STUDIES ON OIL-WATER FLOW IN INCLINED PIPELINES

A Thesis Presented to
The Faculty of Russ College of Engineering and Technology
Ohio University

In Partial Fulfillment
of the Requirement for the Degree
Master of Science

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March 1999
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Variation of water layer height with mixture velocity
(96 cP oil in horizontal pipes)
CHAPTER I
INTRODUCTION

The occurrence of two phase and three phase flows in pipelines is very common in the petroleum industry. The wide spread existence of multiphase flow has prompted extensive research in this area. Two phase flows in pipelines can be classified as: (1) gas-liquid flow, (2) liquid-liquid flow (3) gas-solid flow and (4) liquid-solid flow. Most of the work done in horizontal pipes has been for gas-liquid flow. In comparison to gas-liquid studies, there is a lack of adequate understanding on the flow and mechanisms of liquid-liquid flows. The flowing mixtures of two immiscible liquids are frequently encountered in the design of a variety of practical equipment. For example, studies have been carried out to understand the reduction in apparent viscosity of heavy crudes by addition of less viscous liquid which is usually water. Reduction in viscosity reduces the pressure gradient and the viscous liquid can be transported at a higher rate as a two-phase flow rather than as a single component, under conditions of equal pressure drop.

A homogenous flow pattern of an oil-water mixture could lead to formation of an emulsion leading to a complicated rheological behavior. Vast difference in pressure gradients are encountered depending on the flow pattern. Another phenomenon that further complicates an oil-water dispersion system is the phase inversion phenomenon, in which the dispersed phase switches to the continuous phase. The phase that coats the pipe wall is called the "continuous" phase or the "dominant" phase and the other, mixed in the continuous phase, is the "dispersed" or the "internal" phase. It is highly desirable in pipeline design to be able to accurately predict this phase inversion point for the flowing oil-water system, since the
pressure drop in the pipeline could greatly differ between an oil-in-water and a water-in-oil systems.

Maturing oil wells produce more and more sea water and natural gas containing carbon dioxide. This leads to a corrosive multiphase mixture of saltwater-oil-carbon dioxide in the pipelines. It is very important always to study the two phase oil-water flow since the presence of an external water phase does lead to these corrosive environments. The presence of a free water phase also leads to hydrate formation resulting in a blockage of pipe line. At low water cuts, a water-in-oil dispersion is observed. As the water cut increases water break out may occur leading to flow of a separate layer of water and at higher water cuts phase inversion may occur.

With increase in the life time of a well the water cut observed will increase. At lower water cuts, corrosion may not be observed. But at higher water cuts significant corrosion rates are observed. Most of these multiphase pipelines are located in remote areas. Therefore, repair, maintenance, clean up or replacement costs are extremely high. Further, most of these pipelines run several hundred miles. Hence the use of corrosion resistant pipe materials is not economically feasible. Use of corrosion inhibitors is an important method to curb corrosion and is currently being studied.

Corrosion inhibitors are substances containing organics that adsorb to the metal surface and form a protective film to prevent corrosion. The effectiveness of the inhibitor depends on the pipeline material, the inhibitor composition and the type of flow. It is necessary to introduce the inhibitor into the phase in contact with the pipe wall and this can be accomplished only if flow patterns and phase distributions under different conditions are
known. This will enable researchers to decide whether to use oil or water-soluble corrosion inhibitors, under different conditions and different flow patterns.

Oil-water flows can be broadly classified into two principal flow patterns, namely stratified (oil and water as separate layers) and mixed (the oil and water mixture flows as dispersion). As the transition occurs from stratified to completely mixed flow, many interim flow patterns are observed. A detailed description is given below.

The flow regimes were observed by Oglesby (1979) for three experimental oils and are shown in Figures 1.1(a) and (b) and Figure 1.2 for the oils described above. The oils had viscosities of 167 cP, 61 cP and 32 cP respectively.

For liquid velocities up to 0.25 m/s, the flow is stratified. The oil and water layers flow as two distinct phases, with no mixing at the interface. As the mixture velocity is increased, some mixing occurs at the interface giving rise to semi-segregated flow (regime B). The other flow regimes in Figure 1.2 are separated by a darkened line which represents the phase inversion point. The flow is said to be semi-mixed (Regime's C and K, Figure 1.1(a)) when there is a segregated flow of a dispersion and a 'free' phase and the dispersion volume is less than half the total pipe volume. The region's C and K in Figure 1.2 depict the semi-mixed flow regime with the oil and water as dominant phases, respectively. Mixed flow occurs when the oil-water dispersion occupies more than half the pipe volume and is observed to occur in the regions D and L for the oil and water dominant phases, respectively. Annular flow develops when there is a core of one phase within the other phase and this regime is marked G on the map. At high mixture velocities the flow pattern is semi-dispersed and with
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<td>Water Dominant</td>
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<th>Segregated - no mixing at the interface</th>
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<th>Semi-segregated - some mixing at the interface</th>
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<th>Semi-mixed - segregated flow of a dispersion and &quot;free&quot; phase. Bubbly interface. Dispersion volume less than half the total pipe volume.</th>
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<td>C [K]</td>
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<td>Example: oil-in-water dispersion with a &quot;free&quot; oil phase [D] [L]</td>
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<th>Mixed - same as the above coding but with the dispersion occupying more than half the total pipe volume.</th>
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<td>D [L]</td>
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<td>Example: oil-in-water dispersion with a &quot;free&quot; oil phase [D] [L]</td>
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Figure 1.1 (a) Description of Flow Pattern Classifications for Oil-Water Flows (Oglesby, 1979)
Flow Direction → FLOW PATTERN CODE

Oil Dominant Water Dominant

Annular of concentric - core of one phase within the other phase

Example: water core in an oil layer

Slug - phases alternately occupying the pipe volume as a free phase or as a dispersion

Semi-dispersed - some vertical gradient of fluid concentrations in the mixture.

Fully dispersed Homogeneous flow.

Figure 1.1 (b) Description of Flow Pattern Classifications for Oil-Water Flows (Oglesby, 1979)
Figure 1.2 Flow Pattern Map for Two-Phase, Oil-Water Flows (Oglesby, 1979)
further increase in velocity the flow pattern is homogeneous. In semi-dispersed flow a steep concentration gradient is observed and in homogeneous flow the gradient is vertical.

The various factors affecting the flow pattern and oil-water distribution across the pipe cross section are the input mixture velocity, the viscosity of the oil, the input water percentage and the pipe inclination. Limited studies on oil-water flows in inclined pipes have always been carried out in the past. Current trend in oil production is characterized by deep waters, smaller oil fields with thin oil layers, increased free water production and development of horizontal and branched wells to easily penetrate larger areas of the reservoir. In oil production from horizontal and deviated wells flow through inclined pipes is common (Figure 1.3). Deep water production would involve transportation of oil-water mixtures from the well head to a central gathering station or to a platform. The terrain is not flat and flow through inclined pipes are encountered. Oil-water mixtures may sometimes be transported through hilly terrain as well. Inclination may lead to more mixing of the oil-water mixture and flow patterns, phase distributions and pressure drop will be affected.

The literature survey conducted found studies in liquid-liquid flow generally lacking in depth and especially with regards to effects of pipe inclination. The presence of gravity driven buoyancy forces may lead to large slippage between the oil and water layers leading to an increased holdup of water in the pipes. Failure to account for slippage could lead to improperly designed separators. Further, back flows within the water layer could also be present challenging production logging measurements. Production logging tools provide an accurate measurement of density, velocity and hold up at the point of measurement. However, extrapolation to entire pipe cross-section could result in inaccurate measurements. So it was
Figure 1.3 Schematic of a subsea processing facility
deemed essential that this study of two phase liquid-liquid flow should undertake an examination of liquid-liquid flow fundamentals with primary emphasis on flow regime and holdup evaluation at various pipe inclinations.

Flow patterns are to be defined through visual observation. An important objective is to study the variation of holdup across the cross-section along the vertical diameter. Holdup (of water) is defined as the ratio of the volume of water to the total volume of the liquid at the point of examination. In stratified flow, holdup is the fraction of the cross section area occupied by water and hence is a measure of the in situ velocities of the two fluids.

Modeling in oil-water flows currently relies on simple homogeneous liquid mixtures for design calculation. Correlations have also been proposed in the past to predict pressure drop and holdup based on experimental results obtained using oils of different viscosities. Two phase gas-liquid flows have been successfully analyzed using mass and momentum balance equations. Similar approaches to describe liquid-liquid flow have been carried out only to a limited extent. The final objective is to develop a mechanistic model to predict the holdup, pressure drop and in situ velocities of the different phases in stratified, semi-stratified, and semi-mixed flow regimes in horizontal and inclined pipes.

The current study would help understand the effect of various parameters on phase distribution and hence help in the choice of corrosion inhibitors to be used when seawater is present as the second phase. Further, prediction of corrosion rates in oil-water flows requires knowledge of the in situ velocity of the water layer to predict mass transfer coefficient. The mechanistic model developed serves this purpose.
CHAPTER 2

LITERATURE REVIEW

In spite of their clear practical relevance comparably few basic studies have been devoted to oil-water flows in inclined pipes. Most studies deal with small diameter horizontal or vertical pipes carrying mixtures of water and oils of various viscosities, together with the transport of oil-in-water emulsions.

2.1 Two phase horizontal flow

Russel et al. (1959) studied oil-water flow in a transparent horizontal pipeline, using white mineral oil with a viscosity of 18 cp at 77°F. They found three distinct flow patterns: bubble flow, stratified, and mixed.

Charles et al. (1961) defined four flow patterns in their equal density oil/water flow in 2.5 cm pipes: water droplets in oil, concentric water with oil flowing in the core, oil slugs in water, and oil bubble in water. Three different oils (viscosity 6.29, 16.8 and 65 cp) were used in their studies. They found that the resulting oil-water flow patterns were mostly independent of the oil viscosities.

Oglesby (1979) studied flow patterns of oil/water mixtures in small diameter horizontal pipes. He used a mixture of SN-250 and Diesel oil No.2 and mixed the oils in order to obtain a range of viscosities for his experiments, conducted in a 3.8 cm internal diameter pipe. Flow regimes from segregated to homogeneous were observed with an increase in mixture velocity. Oglesby also reported a slug-flow pattern near the point of inversion. There was a drastic change in the pressure drop at the inversion point and the
magnitude of this change increased with the increasing mixture velocity and oil viscosity. Figures 1.1(a) and 1.1(b) show the flow patterns obtained by Oglesby.

Malhotra (1995) has reported three distinct flow patterns (bubble, semi-segregated and semi-mixed) for LVT 200-water mixture. Figure 2.1 shows the flow patterns observed by Malhotra. Bubble flow is observed for a mixture velocity in the range 0.4 to 0.6 m/s and an input oil percentage less than 10%. Semi-segregated flow is observed for an oil cut above 20% and mixture velocity in the range 0.4 to 0.8 m/s; above 0.8 m/s semi-mixed flow is observed. The volume occupied by the oil/water dispersion increases with an increase in mixture velocity. For velocities greater than 1.4 m/s almost homogenous mixture is obtained. Extensive work on the variation of water percentage across a pipe cross section for two different oils (viscosity 2 cp and 100 cp) in horizontal pipes was also done.

For the high viscosity oil, not much mixing was observed at the interface. The viscous oil layer held up in the pipe occupying a much greater cross section than that calculated based on the input water cut. This results in a slow-moving oil phase and the compressed water phase at the bottom travels at a very high velocity. The in situ water layer velocity was three times the mixture velocity for certain water cuts. The increased water layer velocity leads to higher corrosion rates.

2.2 Two phase inclined flow

Mukherjee et al. (1981) studied the effect of inclination on pressure drop and water holdup for inclinations ranging from ±30° to ±90° from the horizontal in a 1.5 inch diameter pipe. Diesel fuel and water were the fluids used. Figure 2.2 shows a comparison of the in situ
Figure 2.1 Flow patterns observed in horizontal oil-water flow in large diameter pipelines (Malhotra, 1995)
Figure 2.2 Comparison of input water cut to the in situ water holdup at various inclinations (Mukherjee et al., 1988)
holdup to the input water cut for various inclinations at a mixture velocity of 2.12 ft/sec as observed by Mukherjee. The water phase being denser, buoyancy causes slippage of oil past the water layer in upward flow and the reverse in downward flow. It was found that maximum slippage occurred at -30° the smallest inclination angle studied. Based on their studies they recommended that further studies need to be carried for an inclination angle between +30° and -30° as maximum slippage might be observed in that range.

Scott (1985) studied the flow of a mixture of water and mineral oil (Soltrol 130) in upward inclined pipes. The experimental system used allowed for a variation in inclination from horizontal to 30 degrees, and flow rates from 0 to 1400 barrels per day of the combined liquid. The physical phenomenon studied were flow regime occurrence and holdup, as a function of flow rate and pipe inclination. For horizontal pipes, the flow regimes observed were: stratified smooth, stratified wavy, bubble flow stratified and bubble flow massive. In inclined pipes, rolling wavy countercurrent, rolling wavy concurrent, bubble flow stratified and bubble flow massive were the flow patterns observed. Figure 2.3 shows the flow pattern observed in inclined pipes.

In inclined pipes, at low water flow rates with medium oil flow rates, the interface seemed to move through a large height range, at times approaching the top or the bottom of the pipe, almost forming a type of slug flow pattern that has been observed in gas-liquid flow. If the general direction of the flow is from right to left a counterclockwise circular motion within the oil phase was observed from the top to the bottom of the phase. The water close to the oil-water interface moves concurrently with the oil as it flows up the pipe. However, towards the bottom of the pipe, gravity and frictional effects overcomes the flowing
Figure 2.3 Flow regimes in 15° upward inclined pipes (Scott, 1985)
(a) Rolling Wavy Counter Current Flow (b) Rolling Wavy Co Current Flow (c) Bubble Flow Stratified
(d) Bubble Flow Massive
momentum of the water, resulting in the fall back of the water phase at the base of the pipe. This was the rolling wavy countercurrent flow. The rolling wavy concurrent flow regime generally developed at medium flow rates of the water and oil phases. The physical processes seen to occur were those observed for countercurrent flow with the only difference being that the water phase does not fall back at the base of the pipe, but flowed concurrently with the oil phase.

The segregated flow patterns seem to be replaced by the rolling wavy regimes, when inclinations increase from horizontal to the angles that were studied. The opposite effect was observed when the inclination decreased. The change in flow regime transition lines when proceeding from 15 to 30 degrees shows the rolling wavy regimes increasing in size. The dependency of these regimes upon the effect of gravity explained this increase. As inclination was increased, the effect of gravity effects tended to act upon the fluid more parallel to the pipe, but against flow, thus increasing the rolling motion of the phases (i.e., generating more of a fluid fall back effect).

