A STUDY OF FLOW REGIME TRANSITIONS FOR OIL-WATER-GAS MIXTURES IN LARGE DIAMETER HORIZONTAL PIPELINES

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This thesis is dedicated to the author's parents, her special aunt and her understanding husband.

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ABSTRACT

The flow regime transitions for flow of water-oil-carbon dioxide mixtures in horizontal pipelines are presented. The experiments were carried out in a 10cm diameter plexiglass pipe. The flow regime transitions differ greatly from those for gas-liquid and oil-water two phase flow systems. Flow regime maps for various oil/water ratios are compared with the flow regime maps for water-carbon dioxide and oil-carbon-dioxide two phase flows and the Taitel and Dukler model. The results confirm that the liquid compositions have a large effect on flow regime transitions and these are not predicted by most commonly used models.

A theoretical model for the prediction of the film thickness of both oil and water for stratified flow for water-oil-gas three phase flow system is developed. The influence of interfacial waves in gas-oil and oil-water interfaces are considered in this study. The model shows that the water and oil layers decrease with increasing gas velocities. The thickness of the water and oil films are affected by flow rate, fluid properties, water/oil composition and pipe diameter.
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1. INTRODUCTION

The simultaneous flow of oil-water-gas mixtures in pipes is a common occurrence in the petroleum industry. This type of flow is frequently found in oil producing wells and associated pipelines. Most well fluids are composed of oil and gas and frequently contain water. Later in the life of well, water and carbon dioxide are often pumped into the well to enhance the oil recovery. In accessible places, eg. subsea and Alaska, it is not practicable to separate the oil, water and gas at the well. The fluids are often transported together in a single pipeline to a platform or central gathering station where the oil, water and gas are separated.

The simultaneous flow of oil and water in a horizontal pipe are classified into three types; bubble flow, stratified and mixed flow. The flow patterns observed by Russell et al. (1959) are illustrated in Figure 1. Bubble flow is characterized by oil droplets flowing in a continuous water phase. Stratified flow consists of the more dense fluid (water) flowing along the bottom of the pipe and the less dense fluid (oil) traveling above with a interface between the two phases. Mixed flow is defined by no phase separation, where water and oil mixture flows as an emulsified liquid phase. Bubble flow occurs at the very low oil velocities and low oil-water ratio. With increase in oil velocity, the flow pattern changes to stratified. Mixed flow results when the both of oil and water velocities are high.

For horizontal gas-liquid flow, various flow patterns have been reported in the literature. Govier (1962), Lin (1984) and Barnea (1980) distinguish flow patterns into four types as described in Figure 2; bubble flow, stratified (smooth, wavy and rolling
Figure 1. Flow patterns for oil-water two phase flow system.
Figure 2. Flow patterns for gas-liquid two phase flow system.
wave), intermittent (plug, slug and pseudo slug) and annular flow. Bubble flow is characterized by gas bubbles flowing in continuous liquid phase with the gas in the upper half of the pipe. Stratified flow is identified as two separate phases with gas at the top and liquid flowing along the bottom of the pipe. A smooth interface exists at low liquid and low gas velocities. When the gas velocity increases, two dimensional waves are formed at the interface. A further increase in gas velocity, causes the waves to appear in the form of rolling waves. For rolling waves, the wave is steeper at the front and rolls forward along the pipe. Lin (1984) showed that the roll waves can combine and this can result in a large roll wave or form a slug.

Plug flow is an intermittent flow and is produced by increasing the liquid velocity in smooth stratified flow. Plug flow is similar to smooth stratified flow except that there are regions where the liquid completely fills the pipe.

When liquid or gas velocity is increased, the waves grow and bridge the pipe which results in slug flow. Slug flow consists of four zones; a stratified liquid film ahead the slug with gas pockets above it, a mixing zone, the slug body, and the slug tail. The blockage is accelerated to close to the gas velocity at the slug front where the liquid film is scooped up and is assimilated into the mixing zone where the high regions of turbulence are created. This mixing zone entrains gas which is passed back to produce the slug body. After the slug passage, liquid is shed from slug tail and mixed with more incoming liquid to produce a film on which the following slug will propagate.

At higher gas velocities, pseudo slugs are formed. Pseudo slugs have a similar structure to slugs. Pseudo slugs are shorter and the frothiness is greater than in a slug
Annular flow is interpreted as liquid film flowing along the entire pipe circumference with gas flowing with entrained liquid drops in the core. The liquid film is thicker at the bottom and thinner at the top of the pipe due to the gravitational force.

Bubble flow exists at a low gas and high liquid velocities. When the gas velocity increases, stratified flow occurs. Plug flow appears when the liquid velocity is increased while the gas velocity is low. With further increase in gas velocity, the flow pattern can be changed to slug flow and then pseudo slug flow. When the gas velocity and the gas-liquid ratio are very high, annular flow is obtained.

Slug flow is, in general, the most common gas-liquid flow pattern in oil and gas industry. It is usually found in oil and gas transport pipelines since high oil and high gas flow rates are needed. The existence of slug flow can cause serious damage to the pipeline. The intermittent nature of the slugs cause large forces due to impact at bonds and at entrance to a separator. Further, Sun and Jepson (1992) showed that slug flow has regions with high shearing forces and flow turbulence that destroy the liquid boundary layer close to the wall. These regions can remove corrosion products and protective corrosion inhibitor films from the pipe wall.

There is a conspicuous absence of work involving oil-water-gas flows in pipes. The flow regime maps, models and correlations for two phase flow systems can not be used to predict the flow behavior in oil-water-gas three phase flow since the flow complexity increases when the third phase is presented. The present work is to determine the flow patterns and flow regime transitions in three phase oil-water-gas flows. Further,
a model to predict the liquid film thickness in stratified flow for three phase flow in horizontal pipeline has been developed.
2. PREVIOUS WORK

2.1 Flow regime maps

Numerous researchers have conducted work in the area related to either gas-liquid or oil-water two phase flow in horizontal pipes. A number of flow regime maps and theoretical correlations have been presented and various flow conditions and affection factors have been widely studied over past 40 years.

2.1.1 Gas-liquid two phase flow

Baker (1954) presented a flow regime map for a small diameter pipe using several fluids. He used mass flow rate together with the fluid properties as coordinates. Wallis and Dobson (1973) produced a similar flow regime map for air-water flow in 2.54 and 30.5cm channels. Presently the most widely used flow regime map is Mandhane’s plot (1974). The transition boundaries in his map are constructed based on 1178 flow observations for an air-water system. The coordinates used are superficial liquid and superficial gas velocity which are calculated from the volume flow rate divided by pipe cross section area. Barnea et. al (1980) proposed a flow regime map for 2.54cm diameter pipe for an air-water system. The results are in good agreement with Mandhane’s map.

