FROM GAS-LIQUID TO LIQUID-LIQUID TWO-PHASE FLOW: A DIFFICULT JOURNEY

by

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1. INTRODUCTION

Although there were a number of publications on liquid-liquid pipeline flow in the 1950s and 1960s, the field has been relatively quiescent until recently. However, the interest in pipeline transport of oil-water mixtures has led to a resurgence of work in the area. In the time span between the early studies and the new emergence of the subject, most attention has been focussed on gas-liquid two-phase flow because of its importance in nuclear reactor systems though here, too, the emphasis is switching to hydrocarbon recovery systems also. The purpose of this lecture is to examine the similarities and differences between liquid-liquid flows and gas-liquid flows and to attempt to draw some lessons from these.

Section 2 discusses flow patterns and in particular the difficulty of observing slug flow in liquid-liquid systems. Section 3 discusses the application of two-fluid models to gas-liquid and liquid-liquid flows respectively. For water-in-oil suspensions, there is evidence of drag reduction and this is discussed in Section 4. Perhaps the most important area of difference between the two systems is that of the effect of the channel wall material. These effects on pressure drop and phase distribution respectively are discussed in Section 5. Section 6 draws some overall conclusions.

2. FLOW PATTERNS

In comparing flow patterns for gas-liquid and liquid-liquid flows, one can make the following general observations:

(1) Stratified flows exist for both types of fluid combination.

(2) Slug flow is, of course, ubiquitous in gas-liquid systems but (as we shall see below) is something of a rarity in liquid-liquid systems.

(3) Though complete dispersion of the gas in the liquid to form a bubble flow is common at low void fractions (typically less than 30%) in gas-liquid flow, complete dispersion of the liquid phase and the gas does not generally occur in gas-liquid flows except under diabatic conditions with hot channel walls which inhibit droplet contact with the walls. On the other hand, interdispersion of the two phases is possible over the full range of phase fraction in liquid-liquid flows, particularly at high velocities. An important phenomenon here is *phase inversion* in which the system changes from being one of water droplets dispersed in oil to one of oil droplets dispersed in water.

(4) Annular flow is arguably the most common of the flow regimes in gas-liquid flows but is rarely seen in liquid-liquid flows (except, perhaps, in a manifestation of a thin liquid layer of one phase on the channel wall in contact with a dispersion in the channel core).

In some of the earlier work on oil-water flows with fluids of nearly equal density, intermitten flows were observed as is illustrated in Figure 1 which is taken from the work of Charles et al (1961) as reported by Govier and Aziz (1962). However, with significant density differences between the phases, the region of intermittent flow is either a very narrow one (Arirachakaran et al, 1989) (see Figure 2) or is not reported at all (Nadler and Mawes, 1995) (See Figure 3).
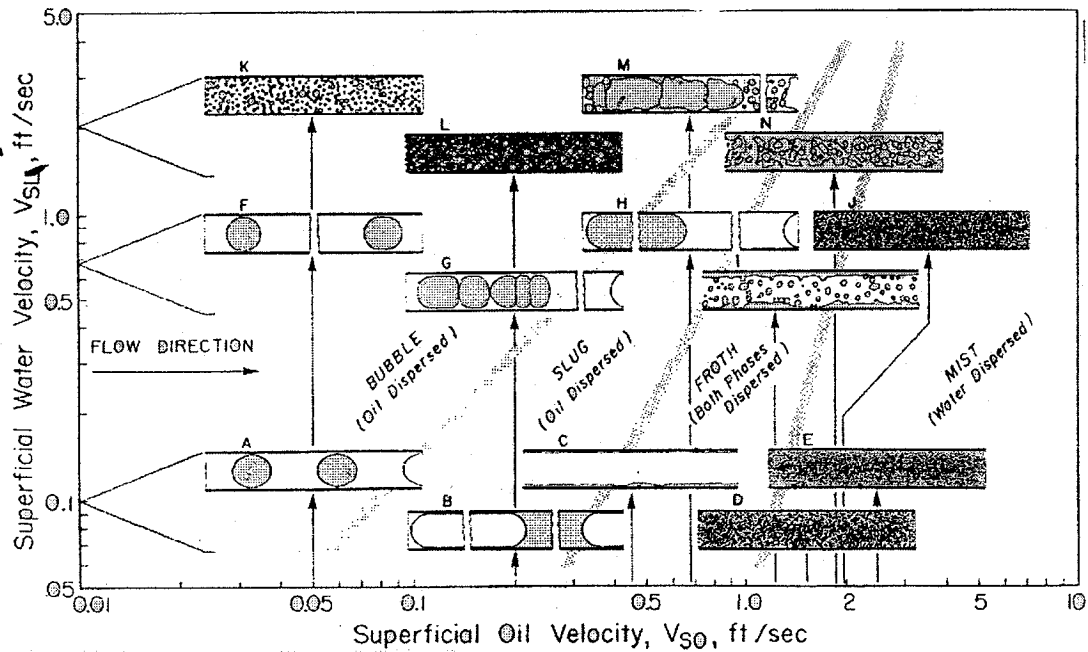

Figure 1: Flow patterns of a 16.8 mPa s, 998 kg/m³ oil and water system in a 0.026 m ID pipe based on observations of Charles et al (1961). Map as published by Govier and Aziz (1972).
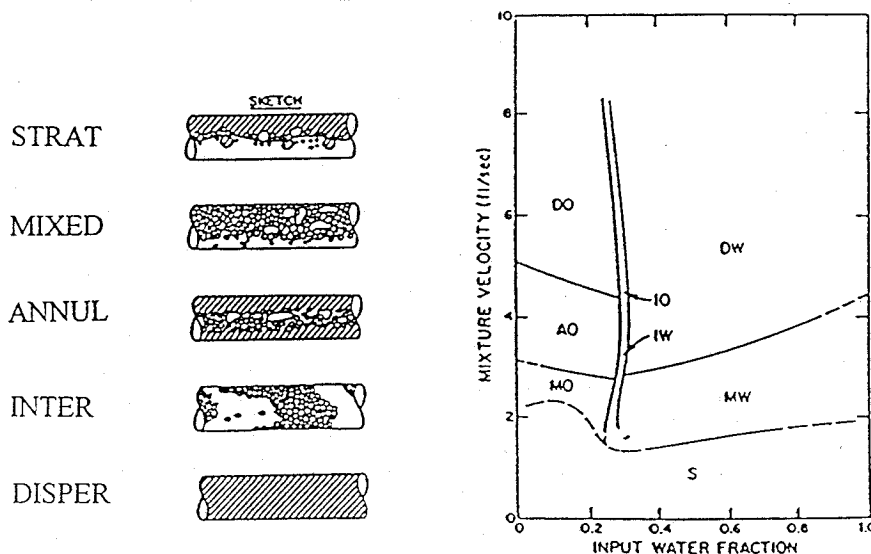

Figure 2: Oil-water flow patterns in a 39.3 mm ID pipe as defined by Arirachakaran et al (1989) and their region of occurrence for a 84 mPa s oil.
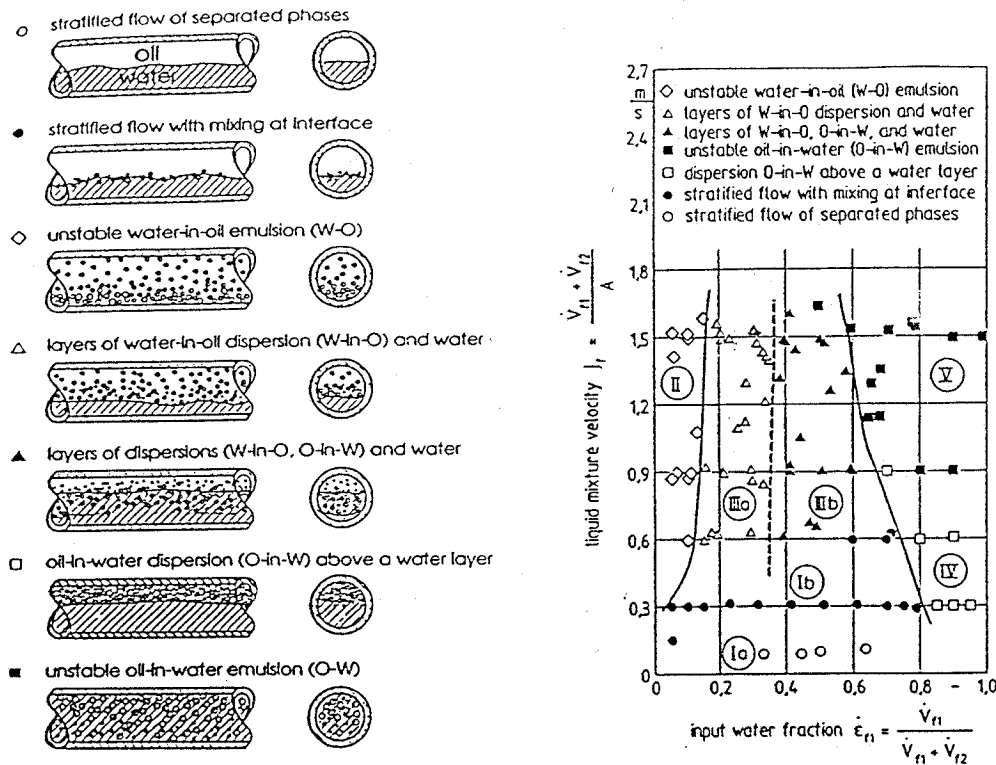
Figure 3: Oil-water flow regimes in a 59 mm ID pipe as identified by Nadler and Mewes (1995) and their respective flow pattern map.