Scott also studied the holdup as a function of the flow pattern. Holdup was defined as the in situ volume fraction of water over a known section of the pipe. Holdup ratio was then defined as the ratio of the average in situ velocities of oil and water at any cross section. In inclined pipes, the motion of water and oil in the rolling wavy regimes were strongly influenced by gravity and thus the holdup phenomena was prevalent. In bubble flow the holdup ratio was close to unity. In the horizontal flow as the superficial oil velocity was increased, holdup shows a gradual increase. However, in inclined flow as the superficial
velocity was increased the holdup ratio merged to a constant value slightly greater than one, indicative of a single fluid flow.

Vigneaux et al. (1988) have conducted experiments on kerosene (density = 0.74) - water mixture for inclinations between 5° and 65° from the vertical in 10 cm and 20 cm I.D. pipes and for mixture velocity in the range 0.1 to 0.5 m/s. In vertical pipes a continuous water phase carrying oil droplets are observed for water cuts greater than 30%, Figure 2.4(a). In the range of 20-30% water cut an intermittent flow pattern, with alternating oil and water dominant phases, is observed and below 20% water cut an oil dominant phase is observed. In deviated pipes intermittent flow patterns are observed even at an oil cut of 10%. At lower oil compositions, the droplets are concentrated in the upper part of the pipe section. They often gather into fast moving droplet "swarms" which may move faster than the mean flow velocity. At intermediate oil fractions, oil droplets are present across the whole pipe section and propagating waves coupled with recirculation are observed in the droplet system, Figure 2.4(b). At very low water compositions, nearly all the water gathers at the lower part of the pipe; the upper part is occupied by a continuous oil phase.

Most of their studies concentrated on the effect of inclination and mixture velocity on the slip velocity between the oil and the water and on water volume fraction radial gradient. At low oil cuts, the slip velocity is very high and is a function of pipe inclination as the oil droplets tend to move as a swarm. As the oil cut is increased, the oil content at the bottom of the pipe increases and the slip velocity reduces due to the recirculating cells. A higher interaction is observed and the back flowing droplets reduce the mean oil velocity. In inclined pipes the gradient of the water volume fraction is very large in the center part of the
Figure 2.4 Flow characteristics observed in vertical and deviated oil-water flows (Vigneaux et al., 1988)
pipe. The upper part of the pipe section is almost occupied only by oil and the lower section by water, the transition between the two occurring over a relatively thin zone (Figure 2.5).

Experimental and theoretical studies on oil-water flow were carried out by Flores (1997) in vertical and inclined pipes to characterize flow patterns and develop models to predict flow pattern transitions, holdup and pressure drop. Studies were carried out in a transparent test section (2 inch, 51 ft long) using mineral oil (viscosity = 20 cP, density = 845 kg/m³) and water for inclination angles of 90°, 75°, 60°, and 45° from horizontal. Figure 2.6 is a schematic of the flow patterns observed in inclined oil-water flows. In water dominant flow patterns significant slippage was observed with a decrease in inclination increasing the slip. At low to moderate superficial oil and water velocities, a dispersed oil in water countercurrent flow pattern is observed. This flow pattern is characterized by oil droplets flowing at the top and a localized countercurrent flow within the water layer at the bottom. A typical velocity profile is shown in Figure 2.7. A net positive flow of the water layer was however observed. This flow pattern is characterized by increased values for water holdup with difference between in situ water holdup and input water cut as high as 39%.

Wicks et al., (1975) found that corrosion in pipelines was usually dominant in areas where there was a possible accumulation of water, e.g., sag bends and valleys. In highly turbulent flow the corrosion rates were much lower than when the flow was intermitted. This was due to formation of a separate water phase at the bottom of the pipes. They studied the minimum oil velocity required to entrain the water droplets. If the oil velocity over an accumulated mass of water was increased, it was found that if the velocity was sufficiently high, Kelvin-Helmholtz waves form on the surface of the water mass. At higher velocities,
Figure 2.5 Variation of water percentage with vertical position (Vigneaux et al., 1988)
(Inclination = 25°; Input Mixture Velocity = 0.47 m/s)
Water Dominated Flow Patterns

- Dispersion Oil in Water-Countercurrent
- Dispersion Oil in Water-Pseudoslugs
- Dispersion Oil in Water-Cocurrent
- Very Fine Dispersion Oil in Water

Transitional Flow Pattern

- Transitional Flow

Oil Dominated Flow Patterns

- Dispersion Water in Oil
- Very Fine Dispersion Water in Oil

Figure 2.6 Schematic representation of inclined oil-water flow patterns (Flores, 1997)
Figure 2.7 Velocity profile in inclined pipes (Flores, 1997)
waves become unstable and water droplets are formed as these waves break. These droplets then circulate in an axial vortex and travel several pipe diameters and then slide back and rejoin the primary water mass. At sufficiently high flow rates, the water droplets get entrained. Equations were proposed to calculate the minimum oil velocity required to entrain the liquid droplets.

2.3 Models for oil-water flows

Methods of physically defining two phase flows have been developed and are classified into three basic categories (Dukler, 1984):

1. Homogeneous models
2. Dimensional Analysis and Similarity
3. Separated Models
   (a) Universal Approach
   (b) Flow pattern dependent method

The homogeneous model treats the two phases as a single pseudo fluid, where the properties of the two phases are treated as a homogeneous mixture. This allows for simplification into single phase flow equations. Malhotra (1995) compared experimental pressure drop with values calculated using the homogeneous model approach. The calculated pressure drop were within the ranges of experimental error in some cases and considerably different to the observed values, in others. He concluded that a detailed study of the dispersion density, viscosity, surface tension and the distribution of phases was required and better correlations have to be developed to predict the in situ mixture properties.
Arirachakaran et al. (1989) developed a model to predict pressure gradient in homogeneous flow. The oil-water mixture was considered as a single phase fluid and friction factor correlations were developed for laminar and turbulent flows. The correlation is:

For laminar flow ($N_{Rem} < 1500$):

$$f_m = \frac{64}{N_{Rem}}$$  \hspace{1cm} (2.1)

For turbulent flow ($N_{Rem} > 1500$):

$$\frac{1}{\sqrt{f_m}} = 1.74 - 2.0 \log \left( \frac{2\varepsilon}{d} + \frac{18.7}{N_{Rem} \sqrt{f_m}} \right)$$  \hspace{1cm} (2.2)

where,

- $N_{Rem}$ = homogenous two phase Reynolds number
- $f_m$ = mixture moody friction factor
- $\varepsilon$ = pipe wall roughness, ft
- $d$ = pipe diameter, ft

The mixture properties such as density and viscosity was based on no slip liquid holdup.
The dimensional analysis and similarity technique makes use of experimental data to correlate relationships among various dimensionless variables. Dimensional analysis is used to allow for a more accurate definition of the problem under consideration by reducing the number of separate variables in the problem to a smaller number of dimensional group of variables. The virtue of dimensional analysis is that it provides correlations that are easy to apply. However, dimensional analysis does have limitation in application. The dimensionless parameters developed by this technique can be used only under similar experimental situations for which these parameters were created.

Soot (1971) developed pressure drop and holdup correlations for two-phase liquid-liquid flow. Pressure drop correlations were proposed in terms of the Lockhart-Martinelli parameters. A correlation for holdup was developed involving Froude number and Reynolds number.

Mukherjee et al. (1981) proposed a correlation for water holdup in uphill and downhill flow based on their experimental studies. The correlation is:

For uphill flow:

\[
H_w = 2.2191 \lambda_w^{1.0508} \frac{\lambda_w}{N_{Re}}^{0.0778} (\sin \theta)^{0.1052}
\]  

(2.3)

For Downhill flow:

\[
H_w = 8.3763 \lambda_w^{1.2428} (\sin \theta)^{0.4947} \frac{1}{N_{Re}}^{0.2093}
\]  

(2.4)
where

\[ H_w = \text{in situ water holdup} \]
\[ N_{Re} = \text{Reynolds number based on no-slip model} \]
\[ \lambda = \text{input water fraction} \]
\[ \theta = \text{inclination with the horizontal} \]

Separated models assume that the two phases are flowing side by side. The separated flow model provides that the two phases have differing properties as well as differing velocities. There are a number of separated flow models that can be considered, the simplest being where flow pattern configuration in the pipe is disregarded (i.e., Universal Approaches). The most complex models use separate equations for continuity of mass, momentum, and energy for each phase and involve simultaneous solution of the equations taking into account flow pattern effects.

Brauner and Maron (1989) analyzed the flow of two immiscible stratified layers for a wide range of viscosity and density differentials. Utilizing an adjustable definition for the hydraulic diameter based on the relative velocity of the two layers, they analyzed all possible flow patterns, viz., laminar-laminar, laminar-turbulent, turbulent-laminar or turbulent-turbulent flows. Predictions of liquid-liquid systems required two parameters, the input water cut and the Martinelli parameter, compared to a single parameter (the Martinelli parameter) as in gas-liquid flows.
2.4 Fundamentals of a separated flow model

Figure 2.8 shows the schematic of a two phase stratified flow of oil and water in a circular pipe. A mass balance yields the following equations:

\[ Q_o = U_o A_o = U_{so} A \]  \hspace{1cm} (2.5)

\[ Q_w = U_w A_w = U_{sw} A \]  \hspace{1cm} (2.6)

\[ Q_o + Q_w = U_o A_o + U_w A_w = \left( U_{so} + U_{sw} \right) A \]  \hspace{1cm} (2.7)

where

\begin{align*}
A & \quad \text{pipe cross-sectional area, m}^2 \\
Q_o & \quad \text{volumetric flow rate of the oil phase, m}^3/\text{s} \\
Q_w & \quad \text{volumetric flow rate of the water phase, m}^3/\text{s} \\
A_o & \quad \text{cross sectional area occupied by the oil layer, m}^2 \\
A_w & \quad \text{cross-sectional area occupied by the water layer, m}^2 \\
U_o & \quad \text{in situ velocity of the oil layer, m/s} \\
U_w & \quad \text{in situ velocity of the water layer, m/s} \\
U_{so} & \quad \text{superficial velocity of the oil layer, m/s} \\
U_{sw} & \quad \text{superficial velocity of the water layer, m/s}
\end{align*}
Figure 2.8 Schematic Diagram of Two-Phase Stratified Flow
If the height of the oil-water interface is $h$ from the bottom of the pipe, then the cross-sectional area occupied by the water phase is given by

$$A_w = \frac{D^2}{4} \left( \pi - \cos^{-1}(2\bar{h} - 1) + (2\bar{h} - 1)\sqrt{1 - (2\bar{h} - 1)^2} \right)$$  \hspace{1cm} (2.8)

where,

$h = h/D$, the dimensionless film height

$D = \text{diameter of the pipe, m}$

A momentum balance is carried out for the oil and water layers as follows:

For the water phase

$$A_w \left( \frac{dp}{dx} \right) - \tau_w S_w - \tau_{il} S_{il} - \rho_w A_w g \sin \alpha = 0$$  \hspace{1cm} (2.9)

For the oil phase

$$A_o \left( \frac{dp}{dx} \right) - \tau_o S_o + \tau_i S_i - \rho_o A_o g \sin(\alpha) = 0$$  \hspace{1cm} (2.10)

where,

$\tau_o = \text{shear stress at wall for oil, N/m}^2$

$\tau_w = \text{shear stress at wall for water, N/m}^2$
\[ \tau_i = \text{interfacial shear stress, N/m}^2 \]

\[ \alpha = \text{pipe inclination, (} \alpha \text{ is positive for upward flow)} \]

\[ S_o = \text{portion of pipe circumference in contact with the oil phase, m} \]

\[ S_w = \text{portion of pipe circumference in contact with the water phase, m} \]

\[ S_i = \text{width of the interface, m} \]

\[ (dP/dx) = \text{pressure gradient, N/m}^3 \]

\[ \rho_o = \text{density of the oil phase, kg/m}^3 \]

\[ \rho_w = \text{density of the water phase, kg/m}^3 \]

The pressure drop is the same in both the phases. Eliminating the pressure drop term yields,

\[ \tau_o \frac{S_o}{A_o} - \tau_w \frac{S_w}{A_w} - \tau_i \left( \frac{S_i}{A_o} + \frac{S_i}{A_w} \right) + \left( \rho_o - \rho_w \right) g \sin \alpha = 0 \]  \hspace{1cm} (2.11)

Following Taitel and Dukler (1976) the shear stresses are evaluated by using a Blasius type equation as shown:

\[ \tau_o = f_o \frac{\rho_o U_o^2}{2} \quad \quad \tau_w = f_w \frac{\rho_w U_w^2}{2} \]  \hspace{1cm} (2.12)

where \( f \) is a Fahning friction factor that depends on the Reynolds number. The friction factors are defined as

\[ f_o = C_o \left( \frac{D_o U_o}{\nu_o} \right)^{-n_o} \quad \quad f_w = C_w \left( \frac{D_w U_w}{\nu_w} \right)^{-n_w} \]  \hspace{1cm} (2.13)
The constants $C$ and $n$ are given the following values: For laminar flow $C = 16$ and $n = 1$ and for turbulent flow $C = 0.046$ and $n = 0.2$. It should be noted here that the Reynolds numbers for the two fluids are based on the equivalent hydraulic diameters. The equivalent hydraulic diameters are defined according to whether the upper layer is the faster one or vice-versa (Brauner, 1989). The interface is considered as free surface when the velocities of the phases on each side of the interface is of comparable levels. Where the velocities are different, the interfacial surface has to be added to the wetted perimeter in the faster phase. In distinction to gas-liquid flow, in liquid-liquid systems the velocities of the two phases may be similar and alternatively one phase velocity exceeds the other. Thus,

\[
D_o = \frac{4A_o}{S_o + S_i} \quad D_w = \frac{4A_w}{S_w} \quad \text{for } U_o > U_w
\]

\[
D_o = \frac{4A_o}{S_o} \quad D_w = \frac{4A_w}{S_w + S_i} \quad \text{for } U_o < U_w
\]

\[
D_o = \frac{4A_o}{S_o} \quad D_w = \frac{4A_w}{S_w} \quad \text{for } U_o = U_w
\]

The interfacial shear stress between the two layers, $\tau_i$, is defined as

\[
\tau_i = f_i \frac{\rho(U_w - U_o)(U_w - U_o)}{2}
\]  

(2.15)
where,

\[ \rho = \text{the density of the faster layer (kg/m}^3\text{)} \]

\[ f_i = \text{the friction factor of the faster layer} \]

All parameters shown in equation 2.11 can be expressed as a function of interface height. Hence solving equation 2.11 for a given oil and water flow rates one can predict the height of the interface. The holdup and pressure drop can then be evaluated.

Kurban et al., (1995) predicted film heights in oil-water flow using the above approach and compared with their experimental results obtained in a 1 inch diameter flow loop. The oil viscosity was 1.6 cP and the density was 800 kg/m\(^3\). The model prediction compared well with the experimental data in the stratified flow regime.
CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3.1 Experimental setup

Figure 3.1 shows the experimental layout of the flow loop. A specified amount of oil-water mixture is placed in a 1.2 m³ stainless storage tank (A). The tank is equipped with two 1-KW heaters (B). In addition, the tank is equipped with 6 m (2.5 cm ID) stainless steel cooling coils to maintain the temperature for corrosion experiments. Oil-water mixture from the storage tank is pumped into a 7.5 cm ID PVC pipeline by means of a 2.2 KW stainless steel pump (C). The liquid flow rate is controlled using a bypass system (D). Flow metering is done with an orifice plate, the pressure differential being measured using a transducer. The bypass system also serves to agitate the oil-water mixture in the tank. At the exit of the pump, before entry into the orifice section a T-junction fitted with a ball valve is present. Liquid samples are with drawn at regular intervals, from this junction, before start of the experiments and while the experiment is in progress, to check for the water percentage. The orifice plate was calibrated for the four different water cuts studied.