Govier and Omer (1962) observed the flow patterns for air-water mixture flow in a 2.54cm diameter pipe. A flow regime map was constructed based on visual observations and the gas and water mass velocities are used as the coordinates. They proposed that the flow patterns are affected by phase velocities, fluid viscosities and densities.

Taitel and Dukler (1976) presented the first generalized flow regime map using
a mechanistic approach. The flow regime transitions are represented by using five dimensionless groups. The model predicts the effects of fluid properties, pipe diameter and pipe inclinations for a gas-liquid flow system. The generalized flow regime map is presented in Figure 3. This is the most widely used model at present. The dimensionless groups used are the modified Froude number \( F \), Martinelli parameter \( X \), wavy flow parameter \( K \), dispersed bubble flow parameter \( T \) and inclination parameter \( Y \).

Lin (1984) conducted an experimental study to investigate the effect of pipe diameter on the transitions of stratified to slug and stratified to annular flow. He concluded that the transition from wavy stratified to annular flow occurs because of the deposition of droplets on the upper part of the pipe. The transition from stratified to slug flow is results from the growth of small amplitude interfacial waves when the gas velocities less than 3m/s. At higher gas velocities, the slug could be formed from the growth of rolling waves if there is sufficient liquid is in the stratified film. The effect of pipe diameter is strong on the transition of stratified to slug flow, and it is small on the transition to annular flow.

Jepson and Taylor (1989) observed the transitions in a 30cm diameter horizontal pipe for an air-water two phase flow system. They concluded that as the pipe diameter is increased, the liquid velocity needed to get slug flow also increased. For large pipe diameters, annular flow occurs at lower gas velocities. Different mechanisms are identified in their study. They reported that the transition from slug to annular flow is caused by increasing the gas velocity in slug flow which induces the upper part of the slug body to become more frothy. Eventually blow-through produces the annular flow.
Figure 3. Generalized flow regime map for horizontal gas-liquid flow. Taitel et al (1976).
They also noted that increasing pipe diameter decreases the slug frequency. Slug length increases with the pipe diameter increase.

Andritsos et. al (1989) noted the effect of fluid viscosities on the flow transition of stratified to slug flow in horizontal pipe. The dimensionless liquid height (h_l/D) and gas superficial velocity (U_{sg}) are used as the coordinates for their plot. The results show the required U_{sg} for initiation of slugs is a function of the pipe diameter for high viscosity liquid. The influence of the pipe diameter is small for low viscosity liquid.

2.1.2 Oil-water two phase flow

Russel et. al (1959) observed the flow patterns of an oil-water mixture in horizontal pipe. The input oil-water volume ratio was examined in their study. They described three flow patterns in their system; bubble flow, stratified and mixture.

Charles et. al (1961) investigated the flow patterns in an equal density oil-water mixture flow in a 2.54cm diameter pipe. They defined four flow patterns: water droplets in oil, oil in water concentric which flows as water film around the pipe periphery with oil in the core, oil slug in water and oil bubble in water. A flow regime map also was presented for equal density oil-water flow system.

Arirachakaran et. al (1989) conducted an experimental study to predict the flow patterns of an oil-water dispersion in a 3.75cm diameter horizontal pipe. Tap water and five oils with viscosity of 4, 7, 58, 84 and 115cp were used in their study. They found that with water being the continuous phase, the effect of oil viscosity on flow patterns was very small.

Coutris et al (1989) developed a theoretical model to predict the relations between
the wall and interfacial shear stresses for the closure issue for a oil-water two layer flow. The height fractions and local instantaneous equations were used in their study.

Brauner (1991) proposed a physical model for the annular flow of two immiscible liquids. The momentum equations for the core and the annular regions were used in their study. The pressure drop and in situ hold up are predicted in their model.

Brauner and Maron (1992) represented a theoretical study for the flow pattern transitions in a two phase liquid-liquid flow. The flow pattern boundaries of stratified, annular dispersed and fully dispersed patterns were identified and the generalized flow pattern maps were presented in their study.

### 2.2 Theoretical studies on the transition to slug flow for gas-liquid two phase flow

For slug flow for gas-liquid flow system, many theoretical correlations have been suggested to model slug flow and the transition to slug flow.

Dukler and Hubbard (1975) provided the first accurate description of the flow in various sections of the slug unit. They found that the liquid film ahead the slug is scooped up and accelerated to the slug velocity and then passed back through the slug. A mathematical model for the process of slug formation was presented.

Jepson (1989) presented a model to predict the transition to slug flow in horizontal conduit. He assumed that slug flow is formed as a result of a hydraulic jump which just bridges the pipe. The model predicts the liquid height required for the transition to slug flow, the degree of aeration within the slug and the transnational velocity of the slug.

Presently, the most widely used model to predict flow regime transitions is the
Taitel and Dukler model (1976). In their theory, the equilibrium stratified flow is considered as the starting flow condition with a smooth gas/liquid interface. The interfacial friction factor used was the same as that for gas phase. The separate momentum balances for gas and liquid phase were used to predict the liquid film thickness in stratified flow. Kelvin-Helmholtz instability theory is used for the prediction of the onset of slug flow. The model does good job on the prediction of the transition from stratified to slug flow. However, the transition to annular flow for large diameter pipe is not at all predicted. In large diameter pipes, the gas fraction is greater at the top of the pipe and this leads to earlier transition to annular flow. This mechanism is different to that at for small diameter pipes. Taitel and Dukler model was developed from small diameter pipe experiments. This model is used as a basis for developing the model for three phase flows. This is described later.