At Imperial College, we have been attempting to identify regions of occurence of slug flow in liquid-liquid systems. In this work, we have used two flow facilities:

(1) The TOWER facility (illustrated in Figure 4) which is a low pressure liquid-liquid flow facility using water and a kerosene-like oil with a viscosity of 1.6 mPa s at 20°C. The rig has two horizontal test sections, one of acrylic resin and the other of stainless steel. The test sections can be operated either with or without mixing devices at the entrance; all of the data discussed in this present review were obtained in relatively fully developed flows without mixing at the entrance.

(2) The Imperial College WASP facility which is illustrated in Figure 5. This rig was operated in the once-through mode, had a test section which is 79 mm in diameter and operates with water and with a lubricating oil which has a viscosity of 45 mPa s at 25°C.

Figure 6 shows data obtained from the TOWER facility showing flow regime as a function of mixture velocity and input water fraction for the stainless steel tube. The flow regime becomes dispersed above mixture velocities of 1-1.5 m/s as shown. At lower velocities, various manifestations of stratified flow and partially mixed flows occur, including "three-layer" flow in which there is layer of water at the bottom of the pipe, a layer of oil at the top and a dispersed layer between them. Slug flow has also proved elusive in tests in the WASP facility; even in the case of flow in a 1° inclined upwards pipe (where, in gas-liquid flow, there is a much greater propensity to slug flow), no intermittent regime was observed (Figure 7).
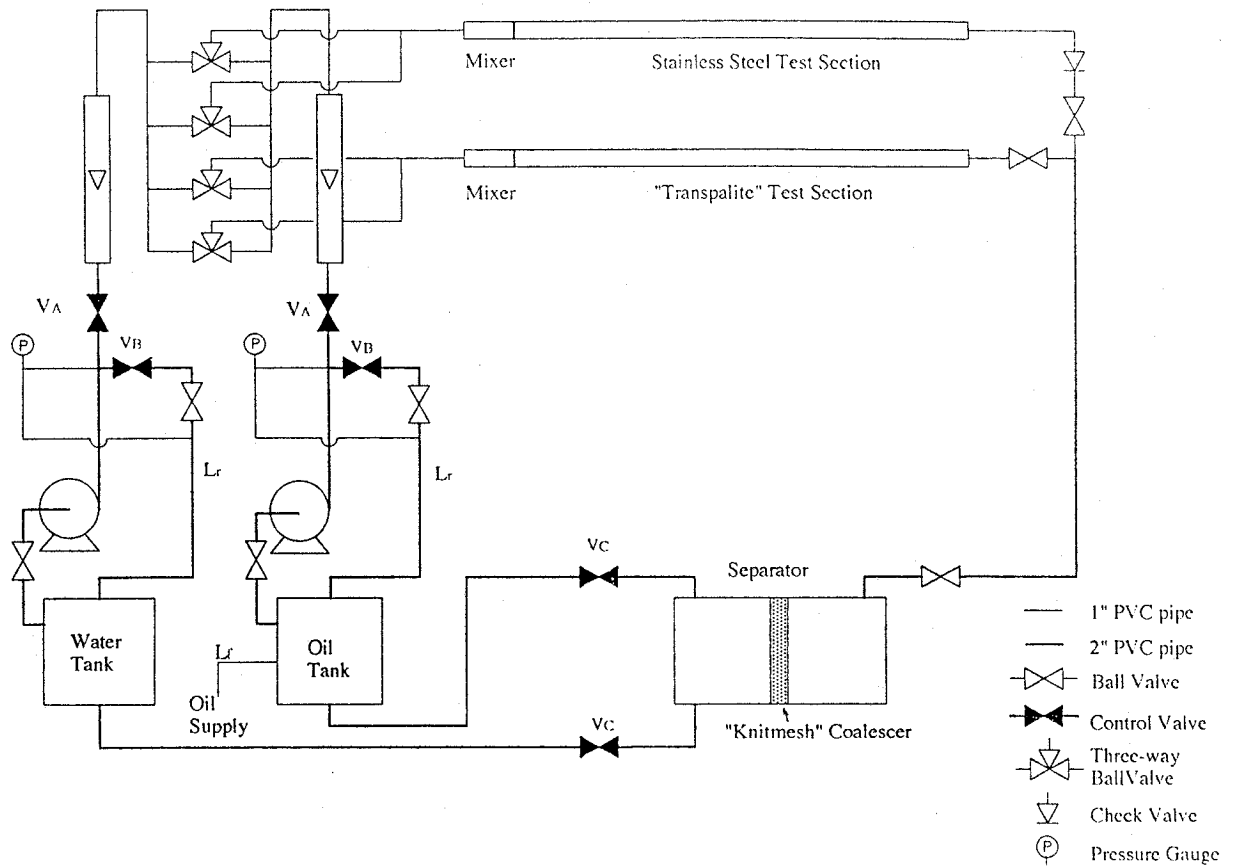
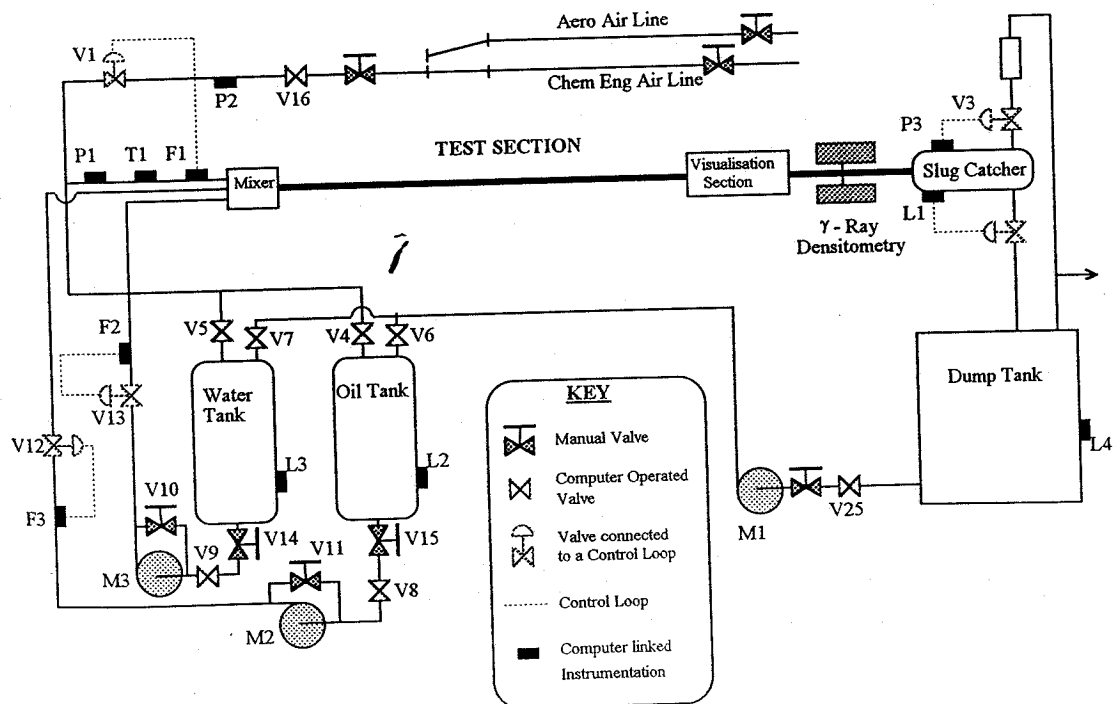*Figure 4: Flow diagram of the Imperial College liiuid-liquid flow facility (TOWER).*

