IN-SITU PHASE FRACTIONS FOR OIL AND WATER OCCUPIED IN PIPE CHANNEL

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ABSTRACT

Using of traversing beam gamma densitometer measurement for the phase fractions distribution of a mixture of water and kerosene namely EXXSOL-D80 was achieved experimentally into 25.4 mm ID in a horizontal pipe channel. The phase fractions distribution was determined with the beam being traversed in three directions for examples 0°, 45° and 90° of the vertical line passing through the axis of the pipe channel. Measurements were made at three positions spaced along the 9.7 m test section length (1.0 m, 5.85 m and 7.72 m along the horizontal pipe channel) with three input water fractions of 40%, 46% and 60%. The measurements were done in Two-phase Oil Water Experimental Rig (TOWER) facility. This facility allows the two fluids to be fed to the test section before they separated and returned once more to the test line. The flow developed naturally from an initial stratified flow in which the oil and water were introduced separately at the top and the bottom of the test section respectively. The flows were such that the liquids were fully inter-dispersed by the end of the test section. The phase fractions distribution was shown to be homogeneously mixed near to the outlet of the test section. The mean hold-up was found to depend on the input phase fraction, the mixture velocity and the position along the test section.

Keywords: phase fraction, gamma densitometer, pipe channel, mean hold-up, mixture velocity.

INTRODUCTION

The in-situ phase fractions ("holdups") of the two phases (ε_O and ε_W for the oil and water respectively) are defined as the fraction of the channel cross-section occupied by the two phases. One may also define input phase fractions (y_O and y_W) for the two phases which correspond to the ratio of the phase input volume flow rate (q_O and q_W) to the total volume flow rate ($q_O + q_W$). In general, $\varepsilon_O \neq y_O$ and $\varepsilon_W \neq y_W$ because the relative motion ("slip") between the phases. We may therefore define a "slip ratio" S as:

$$S = \frac{U_O}{U_W} \tag{1}$$

U_O and U_W differ from the superficial velocities U_{SO} and U_{SW} of the two phases which are defined as the ratio of the volumetric flow rates to the channel cross sectional area, A. Thus:

$$U_{SO} = \frac{q_O}{A} \qquad \text{and} \qquad U_{SW} = \frac{q_W}{A} \tag{2}$$

The following relationships also apply:

$$U_O = \frac{U_{SO}}{\varepsilon_O} \qquad \text{and} \qquad U_W = \frac{U_{SW}}{\varepsilon_W} \tag{3}$$

$$S = \frac{U_{SO}}{U_{SW}} \cdot \frac{\varepsilon_W}{\varepsilon_O} = \frac{\varepsilon_W(1 - y_W)}{y_W(1 - \varepsilon_W)} = \frac{y_O(1 - \varepsilon_O)}{\varepsilon_O(1 - y_O)} \tag{4}$$

Thus, the "slip ratio" is given by

$$S = \frac{U_O}{U_W} \tag{5}$$

We may also define a "slip velocity" U_S as:

$$U_S = U_O - U_W \tag{6}$$

from which it follows that:

$$U_S = \left(U_{SO} - U_{SW}\right)\left(\frac{y_O}{\varepsilon_O} - \frac{y_W}{\varepsilon_W}\right) \tag{7}$$

Relative motion between the phases can occur for two reasons:

(1)   Local relative motion due to the fact, for instance, that dispersed phase elements are moving at a different velocity to the continuous phase which surrounds them.

(2)   Average relative motion due to the differences in the profiles of phase hold-up and velocity in the pipe. This type of relative motion can appear even if the local velocities of the dispersed and continuous phases are identical at all points in the pipe cross section.

It has often been suggested by Arirachakaran [4] that liquid-liquid dispersed flows can be predicted on the basis of the homogeneous model for which

$$U_S = 0, \quad \varepsilon_O = y_O, \quad \varepsilon_W = y_W \text{ and } S = 1$$

This model is applied by considering the flow to be equivalent to a single phase flow with a density and viscosity given a suitable (e.g. linear) interpolation between the viscosities of the two fluids [9].