Andritsos and Hanratty (1987) conducted experiments to study the interfacial instabilities for stratified flow for a gas-liquid system. They defined two types of waves at the gas-liquid interface: regular two dimensional waves and large-amplitude irregular roll waves. They reported that the interfacial shear stress increases when the large-amplitude waves exist. This is due to the increase in roughness at the gas/liquid interface caused by the waves. Later (1987) they extended Taitel and Dukler's model by considering the influence of interfacial waves. They proposed that when waves exist at the interface, the assumption of \( f_i = f_o \) can cause large errors. In their study, the Taitel and Dukler model was modified to include the interfacial friction factor that are dependent on the dimensionless liquid film height and gas velocity.
3. EXPERIMENTAL SETUP

The experiments were conducted in a horizontal water-oil-gas flow system. The fluids used were water, Conoco LVT200 oil and Arcopak90 oil. The oil viscosities are 2 and 15cp at 25C respectively. Carbon dioxide was used as gas. The flow regime transitions were examined under three fluid compositions which are 25% water, 75% oil, and gas, 50% water, 50% oil, and gas and 75% water, 25% oil, and gas for both oils. The schematic diagram of the flow loop system is shown in Figure 4. The oil and water are pumped from their respective tanks into separate 7.5cm ID PVC pipes. The liquid flow rate is controlled by using a by-pass system for each liquid and it is measured by individual orifice plates and manometers in the 7.5cm PVC pipe. The water and oil are combined at the T junction and mixed with gas in a mixing tank. The mixture then passes into a 10cm diameter, 10m long plexiglass section where the flow patterns can be observed and recorded. The discharge from the pipe then flows back into a 700 gallon separator. The gas is discharged to the atmosphere. The separated oil and water return to their respective tanks.

The test section is installed in plexiglass section as shown in Figure 5. It consists of a 2m long plexiglass pipe, a sample tube and four pressure taps. The sample tube is used to withdraw flow samples. The probe can be set at any point in a vertical diameter. The sample is passed into a one meter long and 1cm ID tube where the flow is allowed to separate. The volume of oil and water can be measured by using a graduated cylinder and the volume of gas can be found by calculation.

Pressure taps are used to measure the local differential pressure gradient. In slug
Figure 4. Diagram of the experiment flow loop.

A. Water-oil separator
B. Water tank
C. Oil tank
D. Liquid-gas mixing tank
E. Pump
F. Orifice plate
G. 7.5cm ID PVC pipe
H. 10cm ID plexiglass pipe
I. Gas feed
J. Gas outlet
K. By-pass valve
Figure 5. Schematic of the test section.

- A. Sample tube
- B. Pressure taps
flow, the pressure profile takes the form of intermittent and sharp jumps. There are large
increases in pressure occur as the slug passes over the transducer. The pressure drop
remains high until the slug passes. This pressure fluctuation characteristic was used to
detect the slug flow in this study. A pressure transducer and a digital strain indicator were
used to detect the slug flow. The transducer used was OMEGA Engineering Inc. model
PX820-002DV. The indicator used was series DP 87/88 digital strain indicator with a
analog output option card which can translate the indicator’s display reading to an analog
output signal. The data from the analog output was recorded by the computer software
package, Labtech Notebook. Figure 6. shows the pressure signals for slug flow.

Superficial velocities, as the flow parameters, have been used in all flow regime
maps. The flow patterns were observed over a range of liquid velocities from 0.05 to
2m/s and a range of gas velocities from 0.5 to 15m/s. The pressure in the system was
maintained at 20psi and a temperature of 25C. The flow patterns and transitions in this
study were determined visually and with pressure transducers. A VHS video camera was
used to help define and classify the flow patterns.
Figure 6. Pressure responses for slug flow.
4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Characteristic flow patterns for oil-water-gas three phase flow

The flow patterns in this study were determined visually with help of a VHS video camera. The slug flow was determined by visual observation and with a pressure transducer. The flow patterns in oil-water-gas three phase flow are similar to those seen by combining the flow patterns in gas-liquid and oil-water two phase flow. The flow patterns are shown in Figure 7. They are distinguished into three types:

Stratified flow. Water flows at the bottom of the pipe, oil flows above the water and gas flows in the upper part of the pipe. Two interfaces exist, one at the gas-oil interface and the other one at the oil-water. Stratified flow include three types of flow patterns: smooth stratified, wavy stratified and rolling wave. At low oil, water and gas velocities, both the interfaces are smooth. When the velocity of oil increases, some oil droplets appear in water phase while the water droplets flow in oil phase close to the interface. Waves are also formed at the oil-water interface. When the gas velocity is increased, waves are produced at the gas-oil interface. With a further increase in gas velocity, waves take the shape of rolling waves at the gas-oil interface. At very high gas velocities, the oil-water interface tends to break up, and the oil and water stream becomes mixed. The oil-water mixture flows as a homogeneous liquid phase with wavy flow and rolling waves at the gas-liquid interface. For Arcopak90 oil, the oil/water mixture become well mixed at lower flow rates. An emulsion is formed at lower liquid velocities.

Intermittent. Intermittent flow also consists of three types of flow patterns; plug,
Figure 7. Flow patterns for water-oil-gas three phase flow system.
slug and pseudo slug flow. In plug flow, the oil flows over a water layer. The oil bridges the pipe and the gas pushes the blockage along the pipe. The oil plug flows at a faster velocity than the water layer. For slug flow at the low gas and low liquid flow rate, oil flow above the water. When either liquid or gas flow rate is increase, the oil will break in to the water layer and produce oil/water mixture. The distribution of oil in water never becomes homogeneous. More oil is found at the top while water settles at the bottom of the pipe. The pressure signals show that the slug frequency and its pressure fluctuation are affected by the gas and liquid velocities. The increasing in gas velocity causes the pressure fluctuation increase, and the increasing the liquid velocity results the slug frequency increase. The pressure signals are presented in Figure 8 and 9 respectively. The pseudo slug pattern resembles the pseudo slug regime for gas-liquid two phase flow.

Annular flow. Thus is similar to gas/liquid two phase annular flow. The oil/water mixture flow is very well mixed.

A video tape has been produced for presenting the flow patterns for gas-liquid two phase and oil-water-gas three phase flow.

4.2 Flow regime transitions

4.2.1. Flow regime transitions for gas-liquid two phase flow.

Three flow regime maps for gas-liquid two phase flow were completed in order to compare with the previous studies and the flow regime maps for three phase flow. The flow systems used are water-carbon dioxide, oil(LVT200)-carbon dioxide and oil(Arcopak90)-carbon dioxide. The coordinates used for all flow regime maps are superficial liquid and superficial gas velocity which are calculated from the volume flow
Figure 8. Effect of increasing gas velocity on slug flow.
Figure 9. Effect of increasing liquid velocity on slug flow
rate divided by pipe cross section area. The flow regime maps are shown in Figure 10, 11 and 12 respectively. The flow maps are constructed from many experimental points as shown in Figure 10a. The transitions are found by drawing curves between the different flow regimes.

A comparison of the present work with Taitel and Dukler (1976) model for above three flow systems is also included in these Figures. The experiment results on slug transition approach Taitel’s prediction. However, the transition to annular flow is not at all predicted.

