Study of Low Loading Heavier Phase in Horizontal Oil-Water Liquid-Liquid Pipe Flow

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Abstract**—**Production fluids are transported from the platform to tankers or process facilities through transfer pipelines. Water being one of the heavier phases tends to settle at the bottom of pipelines especially at low flow velocities and this has adverse consequences for pipeline integrity. On restart after a shutdown, this could result in corrosion and issues for process equipment, thus the need to have the heavier liquid dispersed into the flowing lighter fluid. This study looked at the flow regime of low water cut and low flow velocity oil and water flow using conductive film thickness probes in a large diameter 4-inch pipe to obtain oil and water interface height and the interface structural velocity. A wide range of 0.1–1.0 m/s oil and water mixture velocities was investigated for 0.5–5% water cut. Two fluid model predictions were used to compare with the experimental results.

Keywords**—**Interface height, liquid-liquid flow, two-fluid model, water cut.

I. INTRODUCTION

IN the petroleum industry, transfer pipelines convey production fluids from the platform to the tankers or onshore production facilities and as a result, immiscible oil–water flows occur. In horizontal flow at low water cuts and mixture velocities, stratified flow pattern occurs where the less dense phase (oil) flows above the denser phase (water) with a well-defined wavy interface. While the density difference between the phases in liquid–liquid flows may be small, very large viscosity differences are frequently encountered. Accurate prediction of the phase behaviour such as flow regimes, fractions, and pressure gradient is essential in determining pumping requirements and these provide valuable information for the design and operation of such pipeline systems. Researchers such as [1] have in the past reported work on the behavior of the phases using various methods of visualization to study the interface behaviour and the mechanisms involved in transition to dispersed flow regimes as mixture velocity increases. In such cases, droplets of one phase are entrained in another, such that there is mixing at the interface in what is called dual continuous flow as discussed in [1]-[5], the pressure drop and phase holdup in such liquid – liquid systems has been predicted using the two-fluid model method [6]-[8]. However, these and other studies have largely focused on water cuts of 10% and above. Here, we present horizontal liquid-liquid experimental campaign conducted using oil of 7 cp viscosity with 0.5–5% water cut. Data and studies for this range of low water cuts is scarce despite the high incidence of such conditions in practical petroleum pipelines.

II. EXPERIMENTAL SETUP

A. The Flow Loop

Oil and water experiments were conducted on the Three-Phase Test Facility at the Process Systems Engineering Laboratory at Cranfield University. As shown in Fig. 1, water and oil are pumped to the test area through a valve manifold system after measurement by flow meters. The length of the horizontal 4” line, in which the tests are conducted, is 26.3 m. The probe spool used in this study is mounted on the 4” horizontal flow line. This horizontal line exits directly into the 3-phase separator.

The water and oil are stored in 12,500 liters capacity tank respectively, and are pumped into the flow loop using two multistage Grundfos CR90-5 pumps. The pumps are identical and have a duty cycle of100 m^3/hour at 10 barg pressure. The flow rates of the water and oil are regulated by their respective control valves. The water flow rate is metered by a 1” Rosemount 8742 Magnetic flow meter (up to 1 kg/s) and 3” Foxboro CFT50 Coriolis meter (up to 10 kg/s) while the oil flow rate is metered by a 1” Micro Motion Mass flow meter (up to 1 kg/s) and 3” Foxboro CFT50 Coriolis meter (up to 10 kg/s).

Water injected into 4” test line via a horizontal 2” flow line which is connected to the 4” flow line by a flexible 11mm i.d. PVC tubing. There is a gate valve to supply the water and another ball valve for flow control upstream of an ultrasonic flow meter on the 2” line. From the flow meter, the water is supplied to the four inch loop through a manifold that separates the flow into the three injection points that have mini-ball valves V2, V4 and V5 on the four inch pipe. During a test, only one valve of the three is opened allowing the water to be injected at a specific location at a time. The three injection points are located 10D, 30D, and 50D from the test spool. The flow meter used for precise water injection is an Atrato ultrasonic flow meter model 760 V10 with an accuracy of ±1.5% repeatability of ±0.1%, turn down of 250:1 and 10bar rating. It uses time of flight method and measures a flow range from 0.1 to 20 liters/min. The maximum full scale error or maximum absolute error is 3.75% for the flow meter.