Slip ratios (ratio of oil velocity to water velocity) were greater than unity when the water was the continuous phase in contact with the pipe wall [5]. When oil was the continuous phase in contact with the pipe wall, the slip ratio was less than unity. Slip ratio became close to unity when the flow velocity was high. According to Russell [10], the slip ratio for turbulent flows depended only on the superficial water velocity. However, in the laminar region the slip ratio agreed reasonably with the predictions from a theoretical model for the laminar flow of two liquids between parallel plates.

Previously, few researchers found that the measurements of the local volume fraction could be obtained using high frequency probes and gamma densitometry [1-3, 14-16]. The local volume fraction can be evaluated and displayed by creating a contour plot over the measured cross section. A typical plot of this type is shown in Figure 1. This data can be averaged over the pipe cross section to yield average hold-up values from which the slip ratios can be calculated using the above equations. The slip ratios for stainless steel pipes were closer to unity than the results from the acrylic pipe under similar conditions by using high frequency probes [1,2]. This was attributed to the fact that the respective flow patterns in the stainless steel pipe were more homogeneous than in the acrylic resin pipe.
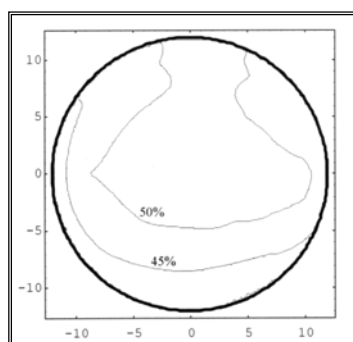

Figure 1: Oil volume fraction distribution in a cross section in the stainless steel pipe for mixture velocity 1.7 m/s and 0.5 of input oil fraction [2].

A test on liquid-liquid flow was carried out in a horizontal tube using both high frequency probes and gamma densitometry [14-16]. Tomographs obtained using the respective techniques are shown in Figure 2. Although there is qualitative agreement, there are also significant deviations between the methods, particularly when in-line mixers had been used and swirl was present [14, 16]. These differences are reflected in differences in calculated in-situ hold-up as exemplified in Figure 3. It can be concluded that the gamma method was the more reliable and

his results for slip ratio obtained by the methods are illustrated in Figure 4 [14,16]. Slip ratios greater than unity were obtained at low total superficial velocities. As velocity increased, the slip ratio approached unity and the use of a mixer produced the same effect.
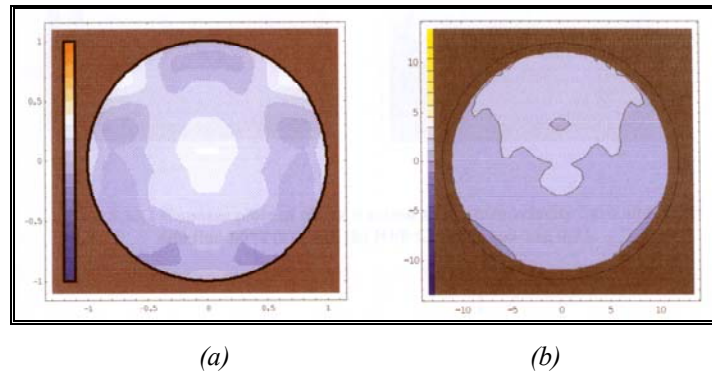

(a)   *(b)*

Figure 2: Contour plots of water phase fraction at mixture velocity 3 m/s and 0.46 input water fraction using (a) Gamma densitometer system (GDS) and (b) High frequency probe (HFP) [14,16].
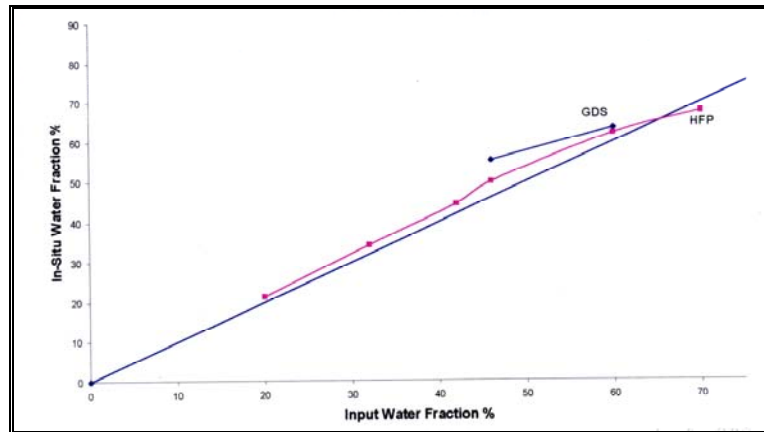