Figure 13 shows the comparison of experimental result with Jepson (1987) for 30cm diameter pipe. The transition from stratified to slug flow appears at a higher liquid velocity in Jepson’s study. This difference is due to the effect of large pipe diameter.

Figure 14 compares the present study with Harwell Laboratory (1989) for a 15cm diameter pipe. The result shows the good agreement on the transition from stratified to slug flow.

4.2.2. Flow regime transitions for oil-water-gas three phase flow.

The flow regime maps for oil-water-gas three phase flow were constructed for three liquid compositions which are 25% water-75% oil, 50% water-50% oil and 75% water-25% oil. The flow regime maps for LVT200 oil are shown in Figure 15, 16 and 17. The superficial velocities of each liquid phase can be obtained by multiplying the total liquid superficial velocity by the liquid composition. It can be seen that the configuration of the flow map is similar to the flow map for gas-liquid two phase flow but with the transitions in different locations. The comparison of flow regime transitions
Figure 10. Comparison of experimental result with Taitel et al (1976) for water-CO$_2$ flow system
Figure 10a. Flow regime map for water-CO2 flow system.
Figure 11. Comparison of experimental results with Taitel et al (1976) for oil(LVT200)-CO₂ flow system.
Figure 12. Comparison of experimental result with Taitel et al (1976) for oil (Arcopak90)-CO$_2$ flow system.
Figure 13. Comparison of Experimental Results with Jepson (1989) for water-gas in a 30cm diameter pipeline.
Figure 14. Comparison of experimental results with Hawell (1989) for water-gas flow system.
Figure 15. Flow regime map for 25% water-75% oil (LVT200)-CO$_2$ flow system.
Figure 16. Flow regime map for 50% water-50% oil (LVT200) - CO$_2$ flow system.
Figure 17. Flow regime map for 75% water-25% oil(LVT200)-CO$_2$ flow system.
for 50% water-50% oil-gas three phase flow with gas-liquid two phase flow are summarized in Figure 18. For water-oil-gas mixtures for LVT200 oil at all concentrations, slug flow occurs at lower liquid velocities than either of the water-gas and oil-gas systems. The smooth stratified flow pattern region exists for a wider range of gas velocities, and the rolling wave region is larger than for both water-gas and oil-gas cases. Pseudo slug flow occurs at similar conditions for all compositions. Annular flow is similar to that of the oil alone.

Similar maps for Arcopak90 oil are shown in Figure 19, 20 and 21. Figure 22 is the comparison of flow transitions for three phase with two phase flow. Here, the slug transition takes place between that for water-gas and oil-gas systems. The smooth stratified flow appears at lower liquid velocities, the wavy stratified flow pattern occurs over a smaller range of gas velocities, and the rolling wave flow pattern appears for a wider range of liquid velocities. The annular flow occurs at the lower gas velocities than for both water-gas and oil-gas systems. The plug flow pattern is not observed in oil-water-gas mixtures for Arcopak90 oil.

A comparison of experiment results for oil-water-gas three phase flow with Taitel et al (1976) for both oils are presented in Figure 23 and 24. The Taitel and Dukler's model does not accurately predict any of the transitions for three phase flow.

4.3 Effect of fluid composition on flow regime transitions.

Figure 25 and 26 compare the flow regime transitions with different water fractions. The results indicate that the transitions are affected by fluid compositions in water-oil-gas three phase flow.
Figure 18. Comparison of flow transitions for water-oil(LVT200)-CO$_2$ three phase flow with liquid-CO$_2$ two phase flow.
Figure 19. Flow regime map for 25% water-75% oil(Arcopak90)-CO2 flow system.
Figure 20. Flow regime map for 50% water-50% oil(Arcopak90)-CO$_2$ flow system.
Figure 21. Flow regime map for 75% water-25% oil (Arcopak90)-CO$_2$ flow system.
Figure 22. Comparison of flow transitions for water-oil(Arcopak90)-CO$_2$ three phase flow with liquid-CO$_2$ two phase flow.
Figure 23. Comparison of flow regime transitions for water-oil(LVT200)-gas mixture with Taitel model for gas-liquid two phase flow.
Figure 24. Comparison of flow regime transitions for water-oil-gas mixture with Taitel model for gas-liquid two phase flow.
Figure 25. Effect of water fractions in oil(LVT200) on flow regime transitions.
Figure 26. Effect of water fraction in oil(Arcopak90) on flow regime transitions.
For LVT200 oil, as the oil concentration increased the transition to slug flow occurs at the lower liquid velocities. For 25% water, slug flow appears at liquid velocity of 0.18 m/s. As the water fraction is increased to 50 and 75%, slug flow is reached at a liquid velocity of 0.2 and 0.22 m/s respectively. The gas velocity to obtain annular flow increases with an increase in water fraction. The transition from slug to pseudo slug flow is not affected much by fluid compositions.

For Arcopak90 oil, similar observations are obtained. The slug flow start at a liquid velocity of 0.2 m/s with water fraction of 25%. When the water concentrations rise to 50 and 75%, the required liquid velocity increases to 0.23 and 0.25 m/s respectively. For the transition to annular flow at liquid velocities below than 1 m/s, the required gas velocity for annular flow increases with water fraction.
5. Model for three phase stratified flow

As discussed earlier, the Taitel and Dukler (1976) model is the most widely used theory at present. The model predicts the flow regime transitions for given fluid properties, pipe diameter and pipe inclinations. It also predicts the frictional pressure drop and liquid height for stratified flow for gas-liquid two phase flows. However, this model does not predict the effect of the second liquid phase which has a large influence on the flow regime transitions. The purpose of this study is to develop a theoretical model to predict the liquid film thickness for water-oil-gas three phase stratified flow.

The flow system is shown in figure 27. Water flows at the bottom of the pipe, oil flows above the water and gas flows along the top of the pipe. Two interfaces exist, one at the gas-oil interface and the other at the oil-water. The shear stress at the pipe wall are defined as \( \tau_w \), \( \tau_o \) and \( \tau_g \) and the shear stress at the interfaces are designated as \( \tau_{11} \) and \( \tau_{12} \). A model to calculate the water and oil height in stratified flow is carried out by modifying the Taitel and Dukler model. Similar procedures and assumptions are used in development of this study. The influence of interfacial waves is taken into account with the method suggested by Andritsos and Hanratty (1987). The equilibrium stratified flow is considered as the starting flow condition. A momentum balance on each phase is developed as:

for gas phase,

\[
-A_g \left( \frac{dp}{dx} \right) - \tau_g S_g - \tau_{12} S_{12} = 0 \tag{1}
\]
Figure 27. Flow system for water-oil-gas three phase flow.
for the oil phase,

$$-A_o \left( \frac{dp}{dx} \right) - \tau_o S_o - \tau_u S_{ul} + \tau_{l2} S_{l2} = 0$$  \hspace{1cm} (2)$$

and for water phase

$$-A_w \left( \frac{dp}{dx} \right) - \tau_w S_w + \tau_{l1} S_{l1} = 0$$  \hspace{1cm} (3)$$

Where

$S_o$, $S_w$ and $S_{ul}$, $S_{l2}$ are the perimeter for each flow phase and interface respectively.