The oil-water mixture enters the inclinable plexiglass section through a 2m long flexible hose (10.16 cm ID). The plexiglass section is 18m long and 10.16 cm I.D. Two test sections are present, one to determine the flow characteristics in the up ward flow (F) and another to determine the flow characteristics in the down ward flow (I). The flow enters the upward inclined pipe, passes through the U bend, and then flows through the down ward inclined pipes. Upon leaving the test section the multiphase mixture enters back into the tank. The recycle stream and the return stream both serve to agitate the mixing tank.
Figure 3.1 Experimental Layout of the Flow Loop
Figure 3.2 shows the test section. The sampling tube (B) is used to measure the phase distribution. There are four pressure taps. One set of two pressure taps 10 cm apart is used to measure the pressure drop. The pressure drop is measured using a manometer.

The system pressure can be maintained by introducing Carbon dioxide into the system. Carbon dioxide from compressed cylinders (E) is introduced into the system at an inlet pressure of 0.27 MPa through a 5 cm (diameter) copper pipe. The gas flow rate can be measured using two high precision flow meters. One is used at a low gas flow rate and the other at high gas flow rates. A back pressure regulator (not shown), which is connected to the exhaust, is used to regulate the system pressure. Three phase flow studies using oil/water/gas can be carried out and the test section has ports for corrosion measurements as shown in Figure 4.2. The storage tank is fitted with a dis-entrainment plate, at the top, just below the point where the multiphase mixture enters the tank. This serves to break up the fluids and the gas entrained with mist enters the vent system at the top of the tank. The vent system consists of a separator that de-entrains the mist and the gas is vented to the atmosphere.

3.2 Experimental procedure

The pump is turned on and the system is allowed to reach equilibrium, at which time the oil and water phases are well mixed. The liquid flow rate is then set using the orifice plates and pressure transducer. Once the flow pattern has stabilized a VHS video camera will be used to make visual observations. To determine oil water distribution the multiphase mixture is allowed to reach a constant phase distribution. Liquid fractions are taken along the vertical
diameter of the pipeline with a sampling/Pitot tube inserted into the test section (Figure 3.2). The liquid sample flows into a 1.2 m long 0.5 inch diameter graduated holdup tube. The tube is then turned to a vertical position and the phases are allowed to separate. The volume of oil and water are measured. The experimental error is expected to be approximately +/- 5%. The system pressure is maintained at 0.13MPa.

To determine the in situ velocity profile across the vertical diameter the sampling tube is replaced with a Pitot tube. The pressure drop between the static and dynamic heads was measured using a manometer. The performance equation for the Pitot tube is of the form given below.

\[ V = k \sqrt{\frac{2 \Delta p}{\rho}} \]  

(3.1)

where,

- \( V \) = Velocity in m/s
- \( k \) = constant to be determined experimentally
- \( \rho \) = Density in kg/m³
- \( \Delta p \) = Pressure drop in Pa

The Pitot tube was calibrated by flowing water and the constant \( k \) was found to be 0.64. In the two phase flow situation, based on the in situ water distribution curve in situ density profiles across the cross-section were calculated. This was then used to generate the velocity profiles.
### 3.3 Test matrix

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>± 2°, ± 5°, ± 15°</td>
</tr>
<tr>
<td>Liquid phase</td>
<td>Oil (viscosity 2 cP) Standard ASTM salt water</td>
</tr>
<tr>
<td>Liquid velocities</td>
<td>0.2 m/s to 2.0 m/s</td>
</tr>
<tr>
<td>Water cut</td>
<td>20%, 40%, 60%, 80%</td>
</tr>
<tr>
<td>Temperature</td>
<td>40° C</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.13 MPa</td>
</tr>
</tbody>
</table>
CHAPTER 4
RESULTS AND DISCUSSION

4.1 Studies on oil-water distribution

A detailed study of the oil-water distribution across the cross-section, from the top to the bottom of the pipe, was carried out for input water percentages of 20, 40, 60, and 80% at six different inclinations of ±2°, ±5°, ±15°. Liquid fractions are taken across the vertical diameter of the pipe with the help of a sampling/pitot tube inserted into the test section. The ratio of the thickness of the liquid layer from the bottom of the pipe to the diameter of the pipeline, h/D, is then plotted against the water percentage.

The effect of mixture velocity on the oil-water distribution in 5° inclined pipes is discussed in section 4.1.1. The water cut also greatly influences the oil-water distribution. The effect of water cut is discussed in section 4.1.2 for inclinations of 2° and ±15°. With an increase in inclination the effect of gravity increases leading to more fluid fall back at the bottom of the pipe. In downward inclined pipes the oil-water phases separate out. The oil-water distribution in 2° and 5° downward inclined pipes is discussed in section 4.1.3 and the effect of increasing the inclination from horizontal to 2° and then to 5° and 15° is then discussed.

4.1.1 Effect of mixture velocity

Figures 4.1, 4.2 and 4.3 show the oil-water distribution curve for input water percentage of 40, 60 and 80% in 5 degree inclined pipes. Figure 4.1 shows the in situ
Figure 4.1 Variation of water percentage with vertical position
(Input Water Cut = 40%; Inclination = +5°)
Figure 4.2 Variation of water percentage with vertical position
(Input Water Cut = 60%; Inclination = +5°)
Figure 4.3 Variation of water percentage with vertical position
(Input Water Cut = 80%; Inclination = +5°)
water distribution for an input water cut of 40%. At a mixture velocity of 0.4 m/s, a water dominant layer is observed at the bottom of the pipe. At the bottom the water percentage is 95% and as the sampling tube is moved up there is a gradual decrease in the water percentage to about 86% at a h/D of 0.3. Between a h/D of 0.3 and 0.6 there is a sharp decrease in the water percentage and above a h/D of 0.6 an oil dominant layer is observed. In horizontal pipes, increasing the mixture velocity when the flow pattern is stratified results in some mixing at the interface leading to a semi-stratified flow pattern. At the interface a thin well mixed layer is observed for this flow pattern. In inclined pipes, at low mixture velocities, a sharp change in the water percentage is observed at the interface. The flow pattern at these velocities cannot be classified as stratified flow because a sharp interface between the two phases is absent. They are instead termed the semi-stratified flow pattern and the thin layer across which a sharp change in water percentage takes place is the mixed layer. A swarm of bubbles is visually observed in this mixed layer. Vigneaux (1988) suggested that at intermediate water cuts, oil moves as a swarm of bubbles near the interface and as a continuous film at the top. Sharp transitions in water cut was also observed as shown in Figure 2.5.

With increase in mixture velocity to 0.8 m/s, the amount of oil reaching the bottom half increases. The swarm of bubbles observed at low mixture velocities disappear and an oil-water dispersion is observed at the center of the pipe. At the bottom, the water percentage is 90% and at a h/D of 0.3 the water percentage has decreased to 60%. This corresponds visually to beginning of the oil-water interface. A sharp transition in water percentage occurs between a h/D of 0.3 and 0.4 where the water percentage has decreased to 40%. A well
mixed zone with an average water percentage of around 35% is observed, between a \( h/D \) of 0.4 to 0.7 and at the top an oil dominant phase is observed. The flow pattern is classified as semi-mixed with a dominant water layer at the bottom, an oil-water dispersion at the center and an oil dominant phase at the top. As the mixture velocity \( v \) is increased to 1.2 m/s, the width of the mixing zone increases. A well-mixed zone is observed between a \( h/D \) of 0.25 and 0.85. Below a height of 0.25 there is a sharp increase in the water percentage and above 0.85 there is a sharp decrease in the water percentage. This flow pattern is still semi-mixed. With further increase in the mixture velocity to 1.6 m/s an oil-water dispersion is seen to occupy the entire cross section of the pipe. There is still some gradient present in the oil-water distribution and the flow pattern is classified as semi-dispersed. Further increase in mixture velocity would lead to homogeneous flow.

Figure 4.2 shows the distribution curve for an input water cut of 60%. At a mixture velocity of 0.4 m/s, a water layer is found up to a height of 0.35. As the sampling tube is moved up the water percentage is still high, above 95%, up to a height of about 0.55. Between 0.55 and 0.75D, there is a sharp decrease in the water percentage from 95% to 10% and above a \( h/D \) of 0.75 negligible water is found. As the mixture velocity is increased from 0.4 m/s to 0.8 m/s, the amount of oil found at the bottom of the pipe increases and the clear water layer at the bottom disappears. However, the distribution curve is very similar with a water dominant layer at the bottom, a sharp transition in the water percentage at a \( h/D \) of 0.45 and an oil dominant layer at the top. Visual observation suggests that increasing the mixture velocity from 0.4 m/s to 0.8 m/s, reduced the relative velocity between the two phases. This reduced the height of the water layer. At a velocity of 1.2 m/s, a water dominant phase is
observed up to a h/D of 0.25, an oil-water dispersion between 0.35 and 0.75D and an oil dominant phase at the top. This corresponds to the semi-mixed flow pattern. Increasing the mixture velocity to 1.6 m/s leads to a semi-dispersed flow pattern. From the nature of the distribution curve obtained for the velocities studied it can be seen that a semi stratified flow regime exits up to a velocity of 1.0 m/s. In the range of 1.0 to 1.4 m/s a semi-mixed flow pattern is observed, with further increase in velocity leading to a semi-dispersed flow pattern.

Figure 4.3 shows the distribution curve for input water cut of 80%. For a mixture velocity of 0.4 m/s, a semi-stratified flow pattern is observed. A clear water layer exists up to a h/D of 0.4 and up to a h/D of 0.75 a water dominant layer is observed. A sharp transition in water percentage is observed between 0.75 and 0.85D and at the top an oil layer is observed. Increasing the velocity to 0.8 m/s reduces the height of the water layer to a h/D of 0.6. However, the flow pattern is still semi-stratified. As the mixture velocity is increased to 1.2 m/s more mixing is observed. Up to a h/D of 0.35 there is a clear water layer and as the sampling tube is moved to the top there is a gradual decrease in the water percentage. Transition to semi-mixed flow pattern takes place at this velocity.

When the mixture velocity is increased to 1.6 m/s the water layer at the bottom disappears. There is a semi-dispersion formed. As we move from the bottom to the top there is a gradual decrease in the water percentage from 95% to about 65%. The center of the pipe is occupied by a dispersion with an average water content of about 80%. From the nature of the distribution curves obtained it can be concluded that a semi-stratified flow regime exists up to a velocity of 1 m/s. In the velocity range 1 to 1.4 m/s a semi-mixed flow pattern is observed and with further increase in velocity a semi-dispersed flow pattern is observed.
Figure 4.4 shows the velocity profile obtained in 5° upward flow for an input water cut of 80%. When the mixture velocity is 0.4 m/s, the oil layer at the top moves faster than the water layer and there is a sharp transition in velocity at h/D of around 0.75. From the distribution curve it is seen that a sharp transition in water percentage occurs at around this height and the flow is semi-stratified. When the mixture velocity increases to 0.8 m/s the relative velocity between the oil and water phase is reduced. The water layer tends to get compressed by the oil layer, as seen in the distribution curve, where the oil-water interface shifts from a height of 0.75 to 0.6. A similar shift was observed for an input water cut of 60% as mentioned earlier.

As the mixture velocity increases to 1.2 m/s the water layer moves faster than the oil layer, the velocity at the center of the pipe being the greatest. This causes an increase in the level of mixing and the amount of water reaching the top of the pipe is increased. When the mixture velocity is increased to 1.6 m/s the velocity profile becomes very turbulent at the center of the pipe between h/D of 0.4 and 0.7. This causes intimate mixing of the oil-water mixture and a semi-dispersed flow pattern is obtained.

From the 5° studies it can be seen that increasing the mixture velocity enhances the mixing of the two phases. As shown in Figure 4.5, at low mixture velocities, a semi-stratified flow pattern characterized by a thick water and oil dominant layers at the bottom and top of the pipe of the pipe with a thin mixed layer at the center is observed. With increase in mixture velocity there is more mixing of the two phases and the thickness of the mixed layer increases. This corresponds to the semi-mixed flow pattern. Further increase in mixture velocity leads to the mixed layer occupying a major cross-section of the pipe and a thin oil and water layer
Figure 4.4 In situ velocity profile for different input mixture velocities
(Input Water Cut = 80%; Inclination = +5°)
Figure 4.5 Analysis of the cross section for the three flow patterns observed
may be observed depending on the input water cut. This is the semi-dispersed flow pattern. From studies carried out in the 5° pipes it can also be seen that the input water cut influences the flow pattern transitions. This is discussed in the next section based on studies carried out at 2° and 15° inclination.

4.1.2 Effect of input water cut

Figures 4.6, 4.7, 4.8 and 4.9 show the oil-water distribution in 2° inclined pipes for water cuts of 20%, 40%, 60% and 80%. For an input water cut of 20%, when the mixture velocity is 0.4 m/s, water is found only below a h/D of 0.65. Between 0.65 and 0.45D, there is a significant increase in the water percentage to about 90% and below 0.45D a water dominant layer exists. This corresponds to the semi-stratified flow pattern as shown in Figure 1.1. With increase in mixture velocity to 0.8 m/s there is no much change in the nature of the distribution curve and the flow pattern is still semi-stratified. The amount of oil reaching the bottom of the pipe is slightly increased. At a mixture velocity of 1.2 m/s, there is more oil reaching the bottom of the pipe but the distribution curve at the top half of the pipe remains unchanged and a clear oil layer is still present above a h/D of 0.55. Between 0.55D and the bottom, there is a gradual increase in the water percentage to about 85%. From the nature of the distribution curve it can be seen that transition to semi-mixed flow patterns takes place around 1.2 m/s. When the mixture velocity is increased to 1.6 m/s there is a significant change in the nature of the distribution curve. There is enhanced mixing observed leading to a uniform distribution of the two phases across the cross section. This is the homogeneous flow pattern.
Figure 4.6 Variation of water percentage with vertical position
(Input Water Cut = 20%; Inclination = +2°)
Figure 4.7 Variation of water percentage with vertical position.
(Input Watercut = 40%; Inclination = +2°)
Figure 4.8 Variation of water percentage with vertical position
(Input Watercut = 60%; Inclination = +2°)
Figure 4.9 Variation of water percentage with vertical position
(Input Watercut = 80%; Inclination = +2°)
For an input water cut of 40%, when the mixture velocity is 0.4 m/s, a clear water layer is seen up to a height of 0.5. Between a h/D of 0.5 and 0.65, there is a sharp decrease in the water percentage and above 0.65D no water is observed. This corresponds to the semi-stratified flow pattern. With increase in mixture velocity to 0.8 m/s the clear water layer at the bottom disappears and there is more oil reaching the bottom of the pipe. At the bottom, the water percentage is 90% and at a h/D of 0.25 the water percentage has decreased to 72%. Between 0.25 and 0.30D, the water percentage drops to 55%, and this corresponds to the beginning of the mixed layer. Between a h/D of 0.3 and 0.6, a well mixed layer with an average water percentage of 50% is present. There is a sharp fall in the water percentage above 0.6D and an oil continuous phase is observed. This corresponds to the semi-mixed flow pattern. Further increase in velocity to 1.2 and 1.6 m/s leads a homogeneous flow pattern where the oil-water mixture is well mixed and a uniform composition is observed across the pipe diameter. A similar flow pattern transition is observed for 60% water cut.

