1. INTRODUCTION

Flows of two immiscible liquids were encountered in a diverse range of processes and equipments. Particularly in the petroleum industry, where mixtures of oil and water are transported in pipes over long distances, accurate prediction of oil–water flow characteristics, such as flow pattern, water holdup and pressure gradient is important in many engineering applications. However, despite of their importance, liquid–liquid flows have not been explored to the same extent as gas–liquid flows. In liquid–liquid systems the density difference between the phases is relatively low. However, the viscosity ratio encountered extends over a range of many orders of magnitude. Moreover, oils and oil–water emulsions may show a Newtonian or non–Newtonian rheological behavior. Therefore, the various concepts and results related (gas–liquid) phase laws cannot be readily applied to liquid–liquid systems.

Diverse, flow patterns were observed in liquid–liquid systems. In most of the reported studies the identification of the flow pattern is based on visual observations, photographic/video techniques, or on abrupt changes in the average system pressure drop. In some recent studies, the visual observation and pressure drop measurements are backed up by conductivity measurements, high frequency impedance probes or Gamma densitometers for local hold-up sampling, or local pressure fluctuations and average hold-up measurements[1].

The flow patterns can be classified into four basic prototypes: Stratified layers with either smooth or wavy interface; Large slugs, elongated or spherical, of one liquid in the other; A dispersion of relatively fine drops of one liquid in the other; Annular flow, where one of the liquids forms the core and the other liquid flows in the annulus. In many cases, however, the flow pattern consists of a combination of these basic prototypes. When the water is the continuous phase, oil viscosity seems to have a minor effect on the flow patterns. However, the oil viscosity affects the location of the phase inversion dispersion oil in water or vice versa (Dw /o to Do/w). The input water-cut, $U_{ws}/ U_{m}$...
required inverting the dispersion decrease with increasing the oil viscosity. Core flow (water annulus) is usually not obtained in oil–water systems of relatively low oil viscosity and relatively high Δρ \(^2\).

As in gas–Liquid systems, the flow pattern depends on the liquids flow rates and physical properties, tube diameter and inclination. However, due to the relatively low density differential between the two fluids, the role of gravity in liquid–liquid systems diminishes. Therefore wall-wetting properties of the liquid and surface tension forces become important and may have a significant effect on the flow pattern. However, for specified operational conditions, different flow patterns may result by changing the tube material hydrophobic or hydrophilic. The start-up procedure (oil flowing in the pipe and then introducing water or vice versa), which affects the effective liquids-wall adhesion, or entry conditions (type of nozzle used to introduction the two-liquids) is also an important factor in controlling the flow pattern\(^3\).

Stratified flow is considered as a basic flow pattern in horizontal or slightly inclined liquid–liquid systems of a finite density differential, since for some range of sufficiently low flow rates, the two liquids phases tend to segregate. The modeling of liquid–liquid stratified flows requires the consideration of additional aspects in comparison to gas–liquid stratified flows. Due to the variety of physical properties that may be encountered, it is not a priori evident which of the phases is the faster (or specified operational conditions). Therefore, the ambiguity concerning the appropriate closure law for representing the interfacial shear is even greater than in the case of gas–liquid flows. Multiple solutions can be obtained for specified operation conditions in co–current and counter–current inclined flows, which are relevant in practical applications. Moreover, as a result of the relatively low density difference, surface tension and wetting effects become important, and the interface shape (convex, concave, plane) is an additional field that has to be solved by Oliemans \(^3\).

2. EXPERIMENTAL SET-UP

The experimental work was performed on the liquid–liquid flow facility shown in Figure 1. The main purpose of the experimental work is to design, build up and operate a simple and easy circulation loop in order to examine and study the single and two phase phenomena of liquid–liquid flow. It was built after several changes in the rig. The test section pipes are horizontal and the length of each section was 127 cm. The location of the test section change for more accuracy readings of pressure and for better flow pattern observation. Also the entrance region of water in gas oil flow changes to reduce the turbulence direction in the entrance region. The one way valve was used in way of water flow to prevent the mixing between gas oil and water flow.