$A_o$, $A_o$ and $A_w$ is the flow cross section area for each phase.

$$\frac{dp}{dx}$$ is the pressure gradient.

$\tau_w$, $\tau_o$ and $\tau_o$ is the shear stress at the pipe wall for each phase.

$\tau_{l1}$ and $\tau_{l2}$ is the shear stress at the oil/water and gas/oil interface respectively.

Dividing by $A_o$, $A_o$ and $A_w$ respectively, and combining equation (1) and (2) and (2) and (3) eliminate the pressure drop term gives

$$\tau_o \frac{S_o}{A_o} - \tau_o \frac{S_o}{A_o} - \tau_u \frac{S_{ul}}{A_o} + \tau_{l2} \left( \frac{S_{l2}}{A_g} + \frac{S_{l2}}{A_o} \right) = 0$$  \hspace{1cm} (4)$$
\[
\frac{\tau_{o}}{A_{o}} - \frac{\tau_{w}}{A_{w}} - \frac{\tau_{i2}}{A_{o}} + \tau_{i2} \left( \frac{S_{i1}}{A_{o}} + \frac{S_{i1}}{A_{w}} \right) = 0
\] (5)

As with the Taitel and Dukler model, the Blasius equation is used to evaluate shear stress at the wall:

\[
\tau_{o} = f_{o} \frac{\rho_{o} U_{o}^2}{2} \quad \tau_{o} = f_{o} \frac{\rho_{o} U_{o}^2}{2} \quad \tau_{w} = f_{w} \frac{\rho_{w} U_{w}^2}{2}
\]

\[
\tau_{i1} = f_{i1} \frac{\rho_{o} (U_{o} - U_{i1})^2}{2} \quad \tau_{i2} = f_{i2} \frac{\rho_{o} (U_{o} - U_{i2})^2}{2}
\]

Where \(U_{o}, U_{o}, U_{w}, U_{i1}\) and \(U_{i2}\) are the bulk flow velocities for each flow phase and interface, and \(f_{o}, f_{o}\) and \(f_{w}\) are the friction factors given by

\[
f_{o} = C_{o} \left( \frac{D_{o} U_{o}}{\gamma_{o}} \right)^{-n} \quad f_{o} = C_{o} \left( \frac{D_{o} U_{o}}{\gamma_{o}} \right)^{-n} \quad f_{w} = C_{w} \left( \frac{D_{w} U_{w}}{\gamma_{w}} \right)^{-n}
\]

Where \(C_{o}, C_{w}\) is the coefficient for gas and liquid phase respectively.

\(D_{o}, D_{o}, D_{w}\) is the hydraulic diameter for each phase.

\(\gamma_{o}, \gamma_{o}, \gamma_{w}\) is kinematic viscosity for each phase.

Substituting into equation (4) and (5) gives

\[
C_{o} \left( \frac{D_{o} U_{o}}{\gamma_{o}} \right)^{-n} \frac{\rho_{o} U_{o}^2}{2} \frac{S_{o}}{A_{o}} - C_{o} \left( \frac{D_{o} U_{o}}{\gamma_{o}} \right)^{-n} \frac{\rho_{o} U_{o}^2}{2} \frac{S_{o}}{A_{o}} - \tau_{i2} \frac{S_{i1}}{A_{o}} +
\]
\[
\tau_{i2} \left( \frac{S_{i2}}{A_G} + \frac{S_{i2}}{A_O} \right) = 0
\]  

(6)

\[
C_L \left( \frac{D_O U_O}{\gamma_O} \right)^n \frac{\rho_O U_O^2}{2} \frac{S_O}{A_O} - C_L \left( \frac{D_W U_W}{\gamma_W} \right)^n \frac{\rho_W U_W^2}{2} \frac{S_W}{A_W} - \tau_{i2} \frac{S_{i2}}{A_O} +
\]

(7)

All the flow conditions were under turbulent flow in this study, and the coefficients used were

\[C_o = C_L = 0.046\]

\[n = m = 0.2\]

The evaluation of interfacial shear stress for gas-liquid two phase flow has been studied substantially in previous work. Depending on the flow conditions, different aspects have been contributed based on the consideration of the interface roughness due to the waves. Taitel and Dukler (1976) assumed that there is a smooth interface existing between the gas and liquid for all of gas velocities. The interfacial friction factor used was the same as the friction factor for gas phase at the pipe wall, i.e. \( f_i = f_o \). Andritsos and Hanratty (1987) argued that the shear stress at the gas-liquid interface is much larger when the large amplitude waves appear. The interfacial friction factor increases as the roughness of the interface increases. They conducted an experimental to study the effect of the waves on the interfacial friction factor in stratified gas-liquid two phase flow. Pressure
drop \((dp/dx)\), the nondimensional liquid height \(h/D\) and evaluated \(\tau_o\) were measured and used to calculate \(\tau_i\) from the equation

\[-A_g \left( \frac{dp}{dx} \right) - \tau_G S_G - \tau_L S_L = 0\]  \hspace{1cm} (8)

The results confirm that \(f_i \neq f_o\) when waves appear at the interface. \(f_i\) increases as the gas velocity increases when waves are presented. The value of \(h/D\) reduces as \(f_i/f_o\) increases. An empirical correlation for \(f_i/f_o\) was proposed as

\[\frac{f_i}{f_G} = 1 \quad \text{for} \quad U_{SG} \leq U_{SG,t}\]

\[\frac{f_i}{f_G} = 1 + 15 \left( \frac{h}{D} \right)^{0.5} \left( \frac{U_{SG}}{U_{SG,t}} - 1 \right)\]  \hspace{1cm} (9)

Where

\[U_{SG,t} = 5 \text{m/s} \left( \frac{\rho_{GO}}{\rho_G} \right)^{1/2}\]

and

\[\rho_{GO} = \text{the gas density at atmospheric pressure}\]

\[U_{SG,t} = \text{the gas velocity where the large irregular waves appear.}\]