The fluids are subsequently piped into the phase separation area where the water and oil are separated. After separation in a horizontal three phase gravity separator, the water and oil are cleaned in the oil and water coalescers before returning to their storage tanks.

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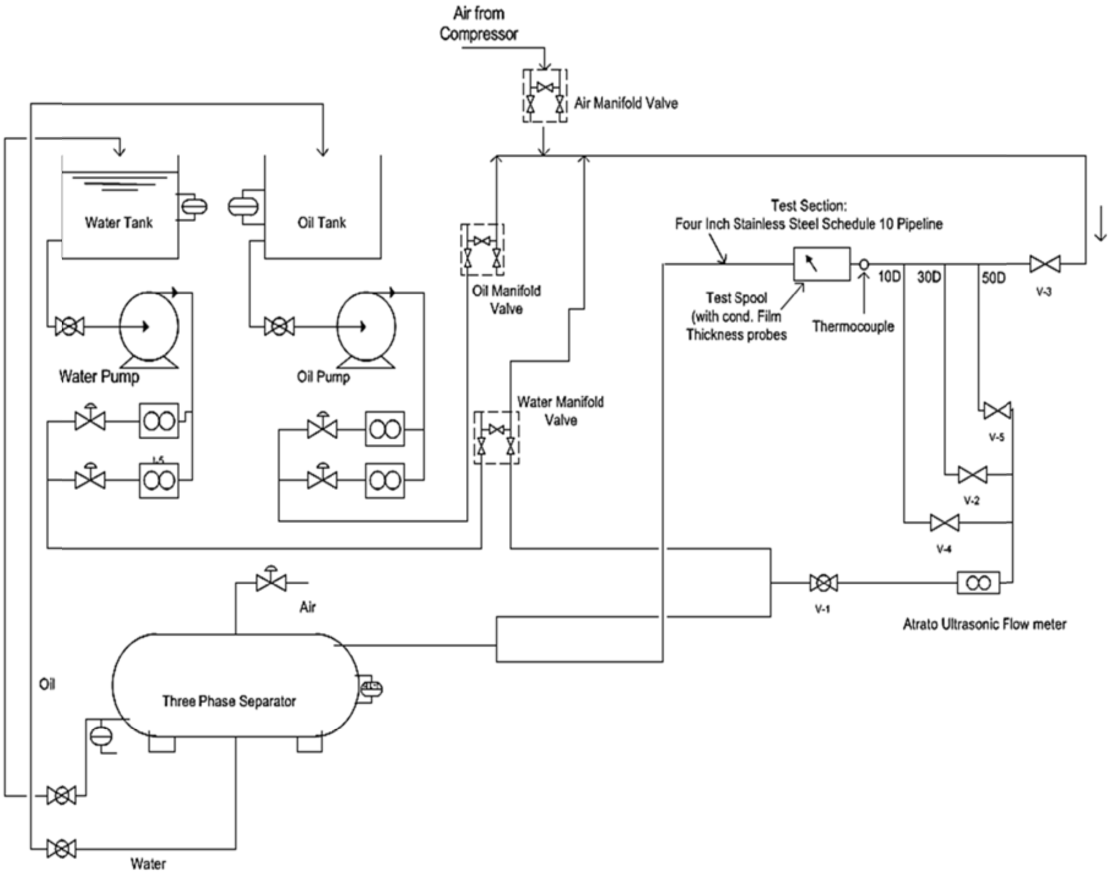


Fig. 1 Four-inch Three Phase Experimental Facility

B. Conductance Film Thickness Probes

To investigate heavier phase in a horizontal pipeline, flush mounted conductivity probes were used for water film detection. For oil and water experiments parallel plate probes were selected and they comprise basically of two strips of stainless steel separated by an insulator. There is a change in the conductivity between the two strips with a change in water film thickness t, from [9] the response could be given by a non-dimensional form;

$$G = \frac{C}{\gamma l_C} \qquad (1)$$

Where C, is conductance across the probes in Siemens, γ is the specific conductivity of the liquid in Siemens per meter and l_c as the characteristic length that depends on the probe design. For this design h as the non-dimensional film thickness and a as the gap between the two conductive plates are related by;