Figure 4.9 shows the in situ water distribution for a water cut of 80%. For a mixture velocity of 0.4 m/s, a clear water layer is present up to a h/D of 0.65. Between 0.65 and 0.85D, there is a sharp decrease in the water percentage and above 0.85 little water is present. With increase in velocity to 0.8 m/s the clear water layer at the bottom of the pipe disappears and there is more oil reaching the bottom of the pipe. There is a water dominant layer up to a height of 0.55. Above 0.55D there is a gradual decrease in the water percentage and at the top the water percentage is 40%. On comparing with the distribution curve obtained for the 20 % water cut, it can be seen that a much better mixing is present when the water cut is 80%. The water percentage at the top of the pipe is 45% and in the bottom half
of the pipe the average oil cut is 10%. Transition to semi-mixed flow pattern takes place around this velocity. Further increase in mixture velocity to 1.2 m/s leads to a significant change in the oil-water distribution. A homogeneous flow pattern is observed for this mixture velocity.

From the distribution curves obtained it can be seen that the input water cut greatly influences the nature of the distribution curves. For 20% water cut, the water layer tends to stratify and mixing is not significant even at mixture velocities of 1.2 m/s. For 40% and 60% water cut, a semi-stratified flow pattern is observed for mixture velocities up to 0.6 m/s, a semi-mixed flow pattern is observed between 0.6 and 1.0 m/s and above 1.0 m/s a semi-dispersed flow pattern leading to homogeneous flow is observed. When the water cut is 80% a semi-stratified flow pattern is observed for mixture velocities up to 0.8 m/s. A semi-mixed flow pattern exists between 0.8 and 1.2 m/s and above 1.2 m/s a homogeneous flow pattern is observed.

Figures 4.10, 4.11, 4.12 and 4.13 show the in situ velocity profile in upward 2° inclined pipes for water cuts of 20%, 40%, 60%, and 80%. For 20% water cut, it is seen that for all the mixture velocities studied the water layer travels slower than the oil layer. At mixture velocities less than 0.8 m/s, back flow within the water layer is observed up to a h/D of 0.45. Within this layer a clock wise movement of the fluid is observed. The oil layer tends to flow past the water layer and not much mixing is observed between the two phases. At a mixture velocity of 1.2 m/s, the back flow is reduced but the water layer still travels much slower than the oil layer. As seen in Figure 4.6, increase in velocity from 0.8 to 1.2 m/s does not significantly affect the distribution curve. There is an increase in the oil reaching the
Figure 4.10 In situ velocity profile for different mixture velocities
(Input Watercut = 20%; Inclination = +2°)
Figure 4.11 In situ velocity profile for different input mixture velocities

(Input Watercut = 40%; Inclination = +2°)
Figure 4.12 In situ velocity profile for different input mixture velocities
(Input Watercut = 60%; Inclination = +2°)
Figure 4.13 In situ velocity profile for different input mixtures velocities
(Input Watercut = 80%; Inclination = +2°)
bottom of the pipe but the oil layer at the top is not disturbed. At a mixture velocity of 1.6 m/s, the slip is reduced. The water layer still travels slower than the other phases but enhanced mixing is observed leading to a homogenous distribution.

For 40% water cut, there is no back flow within the water. The mixed layer at the center of the pipe travels the fastest and the water layer at the bottom of the pipe travels the slowest. The velocity profiles were integrated to obtain the in situ velocities of the oil, mixed and the water layer. The mixed layer traveled at 1.2 times the mixture velocities. For 60% and 80% water cut, the in situ velocity profiles are similar.

Figures 4.14, 4.15, 4.16 and 4.17 show the in situ water distribution curves in 15 degree upward inclined pipes for mixture velocities of 0.4, 0.8, 1.2 and 1.6 m/s. It is seen in Figure 4.14 that for a mixture velocity of 0.4 m/s a semi-stratified flow pattern is observed for all the input water cuts studied. For an input water cut of 80%, a clear water layer is found up to a h/D of 0.35. Between a h/D of 0.65 and 0.85, there is a significant decrease in the water cut from 85% to 20%. Above 0.85D, there is an oil layer with an average water content of 15%. A similar distribution curve is observed for 60% water cut. However, the distinct water phase at the bottom disappears and there is more oil reaching the bottom. This could be due to both the increase in input oil percentage and a better mixing of the two phases as observed in the 2° studies. At 40% water cut, the water percentage at the bottom is 86%. As the sampling tube is moved up there is a gradual decrease in the water percentage. A similar distribution is seen at 20% water cut. However, the water percentage at the bottom has increased to 93%. At higher input oil cuts more oil would be expected to reach the bottom. The increase in water cut at the bottom suggests a tendency for the water phase to
Figure 4.14 Variation of water percentage with vertical position (Mixture Velocity = 0.4 m/s; Inclination = +15°)
Figure 4.15 Variation of water percentage with vertical position
(Mixture Velocity = 0.8 m/s; Inclination = +15°)
Figure 4.16 Variation of water percentage with vertical position
(Mixture Velocity = 1.2 m/s; Inclination = +15°)
Figure 4.17 Variation of water percentage with vertical position
(Mixture Velocity = 1.6 m/s; Inclination = +15°)
stratify at low water cuts. The flow pattern corresponding to this distribution is semi-stratified.

Figure 4.15 shows the oil-water distribution for a mixture velocity of 0.8 m/s. At 80% water cut, on comparing with the distribution at 0.4 m/s, we see that more oil reaches the bottom. However, the flow is still semi-stratified with a water dominant phase at the bottom and an oil dominant phase at the top. For the same mixture velocity at 60% and 40% water cuts, the distribution curve shows a distinct difference. A well-mixed layer is observed at the center and the flow pattern is semi-mixed. On reducing the water percentage to 20%, the flow pattern changes to semi-stratified flow. The amount of oil reaching the bottom decreases and the water tends to stratify and form a separate phase. The velocity profile was studied for the 20% case and is discussed later.

Figure 4.16 shows the variation of water percentage at a velocity of 1.2 m/s. When the input water percentage is 80%, a semi-mixed flow pattern is observed. A well-mixed layer is observed between a h/D of 0.55 and 0.75D. At 40% and 60% water cuts, a homogenous flow pattern is observed with an average water percentage close to the input water cuts. When the water cut is reduced to 20%, the amount of oil reaching the bottom reduces. A semi-mixed flow pattern is observed at this velocity and a well-mixed layer exists between a h/D of 0.25 and 0.45. Above 0.45D, there is a sharp drop in the water percentage and negligible amount of water is found above 0.85D.

For an input water cut of 20% and 80%, a small layer of dispersion is observed at a h/D of about 0.3 and 0.65 respectively. From the nature of the distribution curve it is concluded that at a velocity of 1.2 m/s a semi-mixed flow pattern is observed for these input
water cut. When the input water cut is 40% and 60% a well-mixed dispersion is seen to occupy a major cross section, corresponding to the semi-dispersed flow regime. On comparing the distribution curves obtained for 20% and 80% input water cuts, it can be seen that in the case of 80% water cut, the water percentage changes from 95% at the bottom to 45% at the top. However, for an input water cut of 20% the water percentage changes from 90% at the bottom to negligible amount of water at the top. This indicates that a better mixing is observed for the 80% water cut suggesting a transition to semi-mixed flow pattern at a mixture velocity of 1.0 m/s and a transition to semi-dispersed flow pattern at 1.4 m/s.

Figure 4.17 shows the oil-water distribution curve for a mixture velocity of 1.6 m/s. For all the input water cuts studied, a dispersion is seen to occupy the entire cross-section of the pipe. The average water percentage across the cross section is comparable to the input water cut. The flow pattern corresponding to this distribution is the semi-dispersed or the homogeneous flow pattern.

Figure 4.18 shows the velocity profile for an input water cut of 20%. When the mixture velocity is 0.4 m/s, up to a h/D of 0.5, back flow within the water layer is observed. The flow is not stream lined within the water layer and a clockwise movement of the fluid is observed. The oil layer at the top moves at a higher velocity. As the velocity is increased to 0.8 m/s the back flow is reduced. From Figures 4.14 and 4.15, it can be seen that the increase in velocity from 0.4 to 0.8 m/s does not affect the water distribution. Due to the back flow the water percentage is almost uniform up to a h/D of 0.3. The velocity profile remains the same even at 1.2 m/s though back flow is no more present and some amount of mixing is seen at a h/D of 0.3. When the mixture velocity is increased to 1.6 m/s there is a change
Figure 4.18 Velocity profile across the cross-section from the top to the bottom
(Input Water cut = 20%; Inclination = +15°)
in the velocity profile. Between a $h/D$ of 0.4 and 0.8, there is a great deal of mixing at the center of the pipe. This induces more mixing of the oil-water mixture and a semi-dispersed flow pattern is observed. For low mixture velocities, the back flow at the bottom of the pipe causes the water layer to separate out and hence even at velocities of 0.8 m/s not much oil is found at the bottom of the pipe.

Figure 4.19 shows the variation of water percentage with vertical position in downward 15° inclined pipe, for a mixture velocity of 1.2 m/s, for the four water cuts studied. For an input water cut of 20%, a semi-stratified flow pattern is observed. A clear oil layer is observed above a $h/D$ of 0.65. As the sampling tube is moved down there is a sharp decrease in the water percentage to about 60% at a height of 0.35 and at the bottom a water dominant layer is observed. When the water cut is increased to 40%, a semi-dispersed or an almost homogeneous flow pattern exists for a mixture velocity of 1.2 m/s. This is similar to what is observed in upward flow. The two phases tend to mix well and a dispersion is obtained even at lower velocities. Similar results are obtained for an input water cut of 60%. When the water cut is increased to 80% it is seen that at a velocity of 1.2 m/s the amount of water reaching the top of the pipe is more than in upward flow and the flow pattern is semi-dispersed.

For a mixture velocity of 1.6 m/s, a homogeneous flow pattern is observed for input water cuts of 40%, 60% and 80% (Figure 4.20). A semi-stratified flow pattern is observed for an input water cut of 20%. A clear oil layer is present above a $h/D$ of 0.65. As the sampling tube is moved down there is a sharp increase in the water cut to about 60% at a $h/D$ of 0.35 below which a water dominant layer is observed.
Figure 4.19 Variation of water percentage with vertical position
(Mixture Velocity = 1.2 m/s; Inclination = -15°)
Figure 4.20 Variation of water percentage with vertical position
(Mixture Velocity = 1.6 m/s; Inclination = -15°)
From the above discussions it can be seen that the input water cut does affect the nature of the oil-water distribution. At intermediate water cuts the two phases tend to mix well. At low water cuts (20%), in upward inclined pipes, the water layer at the bottom does not move easily and is only carried away very slowly by the oil layer as suggested by Vigneaux et al. (1988). At low mixture velocities, the gravitational effects partially overcome the momentum of the water layer and hence back flow within this layer is observed. This effect is very prominent in 15° inclined pipes, where the counter current flow within the water layer is observed up to a mixture velocity of 0.8 m/s. This is very similar to the observation of Flores (1997) where countercurrent flow was observed at low mixture velocities. At intermediate water cuts the position of the interface is close to the center of the pipe. Closer to the center of the pipe the turbulence level is higher and this helps in better mixing of the two phases. Another factor is the interfacial area. At the center a larger interfacial area is available. This helps in better contact of the two phases. The influence of interfacial area is better explained in downward inclined pipes. In downward inclined pipes the water layer tends to move faster than the oil layer. At 20% water cuts, this leads to a thin fast moving film providing a very small interfacial area. However, at 80% water cut due to the increased velocity of the water layer, the interface is closer to the center of the pipe than closer to the top leading to larger interfacial area. This results in better mixing of the two phases as can be seen from the distribution curves.
4.1.3 Effect of inclination on oil-water distribution

Figures 4.21, 4.22 and 4.23 show the in situ oil distribution curve for 40%, 60% and 80% water cuts in downward 2 degree inclined pipes. For an input water cut of 40%, a stratified flow pattern is observed at a mixture velocity of 0.4 m/s. A distinct oil-water interface is observed at a h/D of 0.3.

With increase in mixture velocity to 0.8 m/s there is some mixing observed at the interface. Water is observed up to a h/D of 0.7. However a clear water layer at the bottom is still observed. When the mixture velocity is increased to 1.2 m/s there is a sharp change in the nature of the distribution curve. There is enhanced mixing observed and the flow pattern is semi-dispersed. Increase in velocity to 1.6 m/s leads to a homogeneous flow pattern.

Figure 4.22 shows the in situ water distribution for an input water cut of 60%. For a mixture velocity of 0.4 m/s, water is observed only below a h/D of 0.6. Between a h/D of 0.6 and 0.4, there is a significant increase in the water percentage to about 90% and below a h/D of 0.4 small amounts of oil is encountered. The flow pattern corresponding to this distribution is semi-stratified. With increase in mixture velocity to 0.8 m/s, there is more water reaching the top of the pipe but the distribution at the bottom half of the pipe remains undisturbed. With increase in the mixture velocity to 1.2 m/s there is a significant change in the nature of distribution. A semi-dispersed flow pattern is observed and further increase to 1.6 m/s leads to a homogeneous flow pattern.

Figure 4.23 shows the in situ water distribution curve for a water cut of 80%. Some amount of water is found at the top of the pipe even at a mixture velocity of 0.4 m/s. As the
Figure 4.21 Variation of water percentage with vertical position
(Input Watercut = 40%; Inclination = -2°)
Figure 4.22 Variation of water percentage with vertical position
(Input Watercut = 60%; Inclination = -2°)
Figure 4.23 Variation of water percentage with vertical position

(Input Watercut = 80%; Inclination = -2°)
sampling tube is moved down, up to a height of 0.75 an oil dominant layer is observed. Between 0.7 and 0.5, there is a sharp change in the nature of the distribution curve and below a h/D of 0.45 only water is observed. With increase in mixture velocity to 0.8 m/s there is no much change in the nature of the distribution curve. The height of the water layer is slightly reduced but from the nature of the distribution curve the flow pattern is still semi-stratified. At a mixture velocity of 1.2 m/s, the flow pattern is semi-dispersed. There is more water reaching the top of the pipe and the clear water layer at the bottom of the pipe disappears. Increasing the mixture velocity to 1.6 m/s causes more oil to reach the bottom of the pipe.