The same theory is used to evaluate the friction factor at the gas-oil interface \((f_{o})\) for water-oil-gas three phase flow in this study. According to the experiment results, the gas
velocity and density were calculated at atmospheric pressure. The approximation of $U_{SGA}$ for design calculations is 3.5m/s. The equation for evaluation of $f_{i2}$ becomes

$$f_{i2} = f_G \times \left[ 1 + 15 \times h^{0.3} \times (\frac{U_{SG}}{3.5} - 1) \right]$$

(10)

According to the flow conditions, the gas velocities are much larger than the gas-oil interface velocities.

$$U_G \gg U_{i2}$$

Using equation (10), the shear stress at the gas-oil interface becomes

$$\tau_{i2} = f_G \left[ 1 + 15h^{0.3} \left( \frac{U_{SG}}{3.5} - 1 \right) \right] \frac{\rho_G U_G^2}{2}$$

(11)

The interfacial friction factor between the oil-water phase, $f_{ii}$ is evaluated by

$$f_{ii} = B \times C_L \left( \frac{D_o U_o}{\gamma_o} \right)^n$$

(12)

B is the augmentation of the oil-water interfacial shear factor which is defined by Brauner (1991). He presented a model for liquid-liquid water-oil annular flow system. He noted that the roughness of the interface due to the waviness is much smaller in liquid-liquid system than in gas-liquid system. The interface can be considered as a long smooth wave, and the augmentation of the interfacial shear stress can be ignored ($B = 1$). A similar phenomenon is observed in water-oil-gas three phase flow. In three phase
stratified flow, some waves, which can be classified as regular two dimensional waves, appear at the oil-water interface at the very low gas velocities. The amplitude of the waves increases as the gas velocity increases. In this model, the variation of the number B does not have a significant effect on the results. This is true even when the gas velocity is high. Comparing with the interfacial friction factor at the gas-oil interface, the alteration of B is much less sensitive to the prediction of the liquid film height, and it is considered can ignored (B = 1). The velocity of the oil-water interface is calculated as the average velocity of oil and water phase.

\[ U_{\text{U}} = \frac{U_O + U_W}{2} \]  \hspace{1cm} (13)

Using equation (13), the shear stress term for oil-water interface becomes

\[ \tau_{\text{U}} = C_L \left( \frac{D_O U_O}{\gamma_O} \right)^n \frac{\rho_O (U_O - U_W)^2}{8} \]  \hspace{1cm} (14)

The hydraulic diameters for a three phase system are found based on the assumption of Agrawal et al (1973). The oil-water interface can be considered to act as a free surface with respect to the water phase, and as a stationery surface with respect to the oil phase. The gas-oil interface can be considered to act as free surface with respect to the oil phase and a stationery surface with respect to the gas phase.
As with the Taitel and Dukler model, all the variables are evaluated in dimensionless form. The reference variables used are: $D$ for length, $D^2$ for area. All dimensionless variables with the superscript $^*$ are functions of $h/D$ or $h_1/D$

\[
D_G = \frac{4A}{S_G + S_{I2}} \quad D_O = \frac{4A}{S_O + S_{II}} \quad D_W = \frac{4A}{S_W}
\]  

(15)

\[
\overline{A_w} = 0.25 \left[ \cos^{-1}(1 - 2\overline{h}) - (1 - 2\overline{h}) \sqrt{1 - (1 - 2\overline{h})^2} \right]
\]  

(16)

\[
\overline{A_o} = 0.25 \left[ \cos^{-1}(1 - 2\overline{h}) - (1 - 2\overline{h}) \sqrt{1 - (1 - 2\overline{h})^2} \right]
\]  

(17)

\[
\overline{A_G} = 0.25\pi - \overline{A_o} - \overline{A_w}
\]  

(18)

\[
\overline{A} = 0.25\pi
\]  

(19)

\[
\overline{S_w} = \cos^{-1} (1 - 2\overline{h})
\]  

(20)

\[
\overline{S_o} = \cos^{-1} (1 - 2\overline{h}) - \cos^{-1} (1 - 2\overline{h})
\]  

(21)

\[
\overline{S_G} = \pi - \cos^{-1} (1 - 2\overline{h})
\]  

(22)

\[
\overline{S_{II}} = \sqrt{1 - (1 - 2\overline{h})^2}
\]  

(23)
\[ \overline{S}_{l2} = \sqrt{1 - (1 - \frac{2h}{l})^2} \]  \hspace{1cm} (24)

\[ \overline{U}_w = \frac{A}{A_w} \quad \overline{U}_o = \frac{A}{A_o} \quad \overline{U}_g = \frac{A}{A_g} \]  \hspace{1cm} (25)

\[ \overline{S}_w = \frac{S_w}{D} \quad \overline{S}_o = \frac{S_o}{D} \quad \overline{S}_g = \frac{S_g}{D} \]  \hspace{1cm} (26)

\[ \overline{S}_{ul} = \frac{S_{ul}}{D} \quad \overline{S}_{l2} = \frac{S_{l2}}{D} \]  \hspace{1cm} (27)

\[ \overline{A}_w = \frac{A_w}{D^2} \quad \overline{A}_o = \frac{A_o}{D^2} \quad \overline{A}_g = \frac{A_g}{D^2} \]  \hspace{1cm} (28)

\[ \overline{U}_w = \frac{U_w}{U_w^s} \quad \overline{U}_o = \frac{U_o}{U_o^s} \quad \overline{U}_g = \frac{U_g}{U_g^s} \]  \hspace{1cm} (29)

\[ \overline{D}_w = \frac{D_w}{D} \quad \overline{D}_o = \frac{D_o}{D} \quad \overline{D}_g = \frac{D_g}{D} \]  \hspace{1cm} (30)