Figure 3: Hold-up measurements at mixture velocity of 3 m/s using gamma densitometry (GDS) and high frequency probes (HFP) [14, 16].
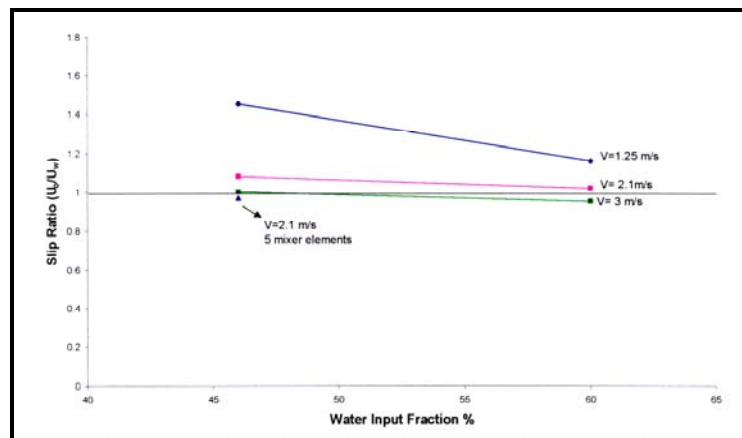

Figure 4: Gamma densitometer system measurement of slip ratio versus water fraction [14,16].

The hold-up was strongly affected by the mixture velocity and the presence of surfactant [13]. At low mixture velocities little water could reach the top of the pipe and no oil could contact the bottom of the pipe without surfactant. At high mixture velocities, a large percentage of the oil was entrained into the water and reached the

bottom and certain amount of water found its way to the top of the pipe. Addition of surfactant could also increase the hold-up of the oil phase. The hold-up was strongly affected by oil-water flow patterns, water cut and inclination of the pipe.

EXPERIMENTAL METHODS AND MEASUREMENT TECHNIQUES

The **T**wo-phase **O**il and **W**ater **E**xperimental **R**ig is a liquid-liquid flow facility designed for studying flows in 25.4 mm (1-inch) horizontal pipes channel. The TOWER facility allows the phenomena occurring during the simultaneous horizontal flow of two liquids, such as oil and water, in a pipe channel to be observed. The TOWER facility flow loop is illustrated in detailed by Hussain [7].

Water and oil were supplied separately from two 0.681 m³ storage tanks to the stainless steel test sections. The test section had an inside diameter of 24.3 mm and was made up of six successive pipe section of lengths of 1 m, 1 m, 1.87 m, 1.87 m, 3.85 m and 0.11 m respectively, giving a total length of 9.7 m. The pipe sections are linked together with flanged connections designed to give a continuous and smooth inner bore. The final 0.11 m section was made from acrylic resin to allow the flow to be observed.

The mixture of the two fluids after the test section was separated in liquid-liquid separator which has 4 m³ horizontal vessel made from PVC reinforced with steel. It consists of a 1.94 m long, 0.54 m ID tank, containing a 0.54 m diameter, 0.3 m long Knitmesh™ coalescer. The Knitmesh™ coalescer is fitted to promote efficient separation of the fluids and is made from filaments of two different materials, metal and plastic, knitted together. These two materials are wetted by water and oil respectively and can therefore collect droplets of either fluid in a continuum of the other. The combination of different materials can also significantly improve the rate of coalescence of captured droplets which pass up or down (depending on which phase is continuous) the Knitmesh™ pad, meeting at the junction points of the two materials.

The two liquid phases used in the experiments were: tap water fed directly into the water tank through a plastic hose and oil namely EXXSOL D-80 (density, 801kg/m³, viscosity, 1.6 cp and interfacial tension air-oil-water, 0.027 N/m², 0.017 N/m²). The oil was pumped from the supply drums into the oil tank through a special branch in the suction line of the oil pump.