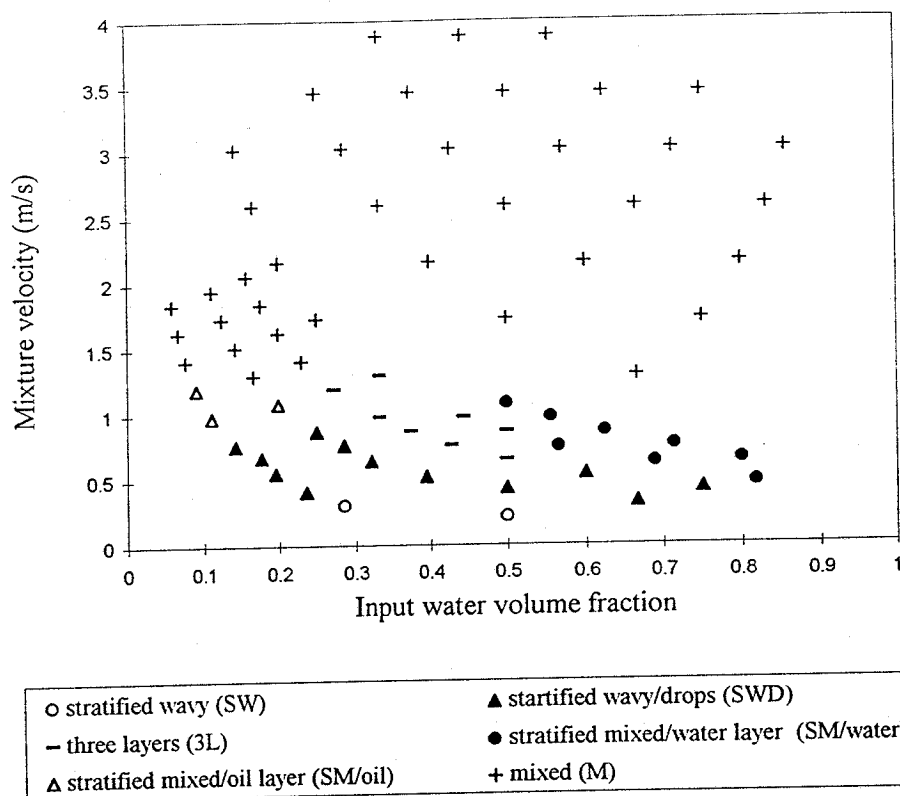*Figure 5: Flow diagram of the Imperial College WASP facility.*

Mixture velocity (m/s)

Input water volume fraction

o stratified wavy (SW)
— three layers (3L)
△ stratified mixed/oil layer (SM/oil)

▲ startified wavy/drops (SWD)
● stratified mixed/water layer (SM/water)
+ mixed (M)

Figure 6: Flow patterns observed in the Imperial College TOWER facility for flow in a stainless steel 25.4 mm diameter pipe (Angeli, 1996).

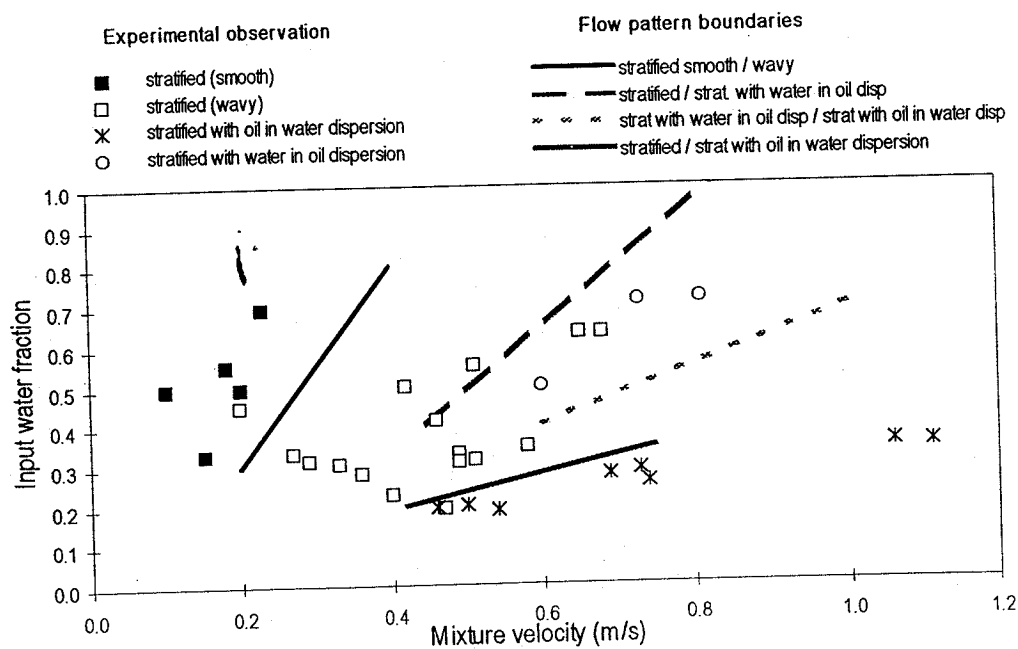Experimental observation

■ stratified (smooth)
□ stratified (wavy)
✕ stratified with oil in water dispersion
○ stratified with water in oil dispersion

Flow pattern boundaries

——— stratified smooth / wavy
— — stratified / strat with water in oil disp
✕ ✕ ✕ strat with water in oil disp / strat with oil in water disp
——— stratified / strat with oil in water dispersion

Input water fraction

Mixture velocity (m/s)

Figure 7: Flow patterns observed in a 1° upwards inclined pipe in the Imperial College WASP facility (Kurban, 1997).
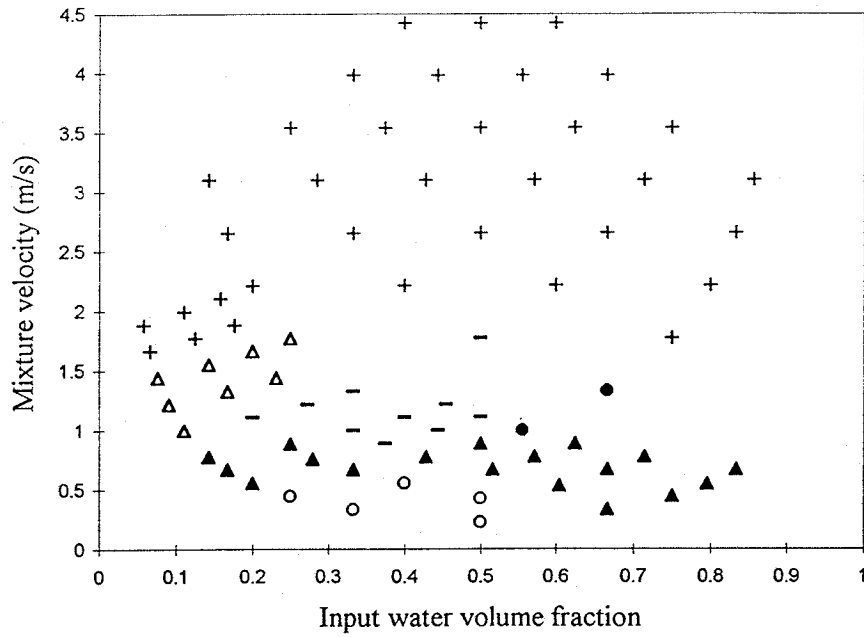
Figure 8: Flow patterns observed in the Imperial College TOWER facility for liquid-liquid flow in 25.4 mm internal diameter tube of acrylic resin (Angeli, 1996).
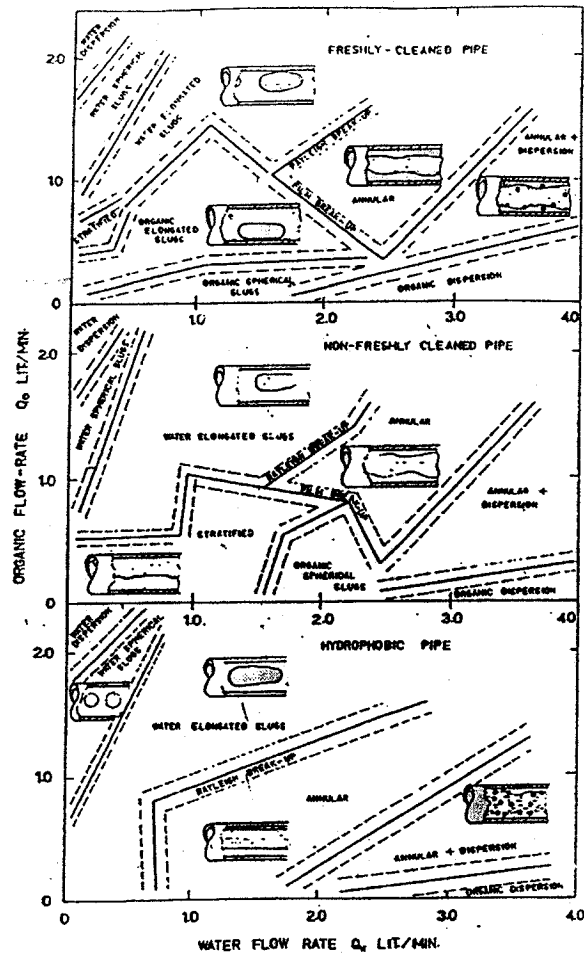

Figure 9: Flow patterns of a 0.82 mPa s, 1020 kg/m³ kerosene-perchlorethyene solution and water system in a 1.26 cm ID glass tube based on observation of Hasson et al (1970).