Substituting into equations (6) and (7) gives

\[ \frac{C_G}{D} \left( \frac{DU_g^s}{\gamma_G} \right)^m \frac{\rho_g U_g^s}{2} \left( \overline{D}_g \overline{U}_g \right)^m \overline{U}_g^2 \overline{S}_g \frac{S_g}{A_g} \]
\[
\frac{C_L}{D} \left( \frac{DU^S_O}{\gamma_O} \right)^n \frac{\rho_O U^S_O}{2} \left( \frac{D_O}{U_O} \right)^n \frac{U^2_O}{A_O} \frac{S_O}{A_O} - \\
\frac{C_L}{D} \left( \frac{DU^S_G}{\gamma_G} \right)^n \frac{\rho_G U^S_G}{2} \left( \frac{D_G}{U_G} \right)^n \frac{U^2_G}{A_G} \left( \frac{U_O}{U_G} \right)^n \frac{S_G}{A_G} + \\
[1 + 15\delta^{0.3} \left( \frac{U^S_G}{3.5} - 1 \right)] \frac{C_L}{D} \left( \frac{DU^S_G}{\gamma_G} \right)^n \frac{\rho_G U^S_G}{2} \left( \frac{D_G}{U_G} \right)^n \frac{U^2_G}{A_G} \frac{S_G}{A_G} * \\
( \frac{S_{I2}}{A_G} + \frac{S_{I2}}{A_O} ) = 0 \tag{31}
\]

\[
\frac{C_L}{D} \left( \frac{DU^S_W}{\gamma_W} \right)^n \frac{\rho_W U^S_W}{2} \left( \frac{D_W}{U_W} \right)^n \frac{U^2_W}{A_W} \frac{S_W}{A_W} - \\
\frac{C_L}{D} \left( \frac{DU^S_W}{\gamma_W} \right)^n \frac{\rho_W U^S_W}{2} \left( \frac{D_W}{U_W} \right)^n \frac{U^2_W}{A_W} \frac{S_W}{A_W} + 
\]
A Fortran computer program was used to solve the above two equations. The program calculates the dimensionless total liquid film height \( \left( h/D \right) \) and water film height \( \left( h_1/D \right) \) for given flow rates, fluid compositions, densities, viscosities and pipe diameter. The predicted liquid film thickness data for Arcopak90 oil for water-oil-gas three phase stratified flow for different water-oil ratios are plotted against gas velocity in Figure 28. Vst is the total liquid superficial velocity. Vsw and Vso are the superficial water and oil velocities respectively. The ratio of the oil and water superficial velocities is the input oil/water fraction superficial velocities. The results show that the thickness of the water film increases with an increase in water fraction. The thickness of the total liquid is not affected much by the water/oil ratio. When the water concentration is fixed, both the total liquid and water film height decreases as gas velocity increases.

The experimental data is given in Figure 29. The visual observations show that at the low liquid velocities below 2m/s, the stratified flow is not fully developed due to a hydraulic gradient in the pipe. The water-oil interface tends to break up, and water and
Figure 28. Effect of fluid compositions on predicted liquid film thickness.
Figure 29. Effect of fluid compositions on experimental liquid film thickness.
oil flow as a mixture above a gas velocity of 7 m/s. The $f_{i2}/f_G$ is calculated as in equation (10). The results show a good agreement for the prediction of effect of fluid compositions on the liquid film thicknesses which the Taitel and Dukler model can not do.

The liquid film thickness $h/D$ and $h_1/D$ with assumption of $f_{i2} = f_G$ is shown in Figure 30. Comparing with experiment data shown in Figure 28, it can be seen that the model with $f_{i2} = f_G$ shows a much higher value for the film thicknesses and these do not agree well with the experimental data.

The variation of $f_{i2}/f_G$ on total liquid film thickness is illustrated in Figure 31. The results indicate that $h/D$ decreases as the value of $f_{i2}/f_G$ increases. This is in good agreement with the modified Taitel and Dukler model for gas-liquid two phase flow as shown in Figure 32. For water-oil-gas three phase flow, the variation of $f_{i2}/f_G$ also affects the thickness of the water film. Figure 33 presents the effect of $f_{i2}/f_G$ on this thickness. It indicates that with an increase in $f_{i2}/f_G$, the thickness of water film decreases.

The comparison of the predicted values with experimental data for total liquid and water film thicknesses for different fluid compositions is shown in Figure 34, 35, 36 and 37 respectively. The results confirm that the present model gives a good prediction on total liquid and water film thicknesses for water-oil-gas three phase stratified flow. The only discrepancies occur at low gas velocities where a hydraulic may still be present and at the very high gas velocities where the films no longer have flat interfaces. The films are spread around the lower part of the pipe giving a lower film thickness.
Figure 30. Effect of fluid compositions on predicted liquid film thickness.
Figure 31. Effect of $f_{i2}/f_G$ on total liquid film thickness with this theory.
Figure 32. Effect of $f_i/f_G$ on liquid film thickness with modified Taitel and Dukler model for gas-liquid two phase flow.
Figure 33. Effect of $f_{i2}/f_G$ on water film thickness with this theory.
Figure 34. Comparison of experimental data with calculated values.
Figure 35. Comparison of experimental data with calculated values.

V_{st} = 0.18 \text{ m/s}
25\% \text{ water-75\% oil-CO}_2
V_{sw}=0.045, \ V_{so}=0.135 \text{ m/s}

- This model
- Experimental data
Figure 36. Comparison of experimental data with calculated values.

V_{st} = 0.18 \text{ m/s} \\
50\% \text{ water-50\% oil-CO}_2 \\
V_{sw}=0.09, \ V_{so}=0.09 \text{ m/s} \\
- \bullet \ \text{This model} \\
- \circ \ \text{Experimental data}
$V_{st} = 0.18 \text{ m/s}$

$75\%$ water - $25\%$ oil - $\text{CO}_2$

$V_{sw} = 0.135$, $V_{so} = 0.045$ m/s

This model

Experimental data

Figure 37. Comparison of experimental data with calculated values.

Water film thickness ($h/D$)

Gas velocity (m/s)
6. CONCLUSIONS

Experimental results were collected for oil-water-gas three phase flow for 2cp and 15cp oils in a horizontal pipe. It is found that the flow patterns and flow regime transitions in oil-water-gas three phase flow differ from those obtained in both gas-liquid and oil-water systems. There is a large effect of fluid compositions on flow patterns and flow regime transitions in these systems.

For LVT100 oil, slug flow occurs at lower liquid velocities in water-oil-gas three phase flow than for both water-gas and oil-gas systems. At higher oil concentrations, annular flow appears at lower gas velocities than two phase flow.

For Arcopak90 oil, the slug transition takes place between that for water-gas and oil-gas flow. The annular flow appears at the lower gas velocity than the water-gas system.

In three phase flow, as the oil fraction is increased, slug flow occurs at lower liquid velocities and annular flow appears at lower gas velocities.

The Taitel and Dukler correlation for gas-liquid two phase flow does not predict the effect of a second liquid phase.

A model for predicting the thickness of total liquid and water film for water-oil-gas three phase stratified flow in a horizontal pipe is presented. The influence of waves at the gas-oil interface is significant, and the waves at the oil-water interface is negligible. The effect of fluid composition is very well predicted. As the water fraction is increased, the thickness of the total liquid film is not affected much, but the thickness of the water film increased. There is good agreement between predicted and experimental data.
The model can be used as an starting point for describing the flow regime transitions in three phase flows.
APPENDIX I

COMPUTER PROGRAM
**PURPOSE**

This program is to calculate the total liquid and water film thicknesses for stratified flow for water-oil-gas three phase flow system.