3. EXPERIMENTAL PROCEDURES

3.1. Experimental Single Phase Procedure

After calibration was achieved the single phase flow process begins by flow gas oil only and taking the readings for pressure drop and flow rates. The readings of the pressure drop taking after steady state for the flow. The readings take with change in the flow rate of gas oil. Also the single phase process performed for water flow in pipe then taking the readings for the pressure drop and flow rate. The pressure drop and flow rates which are measuring for water and gas oil used for calculation the friction factor and other parameters, so that the pressure drop increasing with increase flow rate of any liquid for all sections pipe. The velocity can be calculated from flow rates for liquids and cross section area of the pipe, also Reynolds number evaluated from other parameters.

The purpose from this process is testing for the system and to be sure that the all parts of system working in a true way by mapping the relations between friction factor with Reynolds number and comparison it with relation in Moody chart.

3.2. Experimental Two Phase Procedures

After the single phase flow process was finished and the all parts of the system work in systematic way, the two phase processes are beginning to take the pressure drop readings and flow patterns in the test section.

The first step is pumping of gas oil from reservoir to the pipes by constant flow rate. The gas oil flow at first in the metallic tube (galvanize tube) and then enters to the transparent tube (plastic tube). The amount of flow which has been pumped to the system are (5, 7, 10, 12 and 15) liter per minute. After the stability of readings for manometers, the pump of the other less viscous liquid begins in the mixing section. The amount of water flow rates 1-15 liter per minute with constant the flow rate of gas oil. When the water pumping in the presence of the other liquid (gas oil)
the reading of U tube manometer and the pressure meter will change as reading taking occur after a period differs according to the amount of flows in the system.

After the stabilization of reading the type of flow should be observed through the transparent pipe and record photographically flow. Also a pointer will be placed at the limiting line between high viscosity liquid and the low viscosity liquid on the Perspex pipe to know the magnitude of the height of water layer toward the gas oil layer and also recording that height. After that pumping of a new amount of gas oil with stabilizing the amount of water from 1-15 liter per minute at a specific and taking the preceding readings (pressure supply, pressure losses and the observation flow patterns). After recording all the required data the flow liquids are separated to start another test.

4. EXPERIMENTAL ANALYSIS

4.1 Geometric Considerations

In order to find the other parameters like stresses and pressure drop it is necessary to express \( S_w, S_o, h_I \) in term of \( A \). This is done by introducing the angle \( \theta \) as shown in Figure 2, which is the angle subtended by the interface in a normal cross section at the center of the pipe, then by simple geometry \(^4\) described as:

\[
S_w = \frac{\theta}{2\pi} \tag{1}
\]

\[
S_o = \frac{2\pi - \theta}{2\pi} \tag{2}
\]

\[
S_I = \sin \frac{\theta}{2} \tag{3}
\]

\[
A = \frac{\theta - \sin \theta}{2\pi} \tag{4}
\]

\[
h_I = \frac{1}{2} - \frac{\cos \frac{\theta}{2}}{2} \tag{5}
\]

All these parameters depending on angle \( \theta \) which are limited by experimental determination by observations on the Perspex pipe which give our the limits for each phase also the increase in water flow rate led to decrease in \( S_o \) and increase in \( S_w \) due to the increasing in hold-up of water in the pipe.