Comparison of the distribution curves for the upward and downward 2 degree flow show that, for mixture velocities less than 1.0 m/s, in downward flow the water layer tends to stratify and flow as a separate layer. Transitions from semi-stratified to semi-mixed flow patterns occur at much lower mixture velocities in upward flow. For mixture velocities greater than 1.2 m/s, a semi-dispersed flow pattern is observed in both upward and downward flow. Similar flow pattern transitions are observed in 5° downward inclined pipes. Figures 4.24, 4.25 and 4.26 show the distribution curve observed for water cuts of 40%, 60% and 80% in 5° downward inclined pipes.

Figures 4.27, 4.28, and 4.29 show the in situ water distribution curve for four different inclinations of 0, +2°, +5° and +15° for input water cut of 60% and mixture velocities of 0.4, 0.8 and 1.2 m/s. In horizontal pipes it is seen that for a mixture velocity of 0.4 m/s a clear water layer is found up to a h/D of 0.25. As the sampling tube is moved up there is a sharp fall in the water percentage to about 50% at a h/D of 0.45. Between a h/D of 0.25 and 0.65, a thin well mixed layer is present and as we move up there is sharp decrease
Figure 4.24 Variation of water percentage with vertical position
(Input Water Cut = 40%; Inclination = -5°)
Figure 4.25 Variation of water percentage with vertical position
(Input Water cut = 60%; Inclination = -5°)
Figure 4.26 Variation of water percentage with vertical position
(Input Water Cut = 80%; Inclination = -5°)
Figure 4.27 Effect of inclination on the insitu water distribution

(Input Water Cut = 60%; Mixture Velocity = 0.4 m/s)
Figure 4.28 Effect of inclination on the in situ water distribution

(Input Water Cut = 60%; Mixture Velocity = 0.8 m/s)
Figure 4.29 Effect of inclination on the in situ water distribution
(Input Water Cut = 60%; Mixture Velocity = 1.2 m/s)
in the water percentage. A clear oil layer is found above a h/D of 0.7. In 2° inclined pipes a water layer is found up to a h/D of 0.4. As we move up there is a sharp decrease in the water percentage at a h/D of 0.55 the water percentage is 40%. Above a height of 0.6 there is gradual fall in the water percentage. In 5° inclined pipes a water layer exists up to a height of 0.5. Above a h/D of 0.6 there is a sharp decrease in the water percentage and above a h/D of 0.8 very little water is found. A similar distribution curve is seen in 15° inclined pipes. At low mixture velocities, it seen that the water layer tends to occupy a greater cross-section in inclined pipes when compared to the horizontal. This is because in inclined pipes the water layer travels the slowest but in horizontal pipes it travels the fastest. Hence it occupies a greater cross section in inclined pipes.

For a mixture velocity of 0.8 m/s, in horizontal pipes, a clear water layer is found up to a h/D of 0.4. As we move up there is a sharp fall in the water percentage and at a h/D of 0.45 the water percentage is 50%. Between 0.45 and 0.75D, a well-mixed layer is present and above 0.8 a clear oil layer is present. The flow pattern is still semi-stratified. In horizontal pipes transition from semi-stratified to semi-mixed flow patterns takes place around this velocity. Inclination to 2° causes more oil to reach the bottom of the pipe. In 2° inclined pipe a water dominant layer is present up to a h/D of 0.25. Between a height of 0.35 and 0.7D, a well-mixed layer is present and above 0.75D there is a gradual decrease in the water percentage to about 30% at the top. In 5° and 15° pipes the flow pattern is still semi-stratified. When compared to horizontal it can be seen that in inclined pipes there is no clear water layer found at the bottom and there is more oil reaching the bottom of the pipe.
With increase in mixture velocity to 1.2 m/s, in the case of horizontal pipes, the mixed layer now occupies a greater cross-section. However, a clear water layer is still present up to a h/D of 0.10 and the flow pattern is semi-mixed. In 2°, 5° and 15° pipes an oil-water dispersion is observed across the cross section. Inclination from horizontal to 2° enhances the mixing of the oil-water mixture. However, further inclination to 5° and 15° does not affect the nature of the distribution curve.

Figures 4.30 and 4.31 compare the variation of water layer height with mixture velocity for 40% and 60% input water cuts for the four different inclinations. For input water cut of 40%, in horizontal pipes, the water layer thickness increases from a h/D of 0.33 to 0.37 as the mixture velocity is increased from 0.4 to 0.6 m/s. With increase in mixture velocity from 0.6 to 1.0 m/s the film thickness decreases from 0.37 to 0.30 h/D. Increase in mixture velocity from 0.4 to 1.0 m/s does not very much affect the distribution curve at the bottom of the pipe. In the case of 2° inclined pipes, the film height decreases from 0.45 to 0.10 h/D as the mixture velocity is increased from 0.4 to 1.0 m/s. For 5° and 15° inclined pipes, the film height decreases from 0.65 to 0.25 h/D and from 0.5 to 0.15 h/D respectively, as the mixture velocity is increased from 0.4 to 1.0 m/s.

When the input water cut was 60%, for horizontal pipes, the film thickness increases from a h/D of 0.43 to 0.48 as the mixture velocity is increased from 0.4 to 0.6 m/s. With further increase in mixture velocity the height of the water layer decreases to a h/D of 0.35 for a mixture velocity of 1.0 m/s. In 2° inclined pipes, the film thickness decreases from a h/D of 0.4 to 0.1 as the mixture velocity is increased from 0.4 to 1.0 m/s. In 5° and 15° inclined pipes the film thickness decreases from a h/D of 0.65 to 0.25 and from 0.5 to 0.15 respectively, as the mixture velocity is increased from 0.4 to 1.0 m/s.
Figure 4.30 Variation of water layer height with mixture velocity (Input Water Cut = 40%)
Figure 4.31 Variation of water layer height with mixture velocity
(Input Water Cut = 60%)
In the case of inclined pipes there is a sharp decrease in the water layer film thickness with increase in mixture velocity. For horizontal pipes, even at velocities of 1.2 m/s a clear layer of water is seen at the bottom of the pipe. Increase in mixture velocities causes more water to reach the top of the pipe but the bottom of the pipe is not very disturbed. Figures 4.32 and 4.33 show the variation of the mixed layer film thickness and the oil layer film thickness with mixture velocity for an input water cut of 60%. For all the inclinations studied the mixed layer film thickness increases with the mixture velocity. For horizontal pipes, the mixed layer height increases from a $h/D$ of 0.25 to 0.5 as the mixture velocity is increased from 0.4 to 1.0 m/s. For 2°, 5° and 15° inclined pipes the mixed layer height increases from a $h/D$ of 0.15 to 0.7, from 0.10 to 0.5 and from 0.15 to 0.7 respectively, as the mixture velocity is increased from 0.4 to 1.0 m/s. For all input water cuts studied, the thickness of the mixed layer increases with mixture velocities. At low mixture velocities, the distribution curve in inclined pipes tends to be stratified and hence the mixed layer is thinner when compared with horizontal. But with increase in mixture velocity there is enhanced mixing observed leading to a thicker mixed layer in inclined pipes when compared with the horizontal.

From Figure 4.33 it can be seen that in the case of horizontal pipes there is sharp decrease in the oil layer film thickness with increase in mixture velocity. As the mixture velocity is increased from 0.4 to 1.2 m/s the oil layer thickness decreases from a $h/D$ of 0.35 to 0.10. In inclined pipes the decrease in the oil film thickness is gradual up to a mixture velocity of 1.0 m/s. For 2° inclined pipes, the oil film thickness decreases from a $h/D$ of 0.45 to 0.4 as the mixture velocity is increased from 0.4 to 0.8 m/s. With further increase in
Figure 4.32 Variation of mixed layer height with mixture velocity
(Input Water Cut = 60%)
Figure 4.33 Variation of oil layer height with mixture velocity
(Input Water Cut = 60%)
mixture velocity to 1.2 m/s there is a sharp decrease in the oil layer height to a h/D of 0.20. In the case of 5° inclined pipes, with increase in mixture velocity from 0.4 to 0.8 m/s there is a small increase in the oil layer thickness from a h/D of 0.3 to 0.35. At a mixture velocity of 1.2 m/s, the oil layer thickness is 0.25. Similar results are observed for 15° inclined pipe. Above 1.0 m/s, in inclined pipes, the flow pattern tends to semi-dispersed flow and hence there is a sharp fall in the oil layer height.

Inclination enhances the mixing of the oil-water mixture. At low mixture velocities, the flow in inclined pipes is stratified and the water layer thickness is higher than those observed in horizontal pipes. This is because in inclined pipes the water layer travels the slowest and in some cases back flow of the fluid within the water layer is present. This results in an increased holdup of the water layer. The oil layer tends to slip and flow past the water layer and not much mixing is observed at the interface. With increase in mixture velocities, however, there is enhanced mixing observed and inclination is found to enhance the mixing of the oil-water mixtures.

4.2 Studies on holdup

In two phase flows, the in situ velocities of the two phases are often different and in general are not the same as the input mixture velocities. This is of course dependent on the flow pattern existing in the pipeline at the given mixture velocity. In homogenous flows as shown in Figure 1.1 the two phases are well mixed and hence will flow at the input mixture velocity. However, in semi-stratified and the semi-mixed flow patterns this is not observed. There is a slip between the two phases and depending on the oil viscosity and inclination,
either the water or the oil phase may move faster. This is of importance in both corrosion rate determination and production logging situations. For a highly viscous oil, the oil phase moves slowly and tends to occupy a higher cross sectional area. This compresses the water phase resulting in increased \textit{in situ} water velocity. Determination of corrosion rates could be erroneous if input mixture velocities were used as the \textit{in situ} velocity is 3 - 4 times higher (Malhotra, 1995) resulting in increased mass transfer at the pipe wall. This in turn results in higher corrosion rates.

Holdup of a given phase in stratified flow is defined as the fractional cross sectional area occupied by that phase. The \textit{in situ} velocity of the two phases can be calculated as follows:

\begin{equation}
V_w = \frac{Q_w}{A_w}
\end{equation}

where, \( V_w \) = \textit{in situ} water velocity, m/s
\( Q_w \) = flow rate of the water phase, m³
\( A_w \) = cross sectional area occupied by the water phase, m²

The in situ holdup of the water phase is

\begin{equation}
H_w = \frac{A_w}{A}
\end{equation}

where, \( A \) = pipe cross sectional area, m²
Now, 

\[ H_w = \frac{A_w}{A} \]  

(4.3) 

where, \( X_w \) = input water fraction 

combining equations 4.1, 4.2 and 4.3 we have 

\[ V_w = \frac{Q \cdot X_w}{A \cdot H_w} \]  

(4.4) 

\[ V_o = \frac{Q \cdot (1 - X_w)}{A \cdot (1 - H_w)} \]  

(4.5) 

where, \( V_o \) = \textit{in situ} velocity of the oil phase, m/s. 

As can be seen from the above equations the \textit{in situ} velocity is a function of the ratio of the input to \textit{in situ} phase fraction. When the ratio is close to unity the \textit{in situ} velocity is close to the input mixture velocity. For ratio’s greater than 1 the \textit{in situ} velocity is greater than input mixture velocity and for ratio’s less than 1 the \textit{in situ} velocity is less than the input mixture velocity. In this situation there is accumulation of the phase in the pipe. 

In situations where flow is not stratified it is not possible to determine the \textit{in situ} holdup as defined by equation 4.2. The \textit{in situ} water distribution curve is integrated across the cross section to obtain an average \textit{in situ} holdup.
Figure 4.34 is a plot of input vs *in situ* water percentage for a mixture velocity of 0.4 m/s. The dotted line shown in the Figure is the non-slip line and a qualitative indicator of the slip is the distance of the points from the non-slip line. In downward 2° inclined pipes the water layer tends to move faster. This would result in the *in situ* water percentage lower than the input water cut. From the Figure it can be seen that the data points are below the non-slip line indicating a faster moving water layer which is as expected. In horizontal flow at the same mixture velocity, the data points are closer to the non-slip indicating a reduction in slip. However, the water layer still travels faster. Inclination to 2° causes an increase in the water holdup. For 20% input water cut, the *in situ* water percentage is 45% suggesting an accumulation of the water phase in the pipe. Increasing the water cut to 40% reduces the slip and at 60 and 80% water cut the data points lie on the non-slip line. Similar results are observed for 15° inclined pipes where an increased accumulation is observed at 20% water cut. The horizontal data points were obtained by Malhotra (1995) in this laboratory.

To understand the effect of inclination, the holdup values observed in this study for -2°, 2° and 15° are plotted along with the data obtained by Malhotra (1995) for horizontal, Vigneaux et al. (1988) for 25° and Flores (1997) for 45° and 90° (vertical). The data points at -2°, 0°, 2° and 15° correspond to a mixture velocity of 0.4 m/s in 0.1016 m diameter pipe. The data points at 25° correspond to a mixture velocity of 0.47 m/s in a 0.10 m diameter pipe and the data at 45° and 90° correspond to a mixture velocity in the range 0.40-0.45 m/s in a 0.0508 m diameter pipe. From Figure 4.35 it can be seen that at 25° inclination, the *in situ* water percentage is 28% for an input water cut of 10%. The water layer travels much slower than the oil layer and a relatively high slip is observed for input water cuts up to 70%. At 90°
Figure 4.34 Input vs in situ water percentage as a function of inclination angle
(Mixture Velocity = 0.4 m/s)
input water cut, negligible slip was observed. In 45° degree pipes, for water cuts up to 80%, there is accumulation of water in the pipe and the \textit{in situ} holdup values are similar to those observed in 25° inclined pipes. Increasing the inclination to 90°, leads to a homogenous flow pattern with relatively negligible slip. The \textit{in situ} water percentages are close to the non-slip holdup values. In upward inclined pipes, changing inclination from 2° to 15° and then to 25° and 45° does not significantly influence the \textit{in situ} holdup. Similar observations were made by Mukherjee (1981) where there was no significant change in holdup values with change in inclination from 30° to 90° (Figure 2.2). However, from Figure 4.35 it can be seen that in vertical flow situations negligible slip is observed. In horizontal and downward inclined pipes the water layer travels faster and the data points are below the non-slip holdup line. In upward inclined pipes negligible slip is observed at high water cuts for all the inclinations studied. This suggests that water dominant flow patterns have negligible slip and oil dominant flow patterns have relatively high slip.

Figure 4.36 is a plot for a mixture velocity of 0.8 m/s. At 20% water cut, there is still an increased accumulation of water in inclined pipes. However, at higher water cuts the data points are close to the non-slip line.
Figure 4.36 Input vs in situ water percentage as a function of inclination angle (Mixture Velocity = 0.8 m/s)
CHAPTER 5
SEREGATED FLOW MODEL FOR OIL-WATER FLOW

5.1 Introduction and model development

The main objective of this model is to predict the holdup (of the different phases) in semi-stratified and semi-mixed flow of the oil-water mixture. From the above discussion on the *in situ* water distribution it can be seen that the flow patterns observed can be classified as semi-segregated, semi-mixed and semi-dispersed (or homogeneous). Further it can be seen that the nature of the distribution curve is influenced by the mixture velocity, oil viscosity, and the pipe inclination.

