information on oil-water flow. Therefore, an oil-water flow study has been initiated. Preliminary experimental work has been completed in this period.

A detailed literature search has been conducted for inclined pipes and deviated wells indicting a lack of comprehensive knowledge in three-phase gas-oil-water flow in inclined pipes and deviated wells.

Near future tasks include the following:

- Compare the horizontal gas-oil-water data with the interfacial shear model based on mixing length theory.
- Develop a three-layer, interfacial sheer model for horizontal configuration.
- Compare all the horizontal configuration data with the unified gas-oil-water model.
- Acquire data for oil-water horizontal and inclined flow and develop closure relationships.

Nomenclature

A	Cross-sectional area
C_S	Constant (Dimensionless)
F	Volume fraction
S	Wall perimeter
v	Velocity
μ	Viscosity
ρ	Density

Subscripts

c	Continuous phase
CD	Chord
d	Dispersed phase
D	Drift
m	Mixture
o	Oil
T	Translational
w	Water

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