Interesting differences occur between the stainless steel and acrylic resin test sections in the TOWER facility and we shall return to this point below. One manifestation of these differences is in flow patterns; results covering a similar range of conditions to those shown in Figure 6 for the stainless steel tube, are presented in Figure 8 for the acrylic resin tube. As will be seen, there is much less tendency for mixing of the phases, the fully mixed region being reached at much higher mixture velocities. The finding that the wall has a significant influence on liquid-liquid mixture flows is not a new one. Though the studies were with fluids of much less density difference (the organic phase had a density of 1020 kg/m^3 in contrast to the fluids used in the TOWER and WASP facilities which have densities of 800 and 865 kg/m^3 respectively), Hasson et al (1970) observed significant differences in flow pattern between freshly cleaned pipes, non-freshly cleaned pipes and hydrophobic pipes (see Figure 9).

3. TWO-FLUID MODELS

A work-horse model for the prediction of stratified two-phase flows is the so-called two-fluid model in its simplest (steady state) form. The model solves the following equations:

$$- A_w \left(\frac{dp}{dz} \right) - \tau_w P_w - \tau_i P_i = 0 \tag{1}$$

$$- A_o \left(\frac{dp}{dz} \right) - \tau_o P_o + \tau_i P_i = 0 \tag{2}$$

where A_w and A_o are the flow cross section areas of the water and oil phases, and τ_w, τ_o and τ_i are the water-to-wall oil-to-wall and oil-to-water interfacial shear stresses respectively. P_w, P_o and P_i are the wall peripheries in contact with the water and oil phases and the interfacial periphery respectively. Approximate relationships can be introduced for the shear stresses (i.e., in terms of friction factors), the pressure gradient (dp/dz) eliminated between the two equations and a solution formulated in the form of a relationship between h_w/D and the Martinelli parameter X_{ow} where h_w is the height of the water layer above the bottom of the pipe, D the pipe diameter and X_{ow} the square root of the ratio of the pressure gradients for the oil and water phases flowing alone in the pipe. A classical version of this model was that of Taitel and Dukler (1976) for gas-liquid flows. It was found that there was little difference in the prediction of the height of the lower phase between assumptions of turbulent and laminar flow respectively in the system. It is interesting, therefore, to compare the predictions of these simplified models with those of more complete numerical solutions which can be carried out accurately for laminar flow situations. In work at Imperial College, (Hall 1992, Hall and Hewitt 1993) a bipolar coordinate system as shown in Figure 10 was used to predict the flow fields and, hence, the liquid levels in stratified gas-liquid and liquid-liquid flows. The results are compared with the simplified two-fluid models in Figures 11 and 12 respectively. The dimensionless parameter $\tilde{\mu}$ is the ratio of the upper phase to the lower phase viscosity. For gas-liquid systems (where $\tilde{\mu} < 1$), the full numerical solution and the approximate two-fluid model agree rather well. For the liquid-liquid system (Figure 12), large discrepancies occur when the viscosities approach one another. At high viscosity ratios, the agreement is again good as one would expect. Many liquid-liquid flow systems have viscosities for the two phases which are of the same order and care must be taken in applying the two-fluid model in this case.
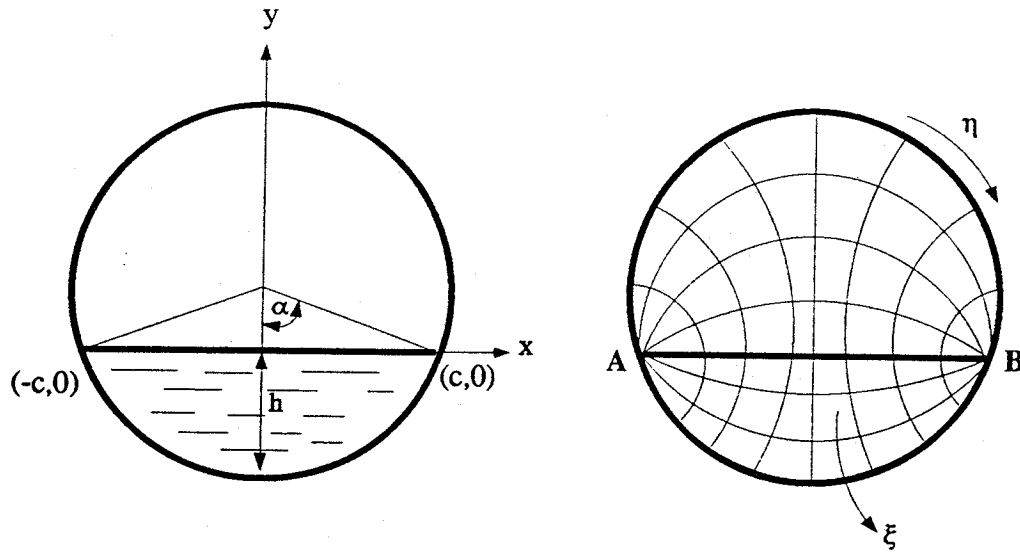
Figure 10: Bi-polar coordinate system for numerical modelling of stratified laminar flows
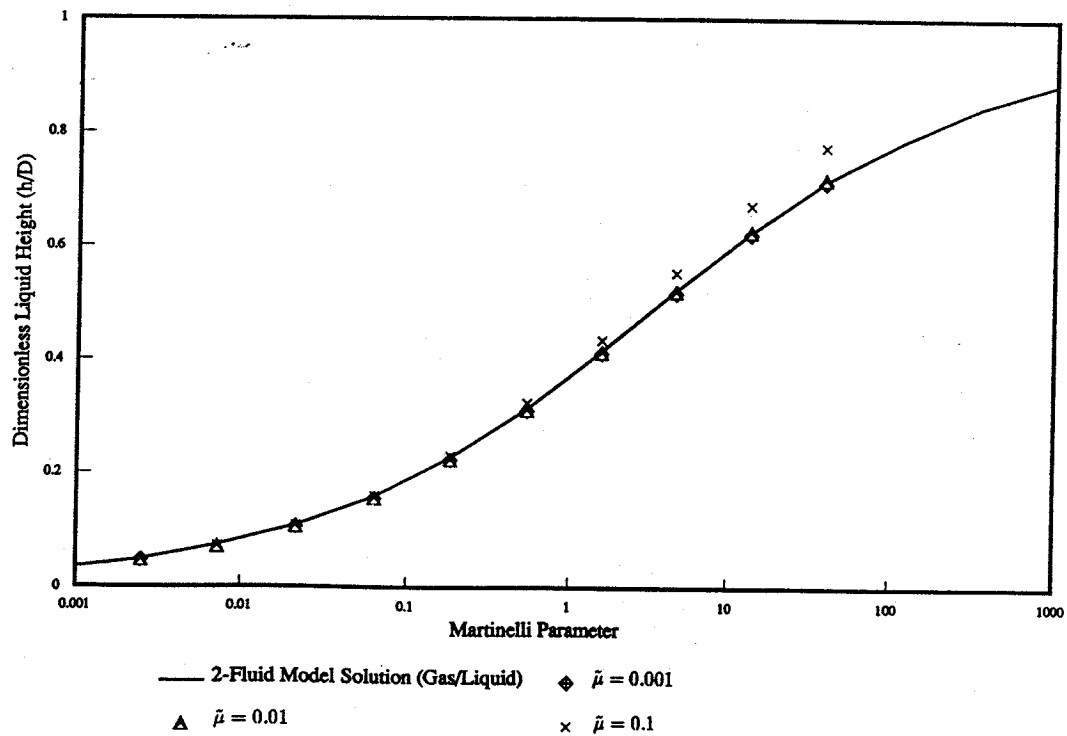(Hall, 1992).