An analysis of the cross section for the three flow patterns studied was shown in Figure 4.5. In the case of semi-segregated flow pattern, a thick water layer and a thick oil layer with a thin well mixed layer across the interface are present. With increase in mixture velocity, the flow pattern becomes semi-mixed. The thickness of the mixed layer increases and that of the oil and water layer decreases. With further increase in the mixture velocity, a semi-dispersion is formed. A very thin oil and water layer may be present.

To obtain the holdup for the semi-stratified and semi-mixed flow pattern, the water, oil and the mixed layer are considered to be three different phases with each phase having its own distinct properties. Hence the problem is redefined as three phase stratified flow of oil, mixture, and water respectively. The approach of this model is very similar to what has already been done by Neogi et al. (1994), Taitel et al. (1995), for the three phase stratified flow of gas-oil-water and by Brauner (1989) for two phase stratified oil-water flows. In
contrast to gas-oil-water flow, in liquid systems, the three layers, i.e., oil, mixed and water may travel at comparable velocities.

Figure 5.1 is a schematic representation of the oil-water flow. A momentum balance is carried out as follows:

For the oil phase:

$$-A_o \left( \frac{dp}{dx} \right) - \tau_o S_o - \tau_{i2} S_{i2} - \rho_o A_o g \sin \alpha = 0 \quad (5.1)$$

For the mixed layer:

$$-A_m \left( \frac{dp}{dx} \right) - \tau_m S_m - \tau_{i1} S_{i1} + \tau_{i2} S_{i2} - \rho_m A_m g \sin \alpha = 0 \quad (5.2)$$

For the water phase:

$$-A_w \left( \frac{dp}{dx} \right) - \tau_w S_w + \tau_{i1} S_{i1} - \rho_w A_w g \sin \alpha = 0 \quad (5.3)$$

where the subscripts o, m, and w refer to the oil, mixed and the water layer respectively and the subscripts i1 and i2 denote the water-mixture interface and mixture-oil interface.

$A_o, A_m, A_w =$ cross-sectional areas

$S_o, S_m, S_w =$ wetted perimeters

$S_{i1}, S_{i2} =$ interfacial perimeters
Figure 5.1 Schematic representation of the oil-water flow.
\( \alpha = \) pipe inclination, \( (\alpha \) is positive for upward flow)

\( \rho_o, \rho_m, \rho_w = \) density of the different phases (kg/m\(^3\))

\( \tau_o, \tau_m, \tau_w = \) wall shear stress (N/m\(^2\))

\( \tau_{i1}, \tau_{i2} = \) interfacial shear stress (N/m\(^2\))

\( (dP/dx) = \) pressure gradient (N/m\(^3\))

The pressure gradient is the same in the three regions. We combine the equations to remove this term.

It yields from 5.1 and 5.2

\[
\tau_o \frac{S_o}{A_o} - \tau_m \frac{S_m}{A_m} - \tau_{i1} \frac{S_{i1}}{A_m} + \tau_{i2} \left( \frac{S_{i2}}{A_o} + \frac{S_{i2}}{A_m} \right) + (\rho_o - \rho_m)g \sin \alpha = 0 \tag{5.4}
\]

and from 5.2 and 5.3

\[
\tau_m \frac{S_m}{A_m} - \tau_w \frac{S_w}{A_w} - \tau_{i2} \frac{S_{i2}}{A_m} + \tau_{i1} \left( \frac{S_{i1}}{A_m} + \frac{S_{i1}}{A_w} \right) + (\rho_m - \rho_w)g \sin \alpha = 0 \tag{5.5}
\]

Following Taitel and Dukler (1976) the shear stresses are evaluated using a Blasius type relation.

\[
\tau_o = f_o \frac{\rho_o U_o^2}{2} \quad \tau_m = f_m \frac{\rho_m U_m^2}{2} \quad \tau_w = f_w \frac{\rho_w U_w^2}{2}
\]
\[ \tau_{i1} = f_{i1} \frac{\rho (U_m - U_w)|U_m - U_w|}{2} \quad \tau_{i2} = f_{i2} \frac{\rho (U_o - U_m)|U_o - U_m|}{2} \quad (5.6) \]

where

\( U_o, U_m, U_w \) = insitu velocities of the different phases.

\( f_o, f_m, f_w \) = friction factors

\( f_{i1}, f_{i2} \) = interfacial friction factors

The friction factors are evaluated using an approach similar to Brauner as given in equation (2).

Figure 5.2 is a schematic of the mixing phenomena. As can be seen, the two known parameters are the volumetric flow rate of oil and of the water. However, the analysis of the oil-water flow as a three phase stratified flow requires knowledge of the superficial velocities of the three phases - oil, water and the dispersion. Hence, a mass balance is carried out as follows:

\[ Q_{w, total} = Q_{purewater} + C_{ml} Q_{mixedlayer} \quad (5.7) \]

\[ Q_{o, total} = Q_{pureoil} + (1 - C_{ml}) Q_{mixedlayer} \quad (5.8) \]

where

\( Q_{w, total} \) = Total input water volumetric flow rate, \( m^3/s \)

\( Q_{o, total} \) = Total input oil volumetric flow rate, \( m^3/s \)

\( Q_{mixed layer} \) = Volumetric flow rate of the mixed layer, \( m^3/s \)
Figure 5.2 Schematic of the mixing phenomena in oil-water flows.
\( Q_{\text{pure water}} \) = Volumetric flow rate of the pure water layer, m³/s
\( Q_{\text{pure oil}} \) = Volumetric flow rate of the pure oil layer, m³/s
\( C_{\text{ml}} \) = Water fraction within the mixing zone

It yields an analogous relation between the superficial velocities:

\[
US_{\text{W input}} = US_{\text{W}} + C_{\text{ml}} US_{\text{M}}
\]

(5.9)

\[
US_{\text{O input}} = US_{\text{O}} + (1 - C_{\text{ml}}) US_{\text{M}}
\]

(5.10)

where

\( US_{\text{W input}} \) = input superficial velocities of the water layer, m/s
\( US_{\text{O input}} \) = input superficial velocities of the oil layer, m/s
\( US_{\text{W}} \) = \textit{in situ} superficial velocity of the water layer, m/s
\( US_{\text{M}} \) = \textit{in situ} superficial velocity of the mixed layer, m/s
\( US_{\text{O}} \) = \textit{in situ} superficial velocities of the oil layer, m/s

The momentum and the mass balance equations are to be solved simultaneously. However, there are four equations containing six unknowns, the unknowns being \( US_{\text{W}}, US_{\text{M}}, US_{\text{O}}, C_{\text{ml}}, A_{\text{w}} \) and \( A_{\text{m}} \). Hence two more relations have to be defined. In this model the two relationships used are the composition of the mixed layer and the \textit{in situ} velocity of the mixed layer. The composition of the mixed layer is the water percentage of the mixed layer.

In the case of the low viscosity oil, it was found from experimental observations that the \textit{in situ} velocity of the mixed layer was approximately 1.2 times the input mixture velocity. This was chosen as a convergence criteria. In most cases studied, the water percentage of the
mixed layer was very close to the input water cut. Hence, the composition of the mixed layer was set equal to the input water cut.

In the case of the high viscosity oil, the oil held up in the pipe and occupied a much greater in-situ cross section of the pipe than that calculated from the input oil fraction. This resulted in the oil phase decreasing in velocity and the local water velocity increasing. For this case, the in situ mixed layer is considered to travel at velocities close to the input mixture velocity. Hence, this was chosen as the convergence criteria. Further, the composition of the mixed layer was taken to be equal to the 50% which is the average water percentage of the mixed layer.

Hence the closure equations are:

\[ C_{ml} = \text{input watercut} \]  \hspace{1cm} (5.11)

and

\[ U_{mi} = 1.2 \times (USW + USO) \] for horizontal pipes,

\[ U_{mi} = USW + USO \] for \( +2^\circ \) pipes \hspace{1cm} (5.12)

5.2 Description of the numerical technique

A flow chart of the technique is shown in Figure 5.3. The fluid properties and the total mixture velocity and the water cut is input. The input superficial oil and water velocities are then calculated. The concentration of the mixed layer is then set to the input water cut. The in situ superficial mixed layer velocity is set to a very low value. Using relations 5.9 and 5.10 the in situ superficial oil and water layer velocity is calculated. At this point, we have
Figure 5.3 Flow chart of the numerical technique
the superficial velocities of the three layers and the properties of the three layers. Equations 5.4 and 5.5 are then solved to predict the height \( H_1 \), the film thickness of the water layer, and height \( H \), the sum of the film thickness of the water and mixed layer. Once the film thicknesses are calculated the \textit{in situ} velocity of the three phases is calculated. Then a check is made to compare the in situ mixed layer. If the criteria set in equation 5.12 is not satisfied then we increase the value of USM and the calculations are redone.

### 5.3 Results and Discussion

Given the oil and water properties, pipe diameter, and the superficial velocities the model predicts the thickness of the water and the mixed layer. The predicted water and mixed layer thickness are compared with the experimental data in Figures 5.4 and 5.5.

Figures 5.4 and 5.5 show the variation of water film thickness with input mixture velocity for the low viscosity oil (2 cP) for four different oil percentages in horizontal pipes. It can be seen that the height of the water layer increases with increasing input water cuts and reduces with increasing input mixture velocity. For 40% water cut, the experimental water film thickness decreases from 0.38 to 0.33 as the input mixture velocity is increased from 0.6 m/s to 1.0 m/s. The predicted values are 0.38 and 0.31 which are very close to the experimental values. At 20% water cut, the experimental values are 0.23 and 0.20. The model slightly under predicts these with values of 0.20 and 0.17. However, due to the presence of waves the location of the interface cannot be defined to less than approximately 3 mm and hence these results are reasonable.
Figure 5.4 Variation of water layer height with mixture velocity.
(2 cP oil in horizontal pipes)
Figure 5.5 Variation of water layer height with mixture velocity.
(2 cP oil in horizontal pipes)
The 60% and 80% water cuts results are presented in Figure 5.5. As the input mixture velocity is increased from 0.6 to 1.0 m/s, the water film thickness decreases from 0.52 to 0.42 for 60% water cut and from 0.61 to 0.47 for the 80% water cut. The predicted water layer thickness decreases from 0.51 to 0.47 and 0.6 to 0.53 respectively. Here the experimental and predicted thickness are very close.

Figures 5.6 and 5.7 show the variation of mixed layer film thickness with input mixture velocity. For 20% and 40% water cut, Figure 5.6 indicates that the mixed layer increases with increase in mixture velocity. The model predicts this trend well. At 40% water cut, the mixed layer thickness changes from 0.24 to 0.42 as the mixture velocity is changed from 0.6 to 1.0 m/s. The predicted values are slightly less at 0.18 to 0.33. Similar results are obtained at 20% water cut. As discussed in chapter 4 sharp interfaces may not be observed but a gradual increase in the water percentage may be present. Hence, defining the positions of interfaces are sometimes difficult. Comparison of the distribution curves, obtained for 20% and 40% water cuts (Malhotra, 1995), with the predicted water and mixed layer thickness (Figures 5.4 and 5.6) shows that the predictive capability of the model is reasonable.

In the case of 60% and 80% water cut, from Figure 5.7 it is seen that the mixed layer increases from 0.25 to 0.45 and from 0.23 to 0.45 respectively. The predicted film thickness increases from 0.23 to 0.41 and from 0.23 to 0.39 respectively. This agrees well with experimental data.

Figure 5.8 shows the variation of the water layer film thickness with input mixture velocity for 2 degree upward inclined pipes. The experimental film thickness decrease with increasing mixture velocity. In the case of 40% input water cut, the film thickness decreases
Figure 5.6 Variation of mixed layer height with mixture velocity.
(2 cP oil in horizontal pipes)
Figure 5.7 Variation of mixed layer height with mixture velocity
(2 cP oil in horizontal pipes)
Figure 5.8 Variation of water layer height with mixture velocity
(2 cP oil in 2 degree upward inclined pipes)
from 0.4 to 0.2 as the mixture velocity is increased from 0.6 to 1.0 m/s. At 60% and 80% water cuts, the film thickness reduces from 0.45 to 0.20 and from 0.61 to 0.42 respectively. When compared with horizontal flow, it can be seen that inclination to 2 degree has enhanced the mixing of the oil and the water and water film thickness observed are much lower. Further, transition from semi-mixed to semi-dispersed flow patterns occurs at much lower velocities. For 40% water cut, the predicted film thickness varies from 0.42 to 0.35 as the mixture velocity is increased from 0.6 to 1.0 m/s. At 60% and 80% water cut, the film thickness reduces from 0.55 to 0.34 and from 0.61 to 0.46 respectively. The water film thicknesses for input water cuts of 40 and 60% are slightly over predicted for input mixture velocity of 1.0 m/s. This is because the flow pattern approaches the semi-dispersed flow regime and a much thinner water layer is observed.

Figure 5.9 compares the predicted water film thickness using two phase and three phase flow model to experimental data for an input water cut of 60%. In the two phase model the oil and water layers are considered to flow side by side with mixing of phases at the interface. The solution procedure for such a model was detailed in chapter 2. At a mixture velocity of 0.6 m/s, the water film thickness is 0.50 h/D. With further increase in mixture velocity to 0.8 m/s the film thickness reduces to 0.45 and at 1.0 m/s the film thickness is 0.40. When a two phase model is used the predicted film thickness reduces from 0.58 to 0.54 h/D. On comparing the experimental data to the predicted results we can see the film thicknesses are over predicted. Using a two phase approach it was observed that the predicted film thickness was very close to the non-slip values for a given water cut. When a three phase model is used the film thickness reduces from 0.51 at 0.6 m/s to 0.48 at 0.8 m/s and 0.44 at
Figure 5.9 Comparison of predicted film heights using two phase and three phase model.
(2 cP oil in horizontal pipes at 60% water cut)
1.0 m/s. On comparing with the experimental data it can be seen that model predicts the trend very well and the predictive capability of the model is reasonable. If a two phase oil-water model is used it does over predict the holdup values as the mixed layer is not considered in the model.

Figure 5.10 shows the effect of input mixture velocity on the water layer film thickness for the high viscosity, 96 cP, oil in horizontal pipes. As seen in the figure, the water layer film thickness is virtually unchanged with increasing mixture velocity. For 20% water cut, a film thickness of about 0.15 h/D is observed. At 40% and 60% water cut, the film thickness is about 0.23 and 0.3 respectively. The predicted film thickness is again very close at 0.15, 0.25 and 0.33 h/D for water cuts of 20%, 40% and 60% respectively. For the mixed layer thicknesses, results similar to those in Figures 5.6 and 5.7 are obtained.
Figure 5.10 Variation of water layer height with mixture velocity
(96 cP oil in horizontal pipes)
CHAPTER 6
CONCLUSION AND RECOMMENDATION

Studies on oil-water flow have been carried out in inclined pipes. The mixture velocities were in the range of 0.2 to 2.0 m/s. The input water cut was varied from 20% to 80% and six different inclinations - ±2°, ±5°, ±15° were tried. The following conclusions can be made based on results obtained in this study.