4.2 Stresses on the phases

The shear stress due to viscous effects on the walls of the pipe and at the interface between the two fluids is usually modeled \(^{[1]}\) as in the form:

\[
\tau_w = \frac{1}{2} \rho_w f_w |u| \tag{6}
\]

\[
\tau_o = \frac{1}{2} \rho_o f_o |v| \tag{7}
\]

\[
\tau_I = \frac{1}{2} \rho_I f_I (v-u)|v-u| \tag{8}
\]

Which are derived from empirical observations and application of Prandtl's mixing length formula \(^{[4]}\). In engineering literature the fanning friction factors \( f_w \) and \( f_o \) are function of the Reynolds number of the flow, and are usually chosen to be the same as the friction factor for the corresponding single phase flow. From experimental studies this is a complicated function of the Reynolds number and the pipe roughness that was indicated by Sunde\(^{[5]}\). However or turbulent flow in smooth pipe the simpler modified Blasius correlation is usually used for stratified two-phase flow:

\[
f = C \Re^{-m} \tag{9}
\]

\[
R_w = \frac{4u AA}{v_o S_w} \tag{10}
\]

\[
R_o = \frac{4u(1-A) A}{v_o(S_o+S_I)} \tag{11}
\]

The increasing of water stresses due to the increasing in water velocity at high water flow rate, but the stresses of gas oil be less than in water due to the lower velocity of gas oil at high section area of gas oil also the high Reynolds number led to decreasing in friction factor. The stresses on the phases and Reynolds numbers are deal with more detailed in prediction of the pressure drop calculations.

4.3 Prediction of Holdup

Having estimated the range of stable stratified flow attempts have next been made to predict the in-situ volume fraction occupied by either of the phases in the conduit. This is an important parameter because the hydrodynamics, heat and other transport characteristics of such flow depend upon of the distribution and proportion of the two phase in the flow passage. It is often equal to the input volume fraction. The parameter has showed by Chakrabarti \(^{[6]}\) as:

\[
H_L = \frac{V_{L2}}{V_{L1} + V_{L2}} \tag{12}
\]

where \( V_{L1} \) and \( V_{L2} \) are the respective volumes occupied by the lighter and the heavier liquids. Here water is the heavier phase and gas oil is the lighter phase.

A further attempt has been made to note the difference between the in-situ and input volume fraction of the two phases in order to note whether the input volume fraction can be used to analyze liquid-liquid flows in the absence of data on in-situ volume fractions. The input volume fraction has been expressed in as:

\[
\beta = \frac{Q_{SW}}{Q_{SW} + Q_{SO}} \tag{13}
\]
where $Q_{SW}$ and $Q_{SO}$ are the respective volume flow rates of water and gas oil. So the hold-up of water increasing with increasing in superficial water flow rate.

### 4.4 Prediction of the pressure drop

The prediction is given in such a way that the system will stabilize to its minimized total energy and at the same time the system will have same pressure drop in both the phases. The consideration of a flat interface during two phase flow through a circular conduit was taken into account by Sunder [5]. From a geometrical consideration of Figure 2, where $A_W = \text{area occupied by water phase}$:

$$A_W = \frac{R^2}{2} (\theta - \sin \theta)$$  \hspace{1cm} (14)

where $R$ is the inner radius of the conduit, and $\theta$ is the angel subtended by the water at the center. $A_O$ is the area occupied by the oil phase and:

$$A_O = \pi R^2 - A_W = \frac{R^2}{2} (2\pi - \theta + \sin \theta)$$  \hspace{1cm} (15)

The system shall stabilize to its minimized total energy corresponding to $\theta_o$. Additionally, the system will have the same pressure drop in both phases – oil phase pressure drop per unit length = water phase pressure drop per unit length:

$$\frac{\partial p_o}{\partial Z} = \frac{\partial p_w}{\partial Z}$$  \hspace{1cm} (16)

If water velocity is more than the oil velocity ($U_w > U_o$) then, force exerted by water phase (per unit length) = shear stress ($\tau$) of water perimeter of wall occupied by water + shear stress at the interface perimeter of the interface:

$$\tau = \tau_w R \theta + \tau_{ow} 2R \sin \left(\frac{\theta}{2}\right)$$

So that:

$$\frac{\partial p_w}{\partial Z} = \frac{1}{A_W} [\tau_w R \theta + \tau_{ow} 2R \sin \left(\frac{\theta}{2}\right)]$$  \hspace{1cm} (17)