Measurement of phase volume fraction using gamma densitometer

A gamma densitometer system has been developed for use on the TOWER facility [7, 14]. The platform was designed such that the beam could be traversed with the beam in the horizontal (0°), vertical (90°) and inclined (45°) orientations. At each orientation it was thus possible to obtain the water hold-up profile. Collection of these three sets of data for a given flow condition also allowed the derivation of tomographic images of phase distribution across the channel [7, 11, 12]. The basic equations for gamma densitometry and the factors influencing measurement accuracy were discussed in detailed [7, 11, 12, 17].

The hold-up of the oil and water phases in terms of the measured intensity I and the full tube values I_{oil} and I_{wat} show as the following equations [7]:

$$\varepsilon_{oil} = \frac{\ln(I/I_{wat})}{\ln(I_{oil}/I_{wat})} \tag{8}$$

$$\varepsilon_{wat} = \frac{\ln(I/I_{oil})}{\ln(I_{wat}/I_{oil})} = 1 - \varepsilon_{oil} \tag{9}$$

In the experiments, I_{oil} and I_{wat} were determined typically over a period of 38.36 seconds and I typically over a period of 38.36 seconds [7]. For typical conditions, the errors in I_{oil}, I_{wat} and I lead to an error of around ± 0.26 mm. This corresponds to an error of around $\pm 1\%$ in phase hold-up for $\frac{H}{2} = \frac{d}{2}$ (i.e. at the central chord position where $H = d$, the tube diameter). The error is greater for other chordal positions and for the phase with the lower phase fractions when the phase fractions are unequal. The error measurement of phase fraction depends on the difference between the count rates for two differences cases. This measurement error is much higher in the oil-water system than an oil-air system due to the small density difference between oil and water. A relation for the error in phase hold-up in this type of measurement has been obtained based on the equation. The data

measured close to the wall are not very reliable due to significant error in these regions. Temperature variation can affect the measurement error, however, in the present system, this temperature fluctuation is negligible.

For each flow condition, 75 chordal mean phase fraction measurements were made (25 at each orientation-i.e. horizontal, vertical and 45^0 inclined). The average phase fraction could be determined from the results at each orientation by taking the average of the chordal mean values weighted according to chord length. Thus, for given flow conditions and axial location, the average phase fraction determined at the three respective beam orientations were in reasonable agreement.

Measurements of local chordal mean phase fraction were made using the Gamma Densitometry System (GDS) at three locations (1.0 m, 5.85 m and 7.72 m from the inlet). The measurements were taken at four mixture velocities (i.e. 1.8 m/s, 2.17 m/s, 2.5 m/s and 2.76 m/s) and three input water fractions (i.e. 60%, 46% and 40%). The data obtained for chordal mean phase fractions could also be interpreted using a tomographic algorithm [7, 8, 11, 12].

RESULTS AND DISCUSSIONS

Local volume fraction

Input water fraction is a very important variable in this work. At the lowest water fraction of 40% studied the water would be expected to be dispersed in the oil and at the highest water fraction of 60% the oil would be expected to be dispersed in the water. However, tomography reveals that the phase mixing patterns are extremely complex as will be seen by examining the full set of tomographic data at mixture velocity of 2.76 m/s and the axial location of 1.0 m given in Figures 5.
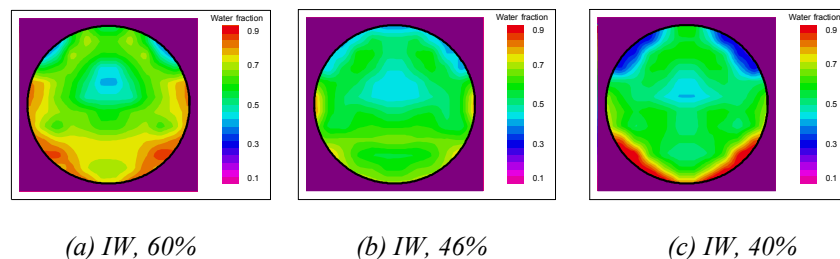

(a) IW, 60%   *(b) IW, 46%*   *(c) IW, 40%*

Figure 5: Influence of input water fraction on phase distribution at a location 1.0 m from the inlet and for a mixture velocity of 2.76 m/s.

At the highest mixture velocity in this case, the phase distributions are more uniform, though a high concentration of water is still observed at the bottom of the pipe, and a high concentration of oil near the top of the pipe, for an input water fraction of 40% where the dispersion is water-in-oil. For 46% input water fraction, (near the expected phase inversion point) the water fraction is reasonably constant across the pipe. For 60% input water fraction, an oil-in-water dispersion would be expected and the oil phase concentration would be expected to be higher (as is observed) at the top of the pipe due the tendency of the (lighter) oil drops to rise upwards.