Figure 11: Comparison of two-fluid model and full numerical solution for gas-liquid flows.
$\tilde{\mu}$ = ratios of viscosities of upper to lower phase (Hall and Hewitt, 1993).
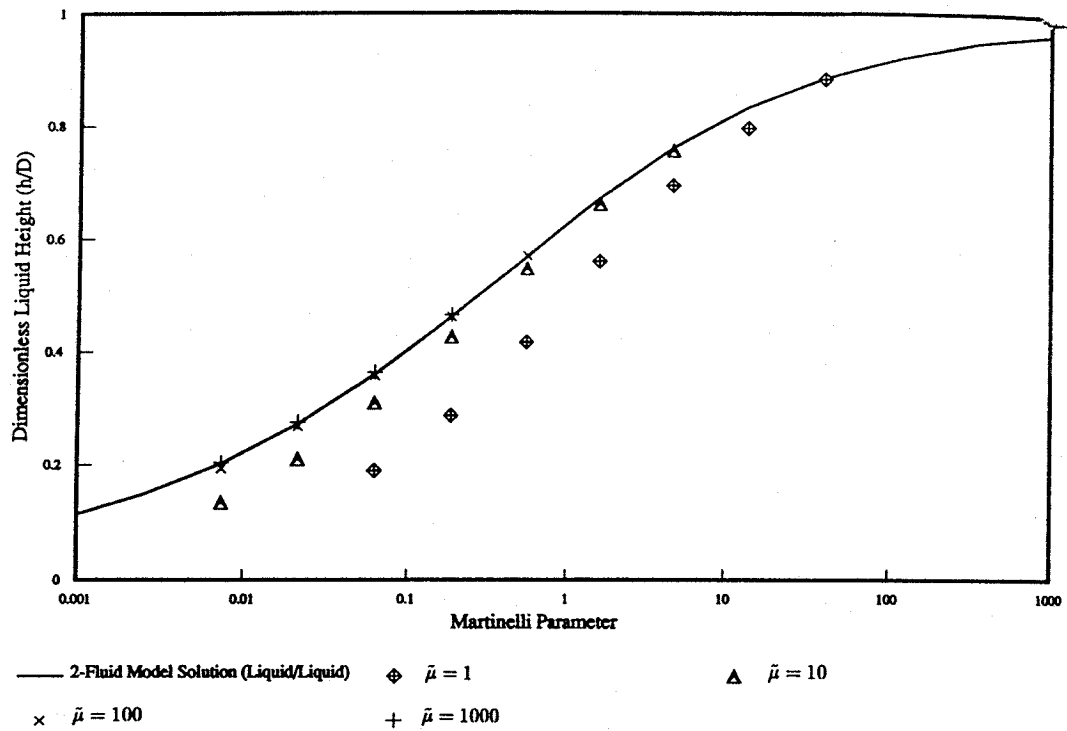
Figure 12: Comparison of numerical solution and two-fluid model for oil-water flows (Hall and Hewitt, 1993).

4. DRAG REDUCTION

When the heavier phase is dispersed in the lighter phase (i.e., water in oil) then a reduction in pressure gradient can occur in turbulent flow. This is illustrated in Figure 13 which shows
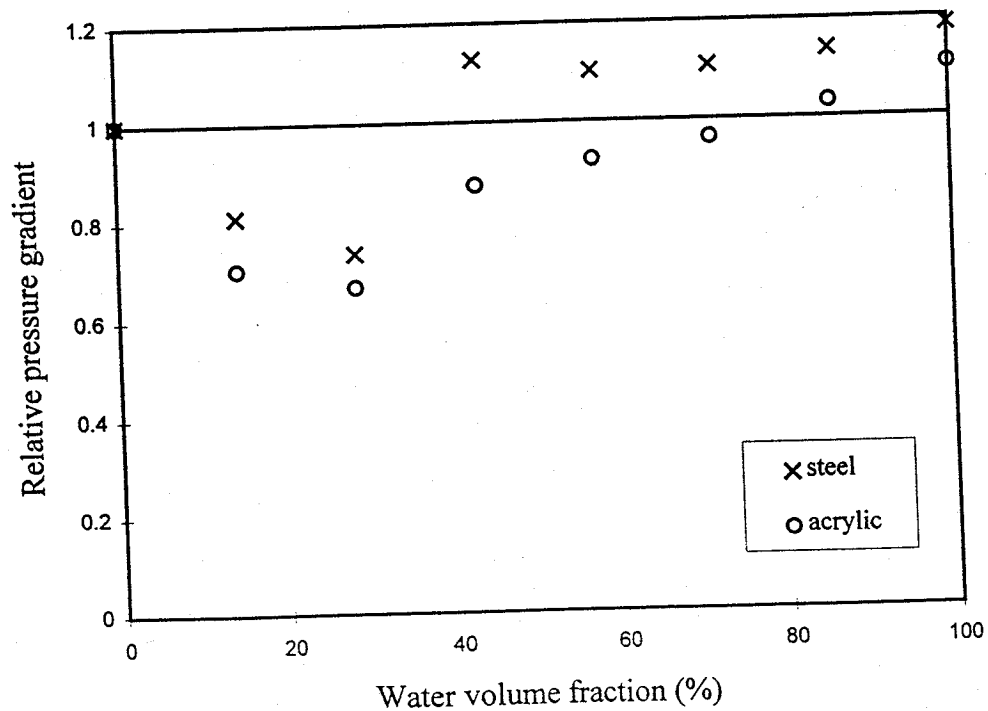
Figure 13: Relative pressure gradient as a function of water volume fraction showing drag reduction effects (Angeli, 1996).

results obtained in Imperial College TOWER facility. Reductions in pressure gradient of up to 30-40% can occur. This is further illustrated in Figure 14 where it is shown that the friction factors for well below those for the individual phases.
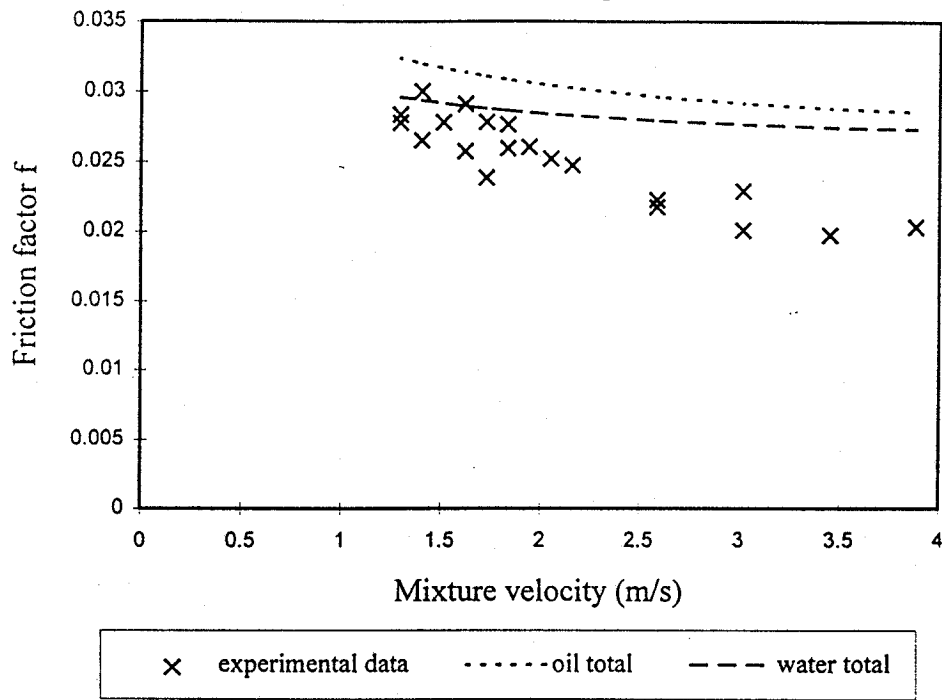