1. Three flow patterns namely the semi-stratified, semi-mixed and the semi-dispersed flows were observed in inclined pipes. At low mixture velocities, a countercurrent flow was observed in the water phase. This was however influenced by the water cut, inclination and mixture velocity. At 20% water cut, a countercurrent flow was observed in the water layer up to a mixture velocity of 0.8 m/s in 15° upward inclined pipes. However, in 2° inclined pipes this was observed up to a mixture velocity of 0.4 m/s. Counter current flow patterns have been reported by both Scott (1985) and Flores (1997) in their studies in inclined pipes.

2. The flow pattern transitions were dependent on the input water cut for all the inclinations studied. At intermediate water cuts (40% and 60%) a much better mixing of the two phases were observed. A semi-stratified flow pattern exists up to a mixture velocity of 0.6 m/s, a semi-mixed between 0.6 and 1.0 m/s and above 1.0 m/s a semi-dispersed flow pattern is observed. At low water cuts (20%), the water layer tends to stratify and not much mixing is observed between the two phases. A semi-stratified flow patterns exits up to 1.0 m/s in upward inclined pipes. In down ward
inclined pipes even at a mixture velocity of 1.6 m/s a semi-stratified flow pattern is observed for 20% water cut.

3. Inclination was found to affect the velocity profile and the oil-water distribution within the pipeline. At mixture velocity less than 0.8 m/s, increase in inclination results in an increased accumulation of the water phase. The water layer tends to travel slower. In horizontal pipes Malhotra (1995) however, found that the water later tends to travel faster. At lower water cuts (20%), the gravity effects tends to overcome the momentum resulting in back flow within the water layer. Increase in inclination from 2° to 15° increased the back flow with the water layer close to the pipe wall stagnant at times being slowly carried by the droplets and waves. However, at higher mixture velocities enhanced mixing was observed resulting in a homogenous flow pattern. Above 1.4 m/s the oil-water mixture is well mixed in inclined pipes. In horizontal pipes a clear water layer is usually present.

4. In downward inclined pipes gravity driven buoyancy effect causes the water layer to stratify. The water layer travels faster. This could result in higher corrosion rates due to increased mass transfer.

5. A study of the effect of inclination on the average in situ hold up showed that in downward inclined pipes the ratio of the in situ hold up to the input holdup was less than unity. In horizontal pipes the slip was relatively less and the value was close to unity for the water cuts studied. In upward inclined pipes the value was greater than unity as a result of the accumulation of water. At lower water cuts, the slip was relatively high and at higher water cuts the values approached unity. Increase in inclination from
2° to 15° and then to 25° and 45° does not significantly influence the ratio. However, in vertical pipes values close to unity is observed.

6. The oil-water flow was treated as a three phase stratified flow comprising of an oil layer at the top, a mixed layer (which is an oil-water dispersion) at the center and a water layer at the bottom. A mechanistic model to predict the in situ hold up of the three phases was developed. The approach was similar to that of Taitel & Dukler (1976) and Brauner & Maron (1989). A two phase oil-water flow that does not take into account the mixed layer at the center would grossly over predict the height of the water layer. The model has been compared with experimental data and there is good agreement between predicted and experimental water film thickness. Small discrepancies were observed when there were no sharp transition in water percentage across the water-mixed layer interface.

7. In oil-water flows it is always desired to be able to predict water break out. This would then help predict the on set of corrosion. The current model works for water cuts in the range of 10% to 90%. A momentum balance approach is not sufficient to predict the formation of a separate water phase with an increase in water cut. A detailed study of droplet coalescence and film formation phenomena needs to be done to be able to predict water break out.

8. Further studies need to be carried out for the inclinations studied with a high viscosity oil to understand the effect of viscosity.
CHAPTER 7
REFERENCES


18. Wicks, M., and Fraser, J.P., Entrainment of Water by Flowing Oil, Materials Performance, Appendix 2, 9-12, May 1975.

APPENDIX

C*******************************************************************************
******
C
C THIS PROGRAM CALCULATES THE WATER AND
C OIL FILM THICKNESSES FOR STRATIFIED FLOW FOR
C OIL-WATER TWO PHASE FLOW SYSTEM. A THREE PHASE FLOW APPROACH
C IS USED.

C THE PROGRAM SOLVES THE TWO NON-LINEAR ALGEBRAIC EQUATIONS.
C
C NEWTON-RAPHSON'S METHOD HAS BEEN USED FOR THIS PURPOSE.
C
C THE NEWTON RAPHSON PROGRAM HAS BEEN WRITTEN EXCLUSIVELY TO
C SOLVE TWO NONLINEAR EQUATIONS
C
C TO USE THE PROGRAM FOR ANY THREE PHASE SYSTEM, FLUID
C PROPERTIES ARE TO BE PROVIDED.
C
*******************************************************************************
******
C
C NOMENCLATURE OF VARIABLES

*******************************************************************************
******
C A#: FLOW CROSS SECTION AREA FOR THE COMPONENT DENOTED BY
C SYMBOL #. SYMBOL # MAY BE W, M, OR O FOR THE COMPONENT WATER
C MIXTURE OR OIL RESPECTIVELY.
C B: RATIO OF WATER TO OIL CONTENT IN THE MIXTURE
C CL: COEFFICIENT OF FRICTION FACTOR TERM FOR LIQUID PHASE
C D: PIPE DIAMETER, m
C DINCH: PIPE DIAMETER, inch
C D#: HYDRAULIC DIAMETER FOR THE COMPONENT DENOTED BY
C SYMBOL #. SYMBOL # MAY BE W, M, OR O FOR THE COMPONENT WATER, OIL, OR GAS
C RESPECTIVELY.
C DH1: VALUE OF STEP SIZE OF H1 FOR NUMERICAL DIFFERENTIATION OF
C FUNCTIONS.
C DH: VALUE OF STEP SIZE OF H FOR NUMERICAL DIFFERENTIATION OF C
FUNCTIONS.
C DEN#: DENSITY OF THE COMPONENT DENOTED BY SYMBOL #. SYMBOL
C # MAY BE W, M, OR O FOR THE COMPONENT WATER, MIXING ZONE OR
C OIL RESPECTIVELY.
C FDEN#: SAME AS DEN# BUT IN AMERICAN UNITS.
C FMU#: SAME AS XMU# (ABSOLUTE VISCOSITY) BUT IN AMERICAN
C UNITS.
C F#: FRICTION FACTOR FOR THE COMPONENT OR FOR THE INTERFACE
C DENOTED BY SYMBOL #. SYMBOL # MAY BE W, O, OR G FOR THE
C COMPONENT WATER, OIL, OR GAS RESPECTIVELY OR IT MAY BE I1 AND
C I2 FOR THE OIL-WATER AND GAS-OIL INTERFACES RESPECTIVELY.
C G: COMPONENT GAS
C GOR: GAS-OIL RATIO
C H1: NONDIMENSIONAL WATER FILM THICKNESS
C H2: NONDIMENSIONAL OIL FILM THICKNESS
C H: NONDIMENSIONAL TOTAL LIQUID FILM THICKNESS
C XMU#: ABSOLUTE VISCOSITY OF THE COMPONENT DENOTED BY
C SYMBOL #. SYMBOL # MAY BE W, O, OR G FOR THE COMPONENT
C WATER, MIXING ZONE OR OIL RESPECTIVELY.
C MU#: DYNAMIC VISCOSITY OF THE COMPONENT DENOTED BY SYMBOL
C #. SYMBOL # MAY BE W, O, OR G FOR THE COMPONENT WATER, MIXING
C ZONE OR OIL RESPECTIVELY.
C M: EXPONENT OF FRICTION FACTOR TERM FOR GAS PHASE
C N: EXPONENT OF FRICTION FACTOR TERM FOR LIQUID PHASE
C O: COMPONENT OIL
C PAREA: PIPE CROSS SECTIONAL AREA, m**2
C PF: PRESSURE OF THE PIPELINE, psia.
C Q#: VOLUMETRIC FLOW RATE OF COMPONENT DENOTED BY SYMBOL #
C SYMBOL # MAY BE W, M OR O.
C QOD: INPUT VOLUMETRIC FLOW RATE OF OIL IN bbl/day
C Re#: REYNOLDS NUMBER OF COMPONENT DENOTED BY THE SYMBOL #.
C SYMBOL # MAY BE W, M OR O.
C S#: FLUID PERIMETER FOR THE COMPONENT DENOTED BY SYMBOL #. C
C SYMBOL # MAY BE W, M, OR O FOR THE COMPONENT RESPECTIVELY.
C T#: SHEAR STRESS FOR THE COMPONENT OR FOR THE INTERFACE
C DENOTED BY SYMBOL #. SYMBOL # MAY BE W, O, OR G FOR THE
C COMPONENT WATER, OIL, OR GAS RESPECTIVELY OR IT MAY BE I1 AND
C I2 FOR THE OIL-WATER AND GAS-OIL INTERFACES RESPECTIVELY.
C TF: TEMPERATURE OF THE PIPELINE, deg. F.
C TOL: TOLERANCE FOR THE CONVERGENCE OF NEWTON RAPHSON
C METHOD.
C US#: SUPERFICIAL VELOCITY OF THE COMPONENT DENOTED BY
C SYMBOL #. SYMBOL # MAY BE W, O, OR G FOR THE COMPONENT
C WATER, MIXING ZONE OR OIL RESPECTIVELY.
C W: COMPONENT WATER
C WOR: WATER-OIL RATIO
C ZS: COMPRESSIBILITY FACTOR FOR GAS AT STANDARD CONDITIONS
C ZF: COMPRESSIBILITY FACTOR FOR GAS AT FLOWING CONDITIONS
C THERE IS A CHOICE BETWEEN AMERICAN OR SI UNITS FOR INPUT
C VARIABLES
C**********************************************************************
C THIS IS THE MAIN PROGRAM. MAIN PROGRAM DOES THE NEWTON
C RAPHSON ITERATIONS. IT CALLS THE SUBROTIONE FUNC WHICH
C CALCULATES THE VALUE OF EACH TERM REQUIRED FOR THE
C FUNCTION AND THE VALUE OF FUNCTION ITSELF AND RETURNS.
C**********************************************************************
C DECLARE VARIABLES
IMPLICIT REAL*8 (A-H,O-Z)
REAL J, JIW
COMMON/FLPROP/DENW,DENM,DENO,XMUW,XMUM,XMUO,D,IPROFILE
C DECLARE THE DIMENSIONS OF ARRAYS.
DIMENSION J(2,2), JINV(2,2), BETA(2)
C PRINT TITLES FOR PROGRAM
WRITE(*,*)"***************************************************"
PRINT*,"ENTER DENSITY OF OIL AND WATER LAYER"
READ*, DENO, DENW
PRINT*,"ENTER VISCOSITY OF OIL AND WATER LAYER"
READ*, XMUO, XMUW
PRINT*, "ENTER DIAMETER OF PIPE IN METER"
READ*, D
PRINT*, "ENTER INCLINATION IN DEGREES"
READ*, ALPHA1
ALPHA = ALPHA1*3.14159/180.0
PRINT*, "ENTER MIXTURE VELOCITY AND WATER CUT"
READ*, USMI
READ*, BB
PRINT*, "ENTER CONCENTRATION OF MIXED LAYER"
READ*, CML
PRINT*, "ENTER VISCOSITY OF MIXED LAYER"
READ*, XMUM

C CONVERSION OF VARIABLES TO AMERICAN UNITS FOR OUTPUT
C D IS CONVERTED TO INCHES
C DENM IS CONVERTED TO API GRAVITY
C DENW and DENO ARE CONVERTED TO lb/ft³
C XMUW, XMUM, and XMOG ARE CONVERTED TO cp

DINCH = D*39.37
FDENW = DENW*0.0624
FDENO = DENO*0.0624
FMUW = XMUW*1000.0
FMUO = XMUO*1000.0

200 CONTINUE
NTEST = 0

C******************************************************************************************
C************ PROPERTIES OF THE MIXED LAYER ************

C MIXED LAYER DENSITY
DENM = (1-CML/100)*DENO+CML/100*DENW
FDENM = 141.5/(DENM/1000.0) - 131.5

C VISCOSITY CONVERTED IN CP
FMUM = XMUM*1000.0

USWI = BB/100*USMI
USOI = USMI-USWI

C******************************************************************************************
C Initialise the mixed layer superficial velocity

\[
USM = 0.02 \\
USW = USWI-CML/100*USM \\
USO = USOI-(1-CML/100)*USM
\]

ICOUNTER = 1
FACTOR = 0.005

C---------------END OF THE MODIFICATION-----------------------------

C INPUT INITIAL GUESS FOR THE VARIABLES TO BE SOLVED, STEP SIZES C FOR TO EVALUATE NUMERICAL DERIVATIVE OF FUNCTIONS AND THE C TOLERANCE FOR THE CONVERGENCE OF NEWTON RAPHSON METHOD.

99 IF(ALPHA.GT.0.0001 .AND. BB.GT.90) THEN
  H1=0.4
  H=0.4001
  WRITE(*,*) "GUESSES USED ARE"
  WRITE(*,*)H1,H
  WRITE(*,*)IGUESS=1
ELSE
  H1=0.01
  H=0.01001
  WRITE(*,*) "GUESSES USED ARE"
  WRITE(*,*)H1,H
  WRITE(*,*)IGUESS=2
ENDIF
GOTO 20

14 WRITE(*,*)"TRY NEW GUESSES OF WATER & TOTAL FILM THICKNESS’
WRITE(*,*)
WRITE(*,604) USM, BB
604 FORMAT(' MIXTURE VELOCITY=',F6.3,' WATER CUT=',F6.3)
WRITE(*,*) USW, USM, USO
WRITE(*,*) H1, H
WRITE(*,*)
WRITE(*,*) "FOR WATER CUTS OF LESS THAN 10%"
WRITE(*,*) "TRY VALUES OF 0.001 FOR H1 AND 0.00101 FOR H"
WRITE(*,*)
WRITE(*,*) "FOR WATER CUTS GREATER THAN 95%"
WRITE(*,*) "TRY VALUES OF 0.4 FOR H1 AND 0.40001 FOR H"
WRITE(*,*) "IF THIS DOES NOT CONVERGE, CHECK YOUR INPUT DATA"
WRITE(*,*) "ENTER GUESSES FOR H1 AND H"
READ(*,*) H1, H
IF (H1 .LT. H) GOTO 21
WRITE(*,*)"THE TOTAL HEIGHT IS LESS THAN THE WATER FILM
HEIGHT"
WRITE(*,*)"CHOOSE NEW VALUES FOR H1 AND H WITH H1 < H !!"
WRITE(*,*)
GOTO 800

20 CONTINUE

************

*****

DH=0.000001
DH1=0.000001
TOL=0.000001
IPROFILE=0

C START OF ITERATIONS
C ITERATION ON THE INPUT SUPERFICIAL VELOCITY

21 CONTINUE

IF ((USW.GT.0.05 * USMI).AND.(USO.GT.0.05 * USMI)) THEN

C CALCULATE FUNTIONS AT GUESS VALUES OF THE VARIABLES TO BE
C CALCULATED.