The results clearly represent an interaction between a number of effects such as mixture velocity and locations of the gamma, other than input water fraction. However, the general indication is that there is a tendency for the phases to mix as they pass along the channel. Furthermore, full set of tomographic data (contour plot) on local volume fraction varied with the mixture velocity and location of the gamma were plotted in details in the previous report [7, 11, 12]. Apart of observing the phase fraction distribution, the measured in-situ values can be compared with the input water fraction due to validate the predicted fraction and the relative motion of the channel cross-section occupied by the two phases in the pipe channel.

Mean cross section hold-up

The average in-situ water fraction $\left(\varepsilon_w = 1 - \varepsilon_o \right)$ can be determined by taking an average of the 25 chordal mean values for a given scan, weighting each chordal mean value by the length of the chord. Good agreement is observed between the mean values obtained for the three scans (horizontal, vertical and 45^0). It is interesting to compare these measured in-situ values with the input water fractions.

The relationship between average mean oil and water velocities (U_O and U_W) and phase fractions were introduced previously. Specifically, the "slip ratio" is given by

$$S = \frac{U_O}{U_W} = \frac{U_{SO}}{U_{SW}} \cdot \frac{\varepsilon_W}{\varepsilon_O} = \frac{\varepsilon_W(1 - y_W)}{y_W(1 - \varepsilon_W)} = \frac{y_O(1 - \varepsilon_O)}{\varepsilon_O(1 - y_O)} \qquad (10)$$

and the "slip velocity" U_S is given as

$$U_S = U_O - U_W = (U_{SO} + U_{SW})\left(\frac{y_O}{\varepsilon_O} - \frac{y_W}{\varepsilon_W}\right) \qquad (11)$$

where y_O and y_W are the input oil and water volume fractions $(y_W = 1 - y_O)$.

For homogeneous (no slip conditions) it follows that
$$U_S = 0, \ S = 1, \ \varepsilon_O = y_O \text{ and } \varepsilon_W = y_W \qquad (12)$$

There are no slip condition can occur because of local and average effects. The latter arrive from differences in the profiles of phase fraction and velocity; since the flow is horizontal the dominant effect is likely to be of this type. The data for average in-situ water fraction is shown in Figures 6, 7 and 8 at differences axial distances of 1, 5.85 and 7.72 m respectively. The corresponding data for slip ratio are given in Figures 9, 10 and 11.

The input water fractions are less than the in-situ values at a distance of 1.0 m but the in-situ values approach the input values and may ultimately fall below them as the flow proceeds along the channel. Correspondingly, the slip ratios go from $S > 1$ to $S < 1$ with increasing distance. These trends again illustrate the tendency for progressive mixing of the phases as the flow proceeds along the pipe.
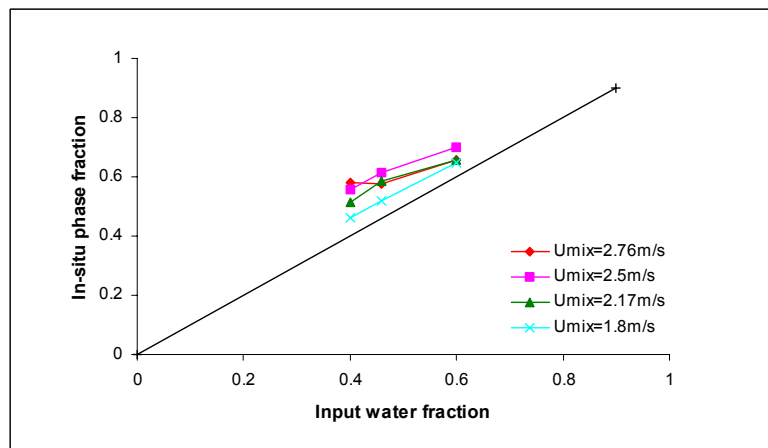