Figure 14: Friction factors for oil-water mixtures showing drag reduction relative to pure fluids (Angeli, 1996).
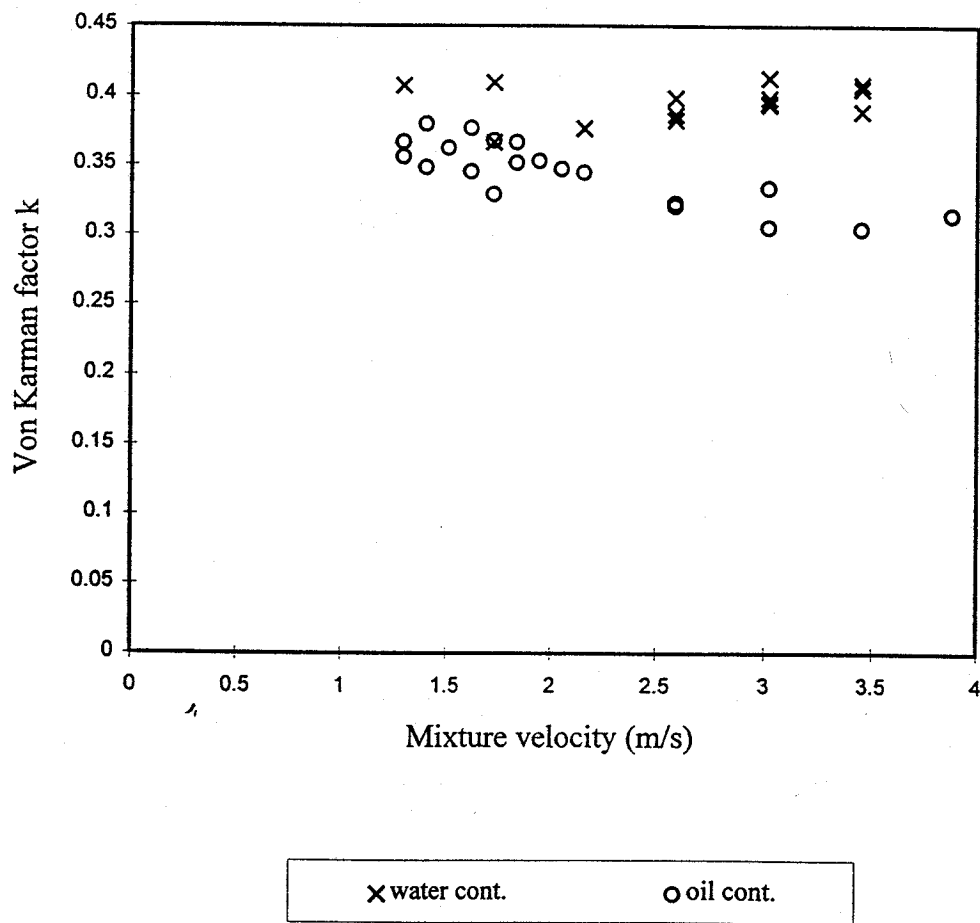

Figure 15: Comparison of von Karman factors for water continuous and oil continuous flows (Angeli, 1996).

Another way of considering the data is to plot it in terms of the von Karman factor k as shown in Figure 15. Though values for oil-in-water suspensions retain their classical value of around 0.4, there is a significant diminution in k for the water-in-oil case.

Drag reduction phenomena of this type have been observed by Pal (1993), also for water-in-oil dispersions. Such drag reduction phenomena are less prevalent in gas-liquid systems but it is noteworthy that Owen 1986 discusses reductions in k by up to around a factor of 2 less than the classical value of 0.4 for the droplet-laden core of annular flows. This reduction occurs when the droplet concentration in the core reaches a high value. To generate a predictive methodology for liquid-liquid flows, it will be necessary to understand these phenomena.

5.   EFFECT OF CHANNEL WALL MATERIAL

One of the most interesting findings in recent work at Imperial College on the TOWER facility has been the identification of large differences between stainless steel and acrylic tubes. In Figure 16, the relative pressure gradient (pressure gradient divided by that for the oil phase alone at a given superficial velocity) is plotted against input water volume fraction in Figure 16 for both stainless steel and acrylic tubing. As will be seen, extremely large differences occur (up to 80%) between the pressure gradients in the two tubes at higher water volume fractions. For the acrylic tube, the flow was relatively stratified and agreed reasonably well with the two-fluid model (see Figure 17). However, the predictions from the two-fluid model lay well below those for the stainless steel tube as is shown in Figure 18. Clearly, the tube surface properties are having a large effect (over and above those associated with the slight differences in roughness of the tubes). These differences were further investigated using high-frequency probe detection of local phase fractions.
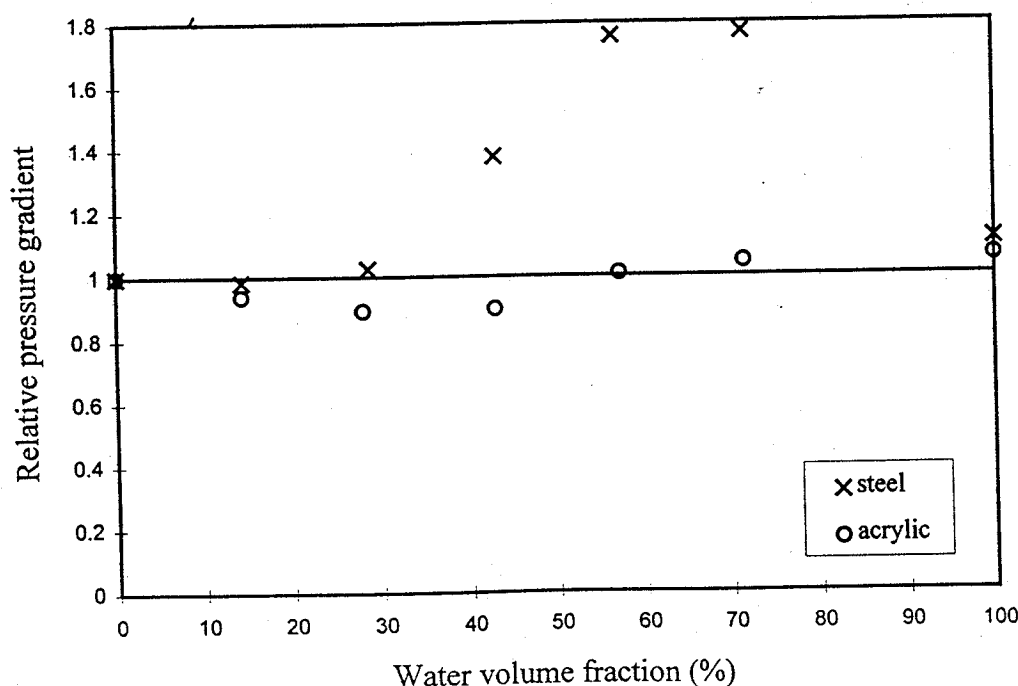