**INPUT VALUES**

- Water, oil and gas densities, viscosities
- Oil and gas superficial velocities
- Water fraction and pipe diameter

**OUTPUT VALUES**

- The thicknesses of total liquid and water film

**DEFINITION OF VARIABLES**

- W: WATER
- O: OIL
- G: GAS
- DEN: DENSITY
- MU: VISCOSITY
- D: PIPE DIAMETER
- S: FLUID PERIMETER
- A: FLOW CROSS SECTION AREA
- I1: OIL-WATER INTERFACE
- I2: GAS-OIL INTERFACE
- US: SUPERFICIAL VELOCITY
- F: FRICTION FACTOR
- T: SHEAR STRESS
- H1: NONDIMENSIONAL WATER FILM THICKNESS
- H: NONDIMENSIONAL TOTAL LIQUID FILM THICKNESS
- B: WATER FRACTION
- CL: COEFFICIENT OF FRICTION FACTOR TERM FOR LIQUID PHASE
- CG: COEFFICIENT OF FRICTION FACTOR TERM FOR GAS PHASE
- N: EXPONENT OF FRICTION FACTOR TERM FOR LIQUID PHASE
- M: EXPONENT OF FRICTION FACTOR TERM FOR GAS PHASE

**DECLARE VARIABLES**

REAL N, M, MUW, MUO, MUG

**SET COEFFICIENT FOR SHEAR STRESS TERM**

CL = 0.046
CG = 0.046
N = 0.2
M = 0.2

**ENTER FLUID VELOCITIES AND PROPERTIES**
WRITE(6, *)'ENTER THE VALUE OF DENW, DENO, DENG'
WRITE(6, *)'MUW, MUO, MUG, D, USG, USO, B'

READ(5, *) DENW, DENO, DENG
READ(5, *) MUW, MUO, MUG, D, USG, USO, B

*** SET INITIAL CONDITION
H1 = 0.1
H = 0.11
DH = 0.01
DH1 = 0.01
USW = B * USO

DO 10 I = 1, 880
   DO 20 J = 1, K

*** COMPUTE THE DIMENSIONLESS FLUID CROSS AREA
AW = 0.25*(ACOS(1-2*H1) - (1-2*H1)*SQRT(1-(1-
   + 2*H1)**2))
AO = 0.25*(ACOS(1-2*H) - (1-2*H)*SQRT(1-(1-
   + 2*H)**2 - AW
AG = 0.25*3.1416 - AW - AO

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

*** COMPUTE THE HYDRAULIC DIAMETER
DW = 4 * AW * D / SW
DO = 4 * AO * D / (SO + SI1)
DG = 4 * AG * D / (SG + SI2)

*** COMPUTE THE FLUID VELOCITIES
A = 0.25 * 3.1416
UW = A / AW
UO = A / AO
UG = A / AG

*** COMPUTE THE FRICTION FACTOR
FG = CG * (D*USG/MUG)**(-M) * (DG*UG)**(-M)
FO = CL * (D*USO/MUO)**(-N) * (DO*UO)**(-N)
FW = CL * (D*USW/MUW)**(-N) * (DW*UW)**(-N)
FI1 = FO

*** CONDITIONS FOR THE COMPUTATION OF FRICTION FACTOR FOR
GAS-OIL INTERFACE
IF(USG .LT. 3.5) THEN
FI2 = FG
ELSE
FI2 = FG * (1+15*H**0.5*(USG/3.5) - 1))
ENDIF

C *** COMPUTE THE SHEAR STRESS
C
TG = FG * UG**2 * USG**2 * DENG/2
TO = FO * UO**2 * USO**2 * DENO/2
TW = FW * UW**2 * USW**2 * DENW/2
TI1 = FI1 * DENO * (USO*UO - USW*UW)**2/8
TI2 = FI2 * UG**2 * USG**2 * DENG/2

C *** COMPUTE EQUATION 31 AND 32
C
F1 = TG*SG/(AG*D) - TO*SO/(AO*D) - TI1*SI1/(AO*D) +
    + TI2*(SI2/(AG*D) + SI2/(AO*D))
C
F2 = TO*SO/(AO*D) - TI2*SI2/(AO*D) - TW*SW/(AW*D) +
    + TI1*(SI1/(AO*D) + SI1/(AW*D))
C
C *** MAGNITUDE ARE LESS THAN PRECISION
C
IF ((ABS(F1) .LT. 1.0 .AND. ABS(F2) .LT. 1.0))
GO TO 30
C
C *** UPDATE TOTAL LIQUID FILM HEIGHT
C
H = H + DH

20 CONTINUE

C *** UPDATE WATER FILM HEIGHT
C
H1 = H1 + DH1

C *** SET STARTING POINT OF TOTAL LIQUID FILM HEIGHT FOR
C NEXT LOOP
C
H = H1 + 0.01
K = (0.98 - H1)/0.01
10 CONTINUE

30 CONTINUE

C *** PRINT RESULT
C
WRITE(6, 100) H1, H
100 FORMAT(5X, F6.4, 5X, F6.4)
C
STOP
END
APPENDIX II

FLUID PROPERTY TABLE
<table>
<thead>
<tr>
<th></th>
<th>WATER</th>
<th>OIL LVT200</th>
<th>OIL ARCPAK90</th>
<th>CO₂ (latm, 0°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW RATE (m/s)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>DENSITY (kg/m³)</td>
<td>998</td>
<td>810</td>
<td>846</td>
<td>1.98</td>
</tr>
<tr>
<td>VISCOSITY (kg/m·sec)</td>
<td>0.001</td>
<td>0.002</td>
<td>0.015</td>
<td>0.000015</td>
</tr>
</tbody>
</table>

Table 1. Fluid Properties
NOTATION

A = flow cross-section area
C = coefficient dependent on the size of disturbance
D = pipe diameter
f = friction factor
h = total liquid level
h1 = water level
m = exponent in friction factor term
n = exponent in friction factor term
p = pressure
S = perimeter over which the stress acts
U = velocity in the x direction
x = coordinate in the downstream direction
ρ = density
τ = shear stress
γ = viscosity

Subscripts and superscripts
G = gas
O = oil
W = water
L = liquid
i1 = oil - water interface
i2 = gas - oil interface
S = superficial
- = dimensionless variable
REFERENCES