IT=0

CALL FUNC(ALPHA,USO,USM,USW,H1,H,F1,F2,IT,UWI,UOI,UMI,HW,HM,
+DPDX,ReO,ReM,ReW,TW,TO,TI1,TI2,F1G,F2G,DM,SM,SO,SW,SI1,SI2)

IF(IT.EQ.1) THEN
IF(IGUESS.EQ.1) THEN
H1=0.01
H=0.014
GOTO 21
ELSE
GOTO 14
ENDIF
ENDIF

C INCREASE THE VARIABLES TO CALCULATE THE NUMERICAL
C DERIVATIVE OF FUNCTIONS.

H1D=H1+DH1
HD=H+DH

C CALCULATE VALUES OF FUNCTIONS INCREASING THE VARIABLES TO
C CALCULATE THE NUMERICAL DERIVATIVE.

IT=0
CALL FUNC(ALPHA,USO,USM,USW,H1D,H,F11,F21,IT,UWI,UOI,UMI,HW,HM,
          +DPDX,ReO,ReM,ReW,TW,TM,TO,TI1,TI2,F1G,F2G,DM,SM,SO,SW,S11,S12)

IF(IT.EQ.1) THEN
  IF(IGUESS.EQ.1) THEN
    H1=0.01
    H=0.014
    GOTO 21
  ELSE
    GOTO 14
  ENDIF
ENDIF

IT=0
CALL FUNC(ALPHA,USO,USM,USW,H1D,H,F12,F22,IT,UWI,UOI,UMI,HW,HM,
          +DPDX,ReO,ReM,ReW,TW,TM,TO,TI1,TI2,F1G,F2G,DM,SM,SO,SW,S11,S12)

IF(IT.EQ.1) THEN
  IF(IGUESS.EQ.1) THEN
    H1=0.01
    H=0.014
    GOTO 21
  ELSE
    GOTO 14
  ENDIF
ENDIF

C CALCULATE ELEMENTS OF THE JACOBIAN MATRIX BY performing
C THE NUMERICAL INTEGRATION.

   J(1,1)=(F11-F1)/DH1
   J(1,2)=(F12-F1)/DH
   J(2,1)=(F21-F2)/DH1
   J(2,2)=(F22-F2)/DH

C CALCULATE THE DETERMINANT OF THE JACOBIAN MATRIX.
C REMEMBER IT IS A 2x2 MATRIX.

   DETER=(J(1,1)*J(2,2)-J(2,1)*J(1,2))

C CALCULATE ELEMENTS OF THE INVERSE OF THE JACOBIAN MATRIX.

   JINV(1,1)=J(2,2)/DETER
   JINV(2,1)=-J(2,1)/DETER
   JINV(1,2)=-J(1,2)/DETER
   JINV(2,2)=J(1,1)/DETER

C CALCULATE ELEMENTS OF THE ERROR MATRIX.

   BETA(1)=JINV(1,1)*F1+JINV(1,2)*F2
   BETA(2)=JINV(2,1)*F1+JINV(2,2)*F2

C CALCULATE THE NEW VARIABLES.

   H1N=H1-BETA(1)
   HN=H-BETA(2)

C CALCULATE ERRORS.

   ERH1=ABS(H1-H1N)
   ERH=ABS(H-HN)

C IF ERRORS ARE LESS THAN TOLERANCE THEN STOP THE ITERATIONS
C AND OUTPUT THE RESULTS.

   IF (ERH1.LT.TOL. AND. ERH.LT.TOL) GOTO 10

C OTHERWISE STORE THE NEW VALUES OF VARIABLES AS THE OLD
VALUES AND REPEAT ITERATION AGAIN.

H1 = H1N
H = HN
GOTO 21

OUTPUT RESULTS.

CONVERSION FROM m TO inch IS 39.37

H2 = H - H1
HH = H * D
HH1 = H1 * D
HH2 = H2 * D
FHH1 = HH1 * 39.37
FHH2 = HH2 * 39.37

USO, USM, and USW ARE CONVERTED TO ft/s

FUSM = USM * 3.28084
FUSW = USW * 3.28084
FUSO = USO * 3.28084

IF (H2 > 0.0) GOTO 17
WRITE(*,*) "OIL THICKNESS IS NEGATIVE" WRITE(*,*) "CHOOSE SMALLER GUESSES FOR H AND H1"
GOTO 14

CONTINUE

******************************************************************************
*****
****** CHECK FOR INPUT MIXTURE VELOCITY *************

VELF = UMI-USMI

IF (ICOUNTER .EQ. 1) THEN
IF (VELF .LT. 0.0) THEN
ISIGN1 = 1
ELSE
ISIGN1 = -1
ENDIF
USM = USM + ISIGN1 * FACTOR
ICOUNTER = ICOUNTER + 1
GOTO 225
ENDIF

IF (VELF .LT. 0.0) THEN
ISIGN2 = 1
ELSE
ISIGN2 = -1
ENDIF

IF (ISIGN2 .NE. ISIGN1) THEN
ISIGN1 = ISIGN2
FACTOR = FACTOR/10
ENDIF

222 USM = USM + ISIGN2* FACTOR

225 IF (ABS(VELF) .GT. 0.1) THEN

USW = USWI-CML/100*USM
USO = USOI-(1-CML/100)*USM
GOTO 99
ENDIF
ENDIF

WRITE(* *)"*******************************************************************************
+*******************************************************************************"

275 OPEN(99, FILE="3PHASE.OUT")
WRITE(99,25)USMI,BB,ALPHAI1,CML

25 FORMAT(' INPUT MIXTURE VELOCITY = ',F10.4/
+ ' INPUT WATER CUT = ',F10.4/
+ 'ANGLE = ',F10.4/
+ 'CML = ',F10.4/)

WRITE(99,4)DENW,FDENW,XMUW,FMUW,DENM,FDENM,XMUM,FMUM,
+ DENO,FDENO,XMUO,FMUO

4 FORMAT(' DENSITY OF WATER =F10.1' kg/m**3',5X,
+ ',1X,F10.3,3X,'lbm/ft**3 )' /
+ ' VISCOSITY OF WATER='F10.6, ' Pa.s',8X,
+ ',1X,F10.3,3X,'cp ') /
+ ' DENSITY OF MIXED LAYER =F10.1' kg/m**3',5X,  
  + '(',1X,F10.3,3X,'deg. API ') /  
+ ' VISCOSITY OF MIXED LAYER =F10.6' Pa.s',8X,  
  + '(',1X,F10.3,3X,'cp ') /  
+ ' DENSITY OF OIL =F10.2' kg/m**3',5X,  
  + '(',1X,F10.3,3X,'lbm/ft*3 ') /  
+ ' VISCOSITY OF OIL =F10.7' Pa.s',8X,  
  + '(',1X,F10.3,3X,'cp ') /  
)

WRITE(99,3)D,DINCH  
3 FORMAT(' PIPE DIAMETER =F10.4' m',11X,  
  + '(',1X,F10.3,3X,'inch ')'/)

WRITE(99,1) USO,FUSO,USM,FUSM,USW,FUSW  
1 FORMAT(' SUPERFICIAL OIL VELOCITY =F10.2' m/s',5X,  
  + '(',F6.2,1X,'ft/s ') /  
+ ' SUPERFICIAL MIXED LAYER VELOCITY =F10.4' m/s',5X,  
  + '(',F6.2,1X,'ft/s ') /  
+ ' SUPERFICIAL WATER VELOCITY=F10.4' m/s',5X,  
  + '(',F6.2,1X,'ft/s ') )

WRITE(99,*)  
WRITE(99,2)H1,HH1,FHH1,H2,HH2,FHH2  
2 FORMAT(' WATER FILM THICKNESS='F10.4' (H/D)'
  + ' OR='F10.4' m',3X,  
  + '(',F8.4,1X,'inch ')'/  
+ ' MIXED LAYER FILM THICKNESS='F10.4' (H/D)'
  + ' OR='F10.4' m',3X,  
  + '(',F8.4,1X,'inch ')')

WRITE(99,9)UWI,UMI,UOI,HW,HM  
9 FORMAT(' INSITU WATER VELOCITY=F10.4' m/s'/  
  + ' INSITU MIXED LAYER VELOCITY =F10.4' m/s'/  
  + ' INSITU OIL LAYER VELOCITY =F10.4' m/s' /  
+ ' INSITU WATER HOLDUP =F10.4' %'/  
  + ' INSITU MIXED LAYER HOLDUP =F10.4' %' )

WRITE(99,33)DM,SM,SO,SW,SI1,SI2  
33 FORMAT('HYDRAULIC DIA OF MIXED LAYER=F10.4'  
  + 'MIXED LAYER PERIMETER=F10.4'  
  + 'OIL LAYER PERIMETER=F10.4'  
  + 'INTERFACE 1 PERIMETER SI1=F10.4'  
  + 'INTERFACE 2 PERIMETER SI2=F10.4' )
WRITE(99,15)TW,TM,TO,TI1,TI2,F1G,F2G
15 FORMAT('TW=',F10.4,3X,'TM=',F10.4,3X,'TO=',F10.4/
+ 'TI1=',F10.4,3X,'TI2=',F10.4/
+ 'F1G=',F10.4,3X,'F2G=',F10.4/)

WRITE(*,*)"**********************************************************************
+**********************************************************************"

C STOP PROGRAM.

800 STOP
END

C**********************************************************************

C THIS IS THE SUBROUTINE WHICH CALCULATES VALUES OF EACH TERM
C REQUIRED TO CALCULATE THE FUNCTION AND VALUES OF FUNCTIONS ITSELF.
C**********************************************************************

SUBROUTINE FUNC(ALPHA,USO,USM,USW,H1,F1,F2,IT,UW1,UIO,UMI,HW,
HM,DPDX,ReO,ReM,ReW,TW,TM,TO,TI1,TI2,F1G,F2G,DM,SM,SO,SW,S1,SI2)

IMPLICIT REAL*8 (A-H,O-Z)
COMMON/FLPROP/DENW,DENM,DENO,XMUW,XMUM,XMUO,D,PROFILE

C DECLARE VARIABLES.

REAL M,N,MUW,MUM,MUO

C WRITE(*,*) H1,H

C INPUT CONSTANT VALUES

CL = 0.046
N = 0.2
M = 0.2

C CALCULATE KINEMATIC VISCOSITY

C START PROGRAM.

800 STOP
END
C CALCULATE AREAS.
P=1-2*H1
Q=1-2*H
IF(P.GT.1.0 .OR. P.LT.-1.0) GOTO 15
IF(Q.GT.1.0 .OR. Q.LT.-1.0) GOTO 15
GOTO 13
15 WRITE(*,*)"THE PROGRAM IS FAILING WHEN CALCULATING AW OR AM"
WRITE(*,*)"(1-2*H) OR (1-2*H1) IS TOO BIG"
WRITE(*,*) P,Q,H1,H
WRITE(*,*)"CHOOSE A SMALLER GUESS FOR H AND/OR H1"
WRITE(*,*)
WRITE(*,*)"IF THE PROBLEM PERSISTS"
WRITE(*,*)"CHECK YOUR INPUT DATA AND LIMITS ON USO AND USM"
WRITE(*,*)
IT=1
RETURN

13  AW = 0.25*(ACOS(1-2*H1) - (1-2*H1)*SQRT(1-(1-
     + 2*H1)**2))
AM = 0.25*(ACOS(1-2*H) - (1-2*H)*SQRT(1-(1-
     + 2*H)**2)) - AW
AO = 0.25*3.1416 - AW - AM

C COMPUTER THE DIMENSIONLESS FLUID PERIMETER.
C
SW = ACOS(1 - 2*H1)
SM = ACOS(1 - 2*H) - ACOS(1 - 2*H1)
SO = 3.1416 - ACOS(1 - 2*H)
SI1 = SQRT(1 - (1 - 2*H)**2)
SI2 = SQRT(1 - (1 - 2*H1)**2)

C COMPUTE THE FLUID VELOCITIES.
A = 0.25 * 3.1416
UW = A / AW
UM = A / AM
UO = A / AO

C CALCULATION OF INSITU VELOCITIES AND HOLD UPS

UWI = UW*USW
UMI = UM*USM
UOI = UO*USO
HW = AW/A
HM = AM/A

C COMPUTE THE HYDRAULIC DIAMETER.

DW = 4 * AW * D / (SW+SI2)
DM = 4 * AM * D / (SM+SI1)
DO = 4 * AO * D / (SO)

C COMPUTE THE FRICTION FACTOR.

ReO = DO*UOI/MUO
ReM = DM*UMI/MUM
ReW = DW*UWI/MUW

IF (ReO.LT.2600) THEN
FO=16/ReO
ELSE
FO = CL * (ReO)**(-M)
ENDIF

IF (ReM.LT.2600) THEN
FM=16/ReM
ELSE
FM = CL * (ReM)**(-N)
ENDIF

IF (ReW.LT.2600) THEN
FW=16/ReW
ELSE
FW = CL * (ReW)**(-N)
ENDIF
C COMPUTE THE SHEAR STRESS.

\[ T_{11} = \text{ABS}(U_{MI}-U_{WI}) \cdot (U_{MI}-U_{WI}) \cdot F_{11} \cdot D_{ENW}/2 \]

\[ T_{12} = \text{ABS}(U_{OI}-U_{MI}) \cdot (U_{OI}-U_{MI}) \cdot F_{12} \cdot D_{ENO}/2 \]

c Compute gravitation term.

\[ F_{1G} = (D_{ENO}-D_{ENM}) \cdot 9.81 \cdot \sin(ALPHA) \cdot A_{M} \cdot A_{O} \]
\[ F_{2G} = (D_{ENM}-D_{ENW}) \cdot 9.81 \cdot \sin(ALPHA) \cdot A_{M} \cdot A_{W} \]

C COMPUTE FUNCTIONS.

\[
F_{1} = T_{O} \cdot S_{O} \cdot A_{M}/D - T_{M} \cdot S_{M} \cdot A_{O}/D - T_{11} \cdot S_{I1} \cdot A_{O}/D + \\
+ T_{12} \cdot (S_{I2} \cdot A_{M}/D + S_{I2} \cdot A_{O}/D) + F_{1G}
\]

\[
F_{2} = T_{M} \cdot S_{M} \cdot A_{W}/D - T_{I2} \cdot S_{I2} \cdot A_{W}/D - T_{W} \cdot S_{W} \cdot A_{M}/D + \\
+ T_{I1} \cdot (S_{I1} \cdot A_{W}/D + S_{I1} \cdot A_{M}/D) + F_{2G}
\]

C COMPUTE PRESSURE GRADIENT

\[ D_{P DX} = (- T_{W} \cdot S_{W} + T_{11} \cdot S_{I1}) / (D \cdot A_{W}) - D_{ENW} \cdot 9.81 \cdot \sin(ALPHA) \]

C RETURN VALUES TO THE MAIN PROGRAM.

RETURN

C END THE PROGRAM.

END