Figure 16: Relative pressure gradients for oil-water flow in stainless steel and acrylic resin tubes (Angeli, 1996).
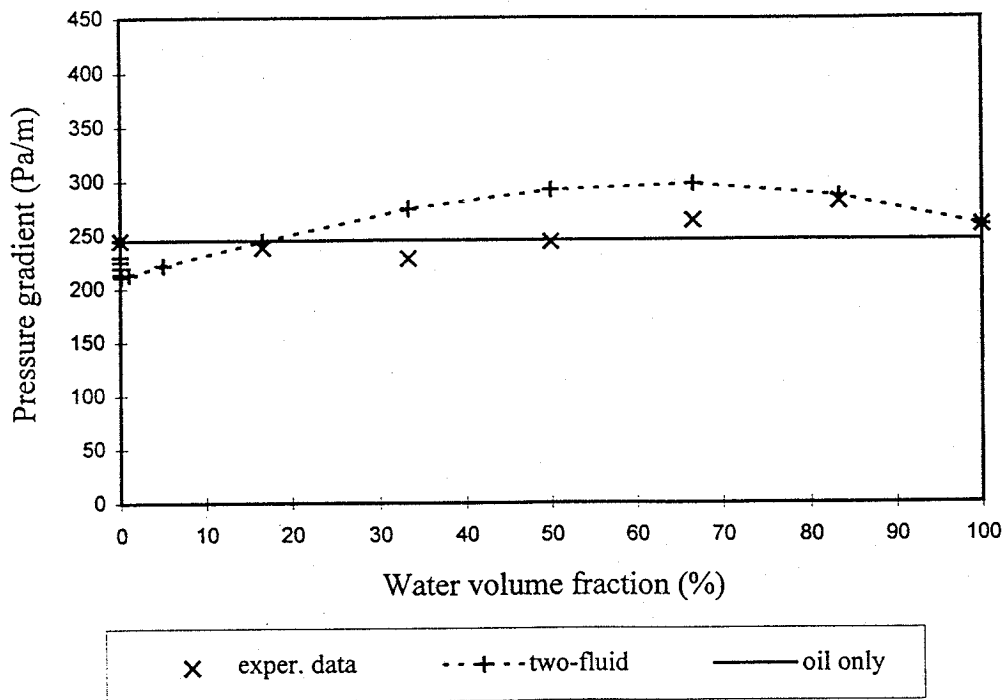
Figure 17: Comparison of two-fluid model with data for liquid-liquid flow in an acrylic pipe with mixture velocity of 0.65 m/s (Angeli, 1996).
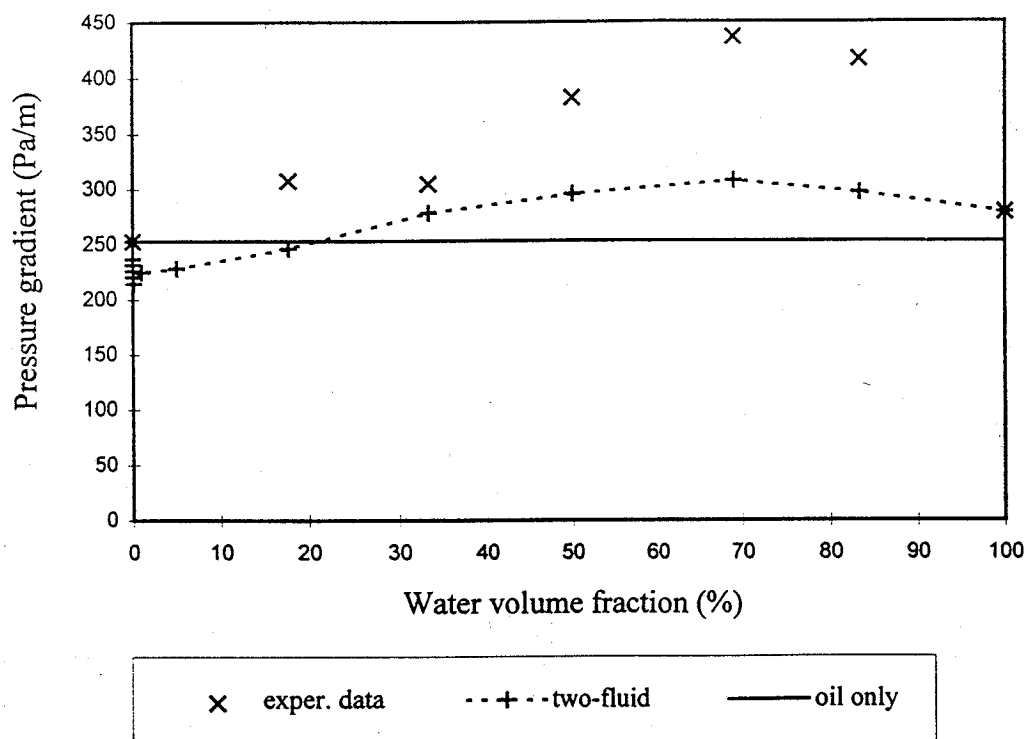

Figure 18: Comparison of two-fluid model with data for liquid-liquid flow in a stainless steel pipe with a mixture velocity of 0.65 m/s (Angeli, 1996).

The high frequency probe used is sketched in Figure 19. The probe was developed by Schlumberger Cambridge Research and operated with a very high frequency (1 GHz). The probe was ranged so that it could be scanned across the tube diameter at various angles (see Figure 20), which allowed profiles of the concentration of the phases to be determined, and the signals were converted into square wave form as sketched in Figure 21.
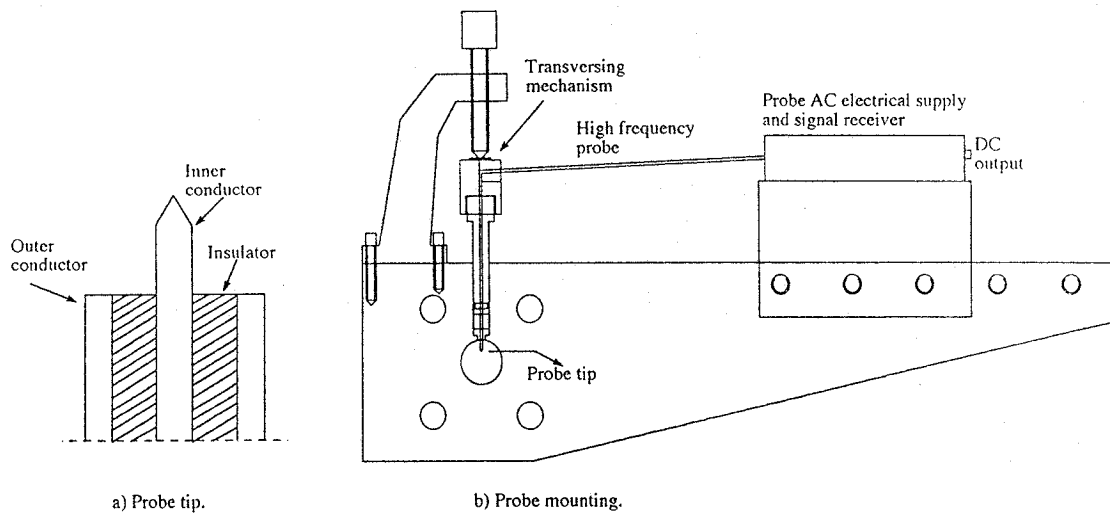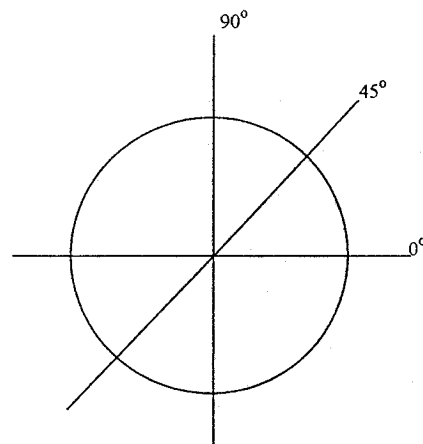
a) Probe tip.   b) Probe mounting.

Figure 19: High frequency probe device for measurement of local phase fraction (Schlumberger Cambridge Research device as used by Angeli, 1996).

Directions for collecting data in a pipe cross section with the
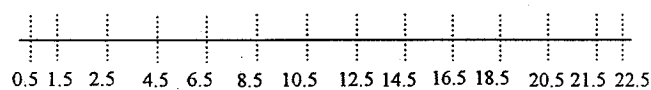high frequency impedance probe.

0.5 1.5 2.5   4.5 6.5   8.5   10.5   12.5 14.5 16.5 18.5   20.5 21.5 22.5
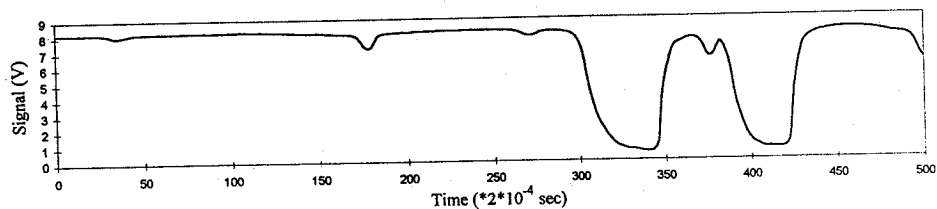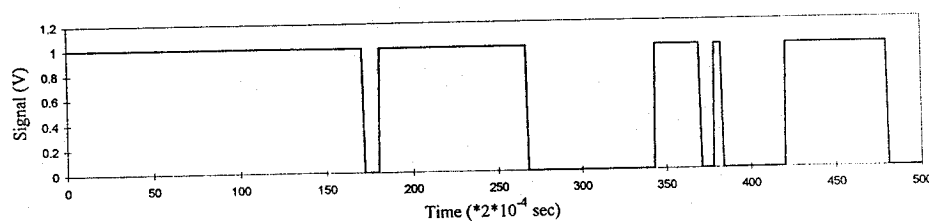
Figure 20: Positions of diametral scans with high frequency probe (Angeli, 1996).

(a) Raw signal from the high frequency probe.

(b) Processed signal in square wave form.