Figure 6: In-Situ water fraction measurements for oil-water in the horizontal tube section at 1.0 m from the beginning of the inlet with different mixture velocity.
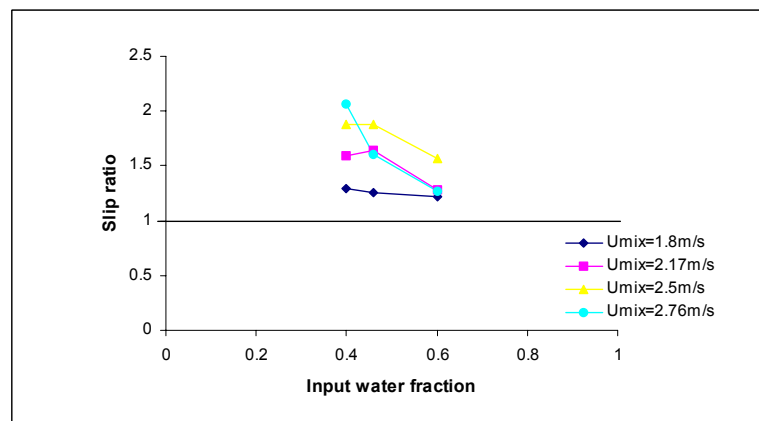

Figure 7: Slip ratio for oil-water in the horizontal tube section at 1.0 m from the beginning of the inlet with different mixture velocity.
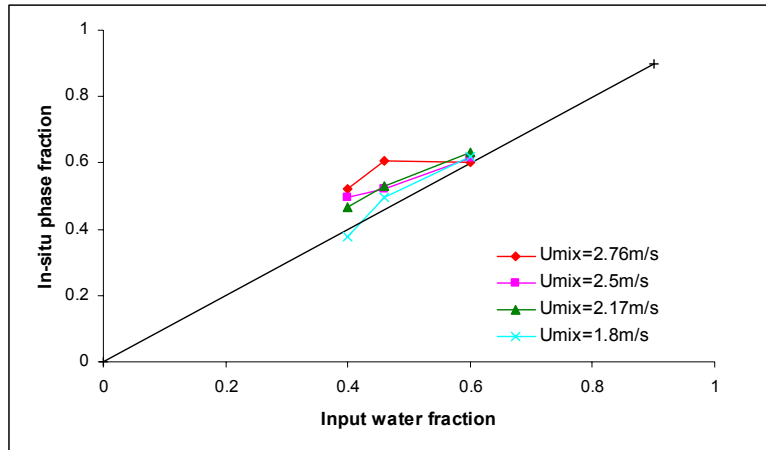
Figure 8: In-Situ water fraction measurements for oil-water in the horizontal tube section with 5.58 m from the beginning of the inlet with different mixture velocity.
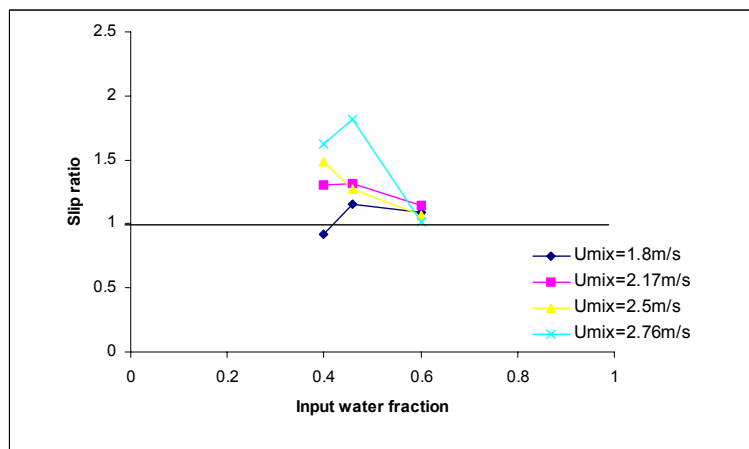