$$h = \frac{t}{\left({}^{a}/_{2}\right)} \qquad (2)$$

From the probe design, the relationship between the non-dimensional conductivity and non-dimensional film thickness is given by;

$$G^{*} = 0.5h \qquad (3)$$

C. Data Acquisition Systems

This test facility is automated by using Delta V, a supervisory control and data acquisition system, supplying a measured and controlled flow rate of water, oil, and air. A data acquisition system collects the signal output from the probes and this consists of a signal conditioning unit and a LabVIEW data acquisition unit that runs by a desktop PC. The conditioning circuit converts the conductivity of the probes into voltage with output being a function of film thickness. It consists of an AC driving circuit, AC signal amplifier, the rectifier and DC signal amplifier.

III. RESULTS AND DISCUSSION

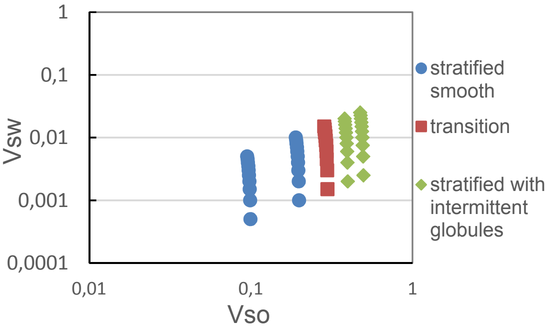
A. Flow Visualisation and Flow Regime Map

Visual observation as well as High speed videos and photography were also used for flow regime identification. As shown in Fig. **2** (a)-(c), which are the bottom views of the pipe during experiments, the oil-water interface at each condition 0.1, 0.2, and 0.3 m/s mixture velocity, is clearly visible and occasional oil globules entrained in the water phase are clearly visible. These help to classify the respective flow regimes as shown in Fig. **2** (d) into stratified, transition, and stratified with intermittent globules.

(a) 0.1 m/s

(b) 0.2 m/s

(c) 0.5 m/s



(d)

Fig. 2 Bottom view photographs of water layer with the oil – water interface clearly visible for mixture velocities of (a) 0.1, (b) 0.2, and (c) 0.5 m/s all at 3% water cut (d) Flow regime map identified using the visual observations and high speed photographs such as a-c above

B. *Comparison of Film Measurements with Predictions of the Two-Fluid Model*

Settled phase (water) holdup and pressure gradient are calculated from the steady-state combined momentum equation for both phases, a modified form of the two-fluid model. The assumption used here is similar to that presented by [10] and [5] as applied to liquid–liquid flows. The main difference with this study is their use of a curved oil–water interface based on the formulation of [7], also taking into account the differing phase velocities. However, for this study, since our experiments are in the low mixture velocity region, a no slip assumption is used. In addition, low water cuts of 5% and less used in the experiments ensures that the geometrical description using a flat interface for our two-fluid model (as shown in Fig. 3) is a good representation. The no-slip holdup is given by;

$$H_L = \frac{V_{L2}}{V_{L1}+V_{L2}} \tag{4}$$

where V_{L1} and V_{L2} are volumes occupied by the phases with subscript 1 representing the lighter phase which is oil and subscript 2 representing the heavier phase which is water in this work. Given that $\tau, f, \rho, S, \upsilon$ and D represent the shear stress, friction factor, density, wetted perimeter, kinematic viscosity and hydraulic diameter of the respective phase. While the constants C and n depend on the value of the corresponding Reynolds number of each phase. The values are C=16 and n=1 for Re <2100 and C=0.046 and n=0.2 for Re > 2100.

$$\frac{\tau_1 S_1}{1-H_L} - \frac{\tau_2 S_2}{H_L} \pm \tau_i S_i \left(\frac{1}{1-H_L} + \frac{1}{H_L}\right) + (\rho_1 - \rho_2)Ag\sin\xi = 0 \tag{5}$$

where τ_1 and τ_2 the wall shear stresses with the respective fluids while τ_i is the interfacial shear stress between the fluids. These are given by:

$$\tau_1 = f_1\rho_1\frac{U_1^2}{2}\ and\ f_1 = C_1\left(\frac{D_1U_1}{\nu_1}\right)^{-n_1} \tag{6a}$$