And similarly:

$$\frac{\partial p_o}{\partial Z} = \frac{1}{A_O} [\tau_o R (2\pi - \theta) - \tau_{ow} 2R \sin \left(\frac{\theta}{2}\right)]$$  \hspace{1cm} (18)

If $U_o > U_w$ then:

$$\frac{\partial p_w}{\partial Z} = \frac{1}{A_W} [\tau_w R \theta - \tau_{ow} 2R \sin \left(\frac{\theta}{2}\right)]$$  \hspace{1cm} (19)

$$\frac{\partial p_o}{\partial Z} = \frac{1}{A_O} [\tau_o R (2\pi - \theta) + \tau_{ow} 2R \sin \left(\frac{\theta}{2}\right)]$$  \hspace{1cm} (20)

where the relation of velocity with shear stress can be expressed as:

$$\tau_w = f_w \rho_w \frac{U_w^2}{2}$$  \hspace{1cm} (21)

$$\tau_o = f_o \rho_o \frac{U_o^2}{2}$$  \hspace{1cm} (22)

$$\tau_{ow} = f_{ow} \rho_o \left(\frac{U_w - U_o}{2}\right)^2$$  \hspace{1cm} (23)

### 5. RESULTS AND DISCUSSION

#### 5.1. Single phase flow

The purpose of the single-phase liquid experimental work was done to determine the pressure losses for each phase alone and to estimate the friction factor. It is noted that the pressure gradient increase with distance $x$ for gas oil flow this increasing is linear with distance $x$. Other relations for friction factor with Reynolds number for gas oil indicated to decrease linearly for friction factor with increase Reynolds number as illustrated in Figure 2. The comparison between friction factor for experimental calculations and friction factor for Moody chart indicate to converge between them as shown in Figures 2 and 3.

In Figure 3, the gradient of the friction factor for water flow is more than in Figure 2 for water flow because of the limits of Reynolds number for water flow which are between 8000 to 20000 be high than in gas oil flow between 4000 to 9000. Also when comparison was done with values of friction factor of Moody chart with those get from experimental calculation we note the converge is valid in all cases.
The flow regime for low gas oil and high water flow rates or vice versa exhibits wavy stratified characteristics. A pictorial representation of the different flow regime is present in Figure 4. Comparing the most widely used maps of Sunder [5] for liquid-liquid flow in Figure 5, it can be seen that the transitions boundaries and the phase inversion limits appear to be very close for all cases so the stratified flow pattern appear in vast range of flow rate for both liquids, also the direction of developing of flow patterns denotes to the same way. It can be concluded that distribution of the two phases are distinctly different for gas-liquid and liquid-liquid cases, and the regimes of the gas-liquid flow cannot be extended to liquid-liquid mixtures merely by substituting the phase physical properties in the transitions equations. The reason behind the existence of the stratified flow over a wider range of phase flow rates can be attributed to a greater tendency of liquids to remain as spherical drops at the interface rather than to form elongated plug like bubbles characterizing gas-liquid flow.

5.2. Pressure drop of two phases

Results of pressure losses measurements for the different flow pattern were plotted against the superficial flow rate of one phase keeping the other phase flow rate as a fixed parameter. The effect of the variation in water superficial flow rate that an increase in the water flow rate (at constant gas oil flow rate) led to substantial increase in the measured pressure drop, see Figures 6 and 7, even for very low flow rates of water. The reason behind this can be attributed to the fact that when the flow rate of water increase, the greater fraction of the pipe wall covered by the rough interface formed between the water and oil [6] leads to an increased fraction factor and pressure gradient. An increase in the oil flow rate also leads to an increase in the losses. Most of this increase is simply due to the scaling of the pressure drop with the square of the velocity where gas should be replaced by gas oil. However, they may be an additional increase due to the splattering of water around a greater portion of the pipe perimeter. This increase area of rough surface increases the pressure drop.
The pressure drop \[5\] becomes follows: It is evident from the observation that for smooth stratified flow, or in the other words for a very low flow rate, wall fraction predominates to give a lower pressure drop with increasing flow rate of water, but approaching dispersion, velocity effects predominate to give a higher pressure drop. As the friction factors in turbulent dispersed flows are less than in other flows, there is a drug reduction in dispersion. Moreover, the pressure gradient during dispersed flows rises sharply with increasing water flow rate because of the water contribution.)
5.3. Mathematical Results