Figure 9: Slip ratio for oil-water in the horizontal pipe at 5.58 m from the beginning of the inlet with different mixture velocity.
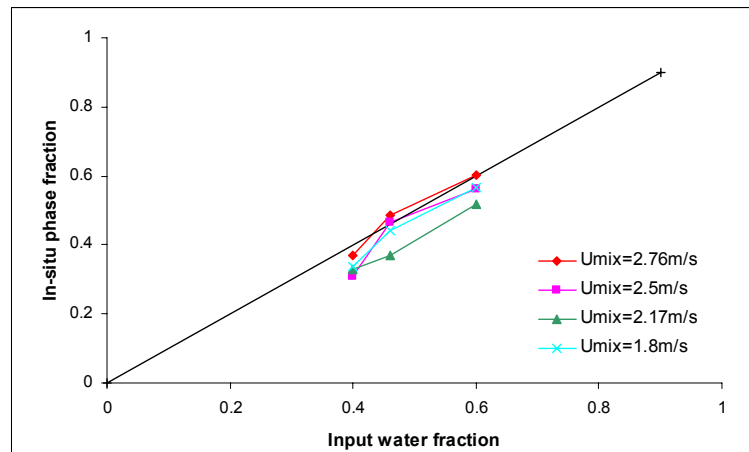

Figure 10: In-Situ water fraction measurements for oil-water in the horizontal tube section with 7.72 m from the beginning of the inlet with different mixture velocity.
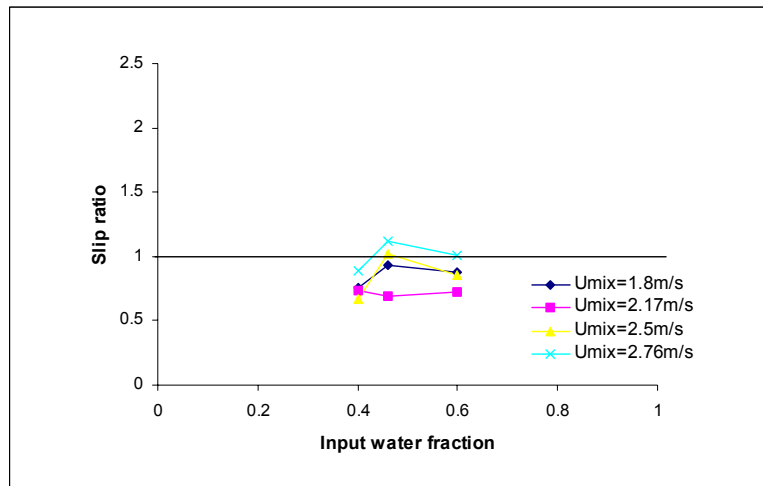
Figure 11: Slip ratio for oil-water in the horizontal pipe at 7.72 m from the beginning of the inlet with different mixture velocity.

The experimental results presented above serve mainly to illustrate the complexity of the processes in liquid-liquid flows. If we regard flow pattern as a characteristic type of phase distribution then it will be seen that this depends not only on phase flow rates but also on the axial position. Pressure gradient passes through a maximum with distance before becoming relatively independent of distance towards the end of the pipe. This may reflect energy losses associated with intense mixing near the inlet. At high enough mixture velocities, the phases ultimately became mixed (dispersion of water in oil or oil in water) but this is achieved only slowly.

CONCLUSIONS

The chordal-mean in-situ water fraction data were averaged (on a chord length weighted basis) to yield average hold-up. For a given flow, the results for the three traversing directions (vertical, horizontal and 45^0) were in good agreements.

The input water fractions are less than the measured in-situ values at a distance of 1.0 m but the in-situ values approach the input values and may ultimately fall below them as the flow proceeds along the channel. These trends again illustrate the tendency for progressive mixing of the phases as the flow proceeds along the pipe.

ACKNOWLEDGEMENTS

NOMENCLATURE

Roman symbols

y_O	Input phase fraction of oil
y_W	Input phase fraction of water
q_O	Input volume flowrate of oil (m^3/s)
q_W	Input volume flowrate of water (m^3/s)
U_O	Average mean velocity of water (m/s)
U_W	Average mean velocity of water (m/s)
U_{SO}	Superficial velocity of oil (m/s)
U_{SW}	Superficial velocity of water (m/s)
U_S	Slip velocity (m/s)
I	Intensity of oil and water (count/s)
I_{wat}	Intensity for single phase of water (count/s)

I_{oil}	Intensity for single phase of oil (count/s)
S	Slip ratio
A	Cross sectional area (m^2)
H	Chord length (m)
d	Tube diameter (m)

Greek letters

ε_O	Average in-situ oil phase fraction
ε_w	Average in-situ oil phase fraction
ε_{oil}	Oil hold up
ε_{wat}	Water hold up

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