$$\tau_2 = f_2\rho_2\frac{U_2^2}{2}\ and f_2 = C_2\left(\frac{D_2U_2}{\nu_2}\right)^{-n_2} \tag{6b}$$

$$\tau_i = f_i\rho_i\frac{(U_1-U_2)}{2}|U_1 - U_2| \tag{6c}$$

The frictional factors $f_i = f_1, \rho_i = \rho_1\ for\ U_1 > U_2$ and $f_i = f_2,\ \rho_i = \rho_2\ for\ U_2 > U_1$, while D_1 and D_2 are the hydraulic diameters calculated as:

$$D_1 = \frac{4A_1}{S_1+S_i} \qquad D_2 = \frac{4A_2}{S_2} \qquad U_1 > U_2 \tag{7a}$$

$$D_1 = \frac{4A_1}{S_1} \qquad D_2 = \frac{4A_2}{S_2+S_i} \qquad U_1 < U_2 \tag{7b}$$

$$D_1 = \frac{4A_1}{S_1} \qquad D_2 = \frac{4A_2}{S_2} \qquad U_1 \approx U_2 \tag{7c}$$

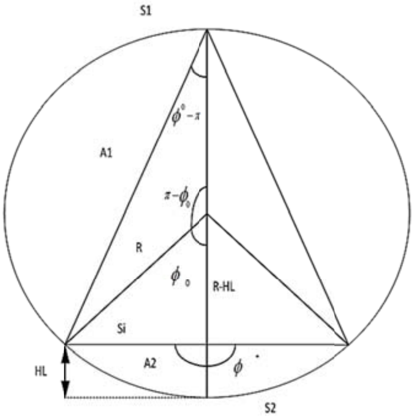


Fig. 3 Modified cross-sectional view of stratified flow used for the current model

The pipe radius is R and A_1 and A_2denote the area of the lighter and heavier phase respectively. Geometrically, these are given as:

$$A_1 = R^2 \left\{\left[\pi - \phi_0 + \frac{1}{2}\sin(2\phi_0) + \frac{sin^2\phi_0}{sin^2\phi^*}\left[\phi^* - \pi - \frac{1}{2}\sin(2\phi^*)\right]\right]\right\} \quad (8)$$

$$A_2 = R^2 \left\{\left[\phi_0 - \frac{1}{2}\sin(2\phi_0) - \frac{sin^2\phi_0}{sin^2\phi^*}\left[\phi^* - \pi - \frac{1}{2}\sin(2\phi^*)\right]\right]\right\} \quad (9)$$

$$S_1 = 2R(\pi - \phi_0), S_2 = 2R\phi_0$$

$$S_i = 2R(\pi - \phi^*)\frac{\sin(\phi_0)}{\sin(\phi^*)} \quad (10)$$

Due to the assumption of a flat interface ϕ^*= 180 degrees, thus (5) becomes (11), while (8) and (9) become (12) and (13). Substituting from the geometry (10) becomes (14):

$$\frac{\tau_1 S_1}{1-H_L} - \frac{\tau_2 S_2}{H_L} \pm \tau_i S_i\left(\frac{1}{1-H_L} + \frac{1}{H_L}\right) = 0 \quad (11)$$

$$A_1 = R^2 \left\{\left[\pi - \phi_0 + \frac{1}{2}\sin(2\phi_0)\right]\right\} \quad (12)$$

$$A_2 = R^2\left\{\left[\phi_0 - \frac{1}{2}\ sin(2\phi_0)\right]\right\} \quad (13)$$

$$S_1 = 2R\left(\pi - \sin^{-1}\frac{S_i}{R}\right), S_2 = 2R\sin^{-1}\frac{S_i}{R}$$

$$S_i = 2R(\pi - \phi^*)\frac{\sin(\phi_0)}{\sin(\phi^*)} \quad (14)$$

When the geometrical expressions are substituted in (12) and solved iteratively for H_L in a code written in MATLAB, the value of the holdup as water film height was obtained at various water cuts and mixture velocities. A comparison of these two-fluid model predictions with the experimentally measured water film height is as shown in Fig. 3. There is an increase in water film thickness with an increase in water cut. The prediction model was also compared with the results of experiments conducted on the three phase facility at Cranfield University Oil and Gas Centre. These are given in Figs. 4-6.