Figure 21: Processing of high frequency probe data into square wave form (Angeli, 1996).
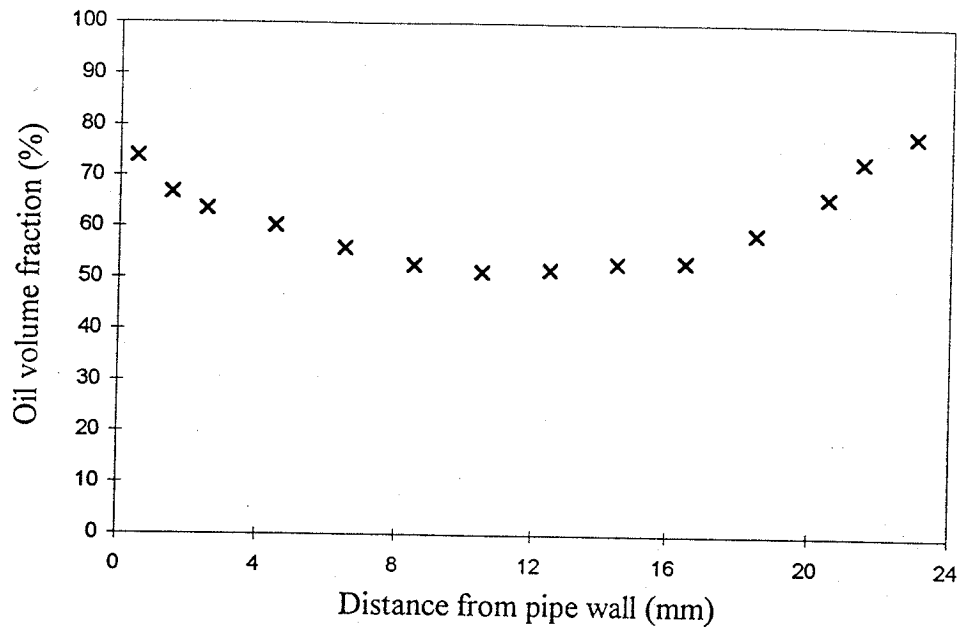
Figure 22: Variation of oil volume fraction along a horizontal pipe diameter in oil-water flow in an acrylic pipe with a mixture velocity of 1.7 m/s and an input oil-volume fraction of 62.5% (Angeli, 1996).
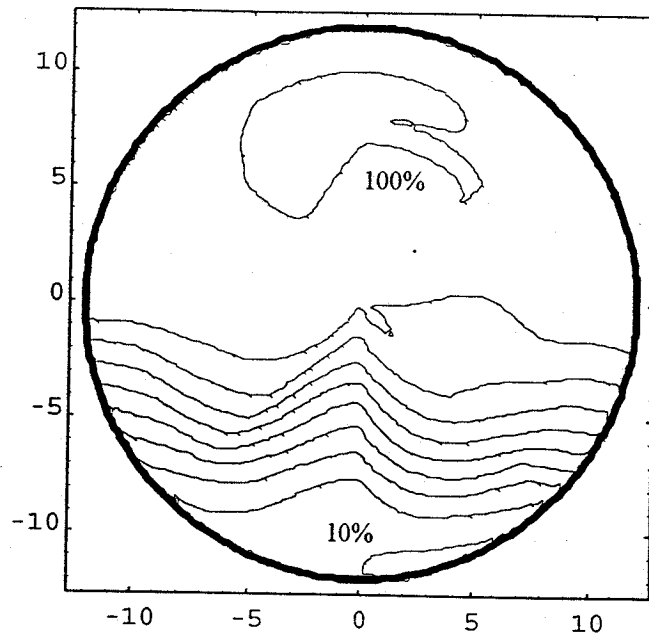

Figure 23: Distribution of oil volume fraction in a 25.4 mm acrylic pipe with separating flow with an oil volume fraction of 66.7% and a mixture velocity of 1.3 m/s (Angeli, 1996).

Figure 22 shows a typical diametral variation of oil volume fraction across a horizontal diameter and Figures 23 and 24 show two dimensional distribution for conditions which are partly stratified and highly dispersed resepectively.
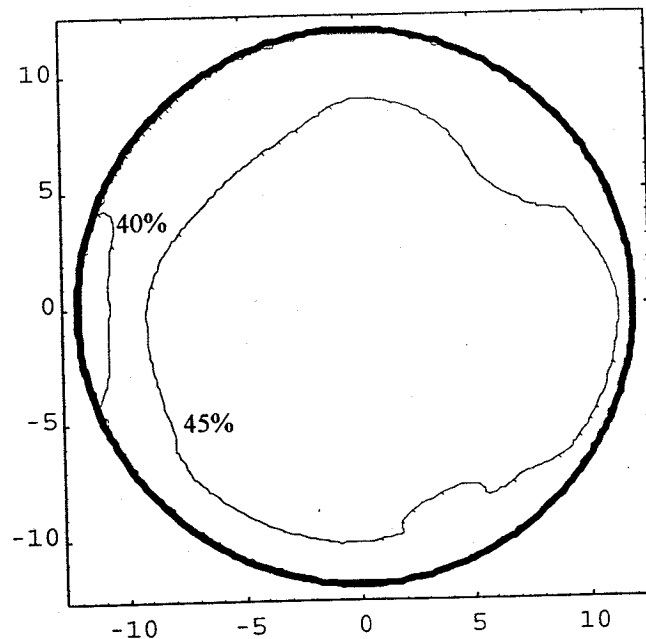

Figure 24: Distribution of oil volume fraction in a 25.4 mm internal diameter stainless steel pipe with a mixture velocity of 2.2 m/s and an input oil volume fraction of 50% (Angeli, 1996).

It is interesting to compare the phase fraction distributions for the same mixture velocity (1.7 m/s) and input oil volume fraction (50%) for the stainless steel and acrylic tubes respectively. These results are shown in Figure 25.
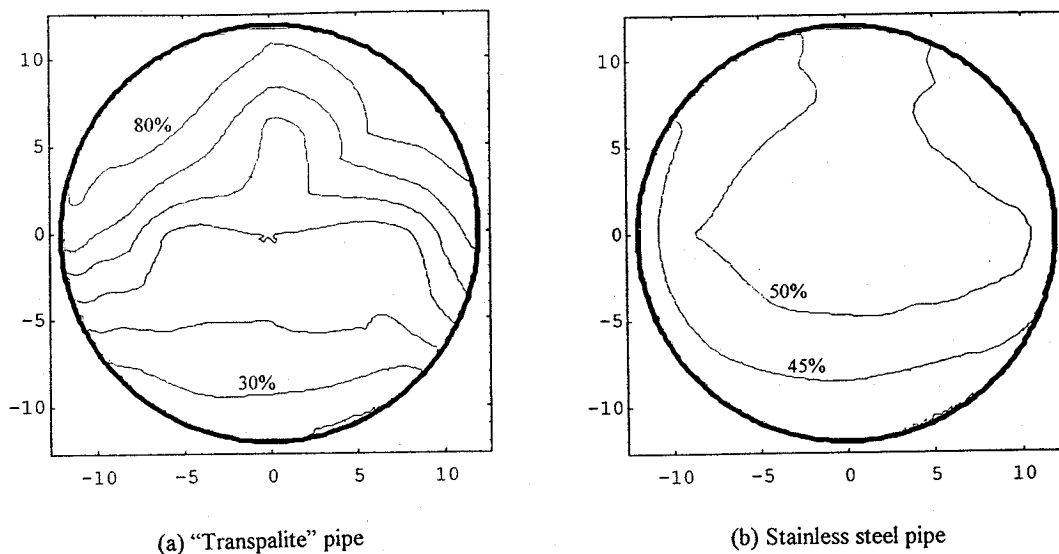

(a) "Transpalite" pipe

(b) Stainless steel pipe

Figure 25: Comparison of oil phase volume fraction distribution for acrylic resin and a stainless steel pipe. Oil imput volume fraction 50%; mixture velocity 1.7 m/s (Angeli, 1996).

As will be seen, there are very large differences between the respective cases.

6. CONCLUSIONS

The following main conclusions may be drawn from the results cited above:

(1)　Despite some obvious similarities, oil-water flows show important differences to gas-liquid flows in a number of aspects.

(2)　Slug flow appears to be an elusive regime in liquid-liquid flows.

(3)　Phase inversion is an important factor in determining the behaviour of liquid-liquid flows.

(4)　Drag reduction may occur for water-in-oil dispersions.

(5)　Most importantly, the nature of the tube wall is an important factor in determining the characteristics of liquid-liquid flows.

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