5.3.1. Prediction of hold-up

The water hold-up is plotted versus superficial water flow rate in Figure 8. It indicates a similar trend of variation of $H_L$ with phase velocity as given by $H_L$ increase with increase Reynolds number of water ($Re_w$), see Figure 9. This reason can be attributed to the increase in height of water lead to an increase in area of water and decrease in area of gas oil.

5.3.2. Prediction of pressure drop

The calculated pressure drop for different velocities is compared with experimental data in Figure 10. At the stratified range of flow rate, the presence of both phases separately enables the system to be potentially stable and the prediction agree closely with the experimental data. This may be attributed to (minimization of energy). At a higher oil fraction the model cannot predict adequately since the pressure gradient does not behave normally during interfacial dispersion or for dispersion oil in water.

That indicated to more effect for water percentage on pressure gradient so the effect of lubricating film of water is clear at high gas oil flow rate (high viscous oil flow rate). The decrease in pressure gradient at a higher oil fraction could be due to the drag reduction phenomenon. It has been observed that the degree of drag reduction increases with the dispersed phase fraction while drag reduction is higher in oil continuous than in water continuous flows. Drag reduction results in a greater reduction in pressure drop for an oil dominated system than that of a water dominated system. In gravity dominated system, e.g., a stratified wavy pattern, at a lower phase velocities energy minimization plays a major role in producing a good prediction.

Nomenclature

The following symbols are used generally throughout the text.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross sectional area of pipe</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_W$</td>
<td>Cross sectional area of water phase</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_O$</td>
<td>Cross sectional area of gas oil phase</td>
<td>m$^2$</td>
</tr>
<tr>
<td>B</td>
<td>Input volume fraction of heavier phase</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>Constant in equation (3.19)</td>
<td>-</td>
</tr>
<tr>
<td>$C_AF$</td>
<td>Core-annular flow</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>Hydraulic diameter</td>
<td>m</td>
</tr>
<tr>
<td>$Dp$</td>
<td>Differential pressure</td>
<td>Pa/m</td>
</tr>
<tr>
<td>f</td>
<td>Fiction factor</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>$H_L$</td>
<td>Hold-up</td>
<td>-</td>
</tr>
<tr>
<td>$h_I$</td>
<td>Height of interface region</td>
<td>m</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of test section</td>
<td>m</td>
</tr>
<tr>
<td>$Re_w$</td>
<td>Reynolds number</td>
<td>-</td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>Q</td>
<td>Flow rate</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>R</td>
<td>Radius of the pipe</td>
<td>m</td>
</tr>
</tbody>
</table>
S: Perimeter of the tube
SS: Smooth Stratified flow
SW: Wavy Stratified
TS: Test section for system
P: Plug flow
TL: Three layers flow
D_o/W&W: Dispersion oil in water and water flow
u: Velocity of water phase m/s
v: Velocity of gas oil phase m/s
V_L: Volume occupied by phase m^3

Greek symbols

- \( \theta \): Angle subtended by water at the center
- \( \mu \): Dynamic viscosity kg/m.s
- \( \rho \): Phase density kg/m^3
- \( \sigma \): Surface tension N/m
- \( \tau \): Sheer stress kg/m.s^2
- \( \Delta P \): Pressure drop Pa/m

Subscript

- 1: Heavier phase
- 2: Lighter phase
- o: Oil phase
- w: Water phase
- ow: Oil-water interfacial condition
- s: Superficial

REFERENCES