As can be seen, the two fluid model predictions at 0.1 m/s mixture velocity (Fig. 4) well matches the experimentally observed values except at higher water cuts where the model under predicts. This can be explained by the fact that as the water cut increases, the curvature of the interface increases thereby deviating from the flat interface assumption of the two fluid model. For the higher mixture velocities of 0.2 and 0.5 m/s in Figs. 5 and 6, more discrepancies occur most of which are over-predictions of the experimental values. An explanation for these may be the increasing phase slip that occurs as the mixture velocity increases, which is occasioned by increasing only the water flow rate. Therefore, the premise of no-slip used in the model is slightly weakened. Nevertheless, the differences between the model predictions and experimental values are no more than ±15%. This means that in order to improve predictions, more complicated geometrical relationships for curved interfaces may be applied. Furthermore, the no-slip assumption may be abandoned, but this may not result in more accurate solutions of the two fluid model at very low mixture velocities.

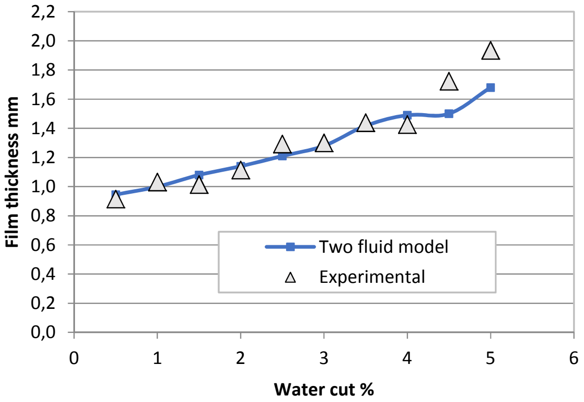


Fig. 4 Variation of experimental and predicted film thicknesses against water cut at 0.5 m/s mixture velocity

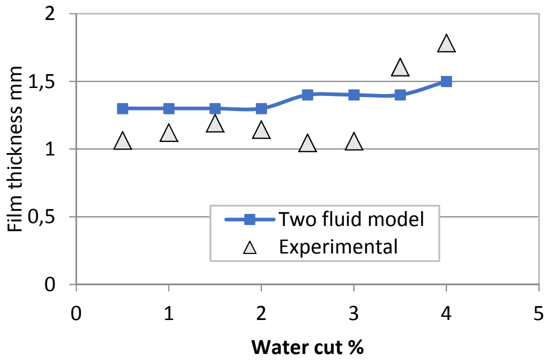


Fig. 5 Variation of experimental and predicted film thicknesses against water cut at 0.2 m/s mixture velocity

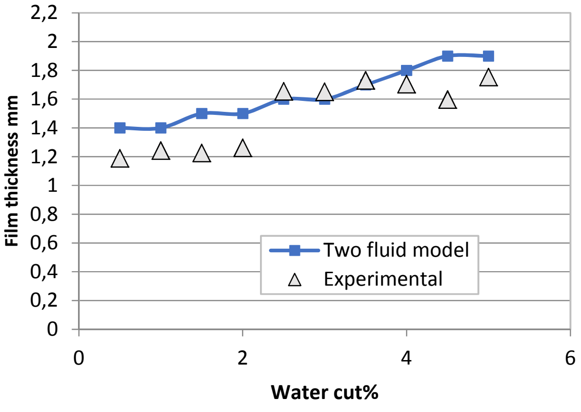


Fig. 6 Variation of experimental and predicted film thicknesses against water cut at 0.5 m/s mixture velocity

IV. CONCLUSION

An experimental study of oil –water two-phase flow has been conducted in a horizontal 4 in. pipe at low water cuts of less than 5% which are rare in the reported literature. Such flow conditions are frequently encountered in the petroleum transfer pipelines. Results show that water height measured using a dual plate conductance sensor, is proportional to both the inlet water cut and mixture velocity. Model predictions using a modified two-fluid model were in agreement with the experimental settled phase heights. Thus, this shows that the adapted two fluid model could be used for holdup prediction for low water cut liquid-liquid stratified flows.

ACKNOWLEDGMENT

A. Koguna, A. Aliyu, and Y. Baba would like to acknowledge the support provided by Nigeria's Petroleum Technology Development Fund for their doctoral studies.

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