ISSN: 0128-7680
Pertanika J. Sci. & Technol. **16 (1)**: 31 - 39 (2008) © Universiti Putra Malaysia Press

Water-oil Flows Transition from Stratified to Inter-dispersed in Horizontal Pipeline System

Siti Aslina Hussain[*1], Wan Hassan Mohd Jamil[2], Xiao Yu Xu[3] and Geoffrey F. Hewitt[4]
[1]Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia
[2]Geowell. Sdn. Bhd., 151 Jalan Aminuddin Baki, Taman Tun Dr Ismail, 56000 Kuala Lumpur, Malaysia
[3,4]Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
**E-mail: aslina@eng.upm.edu.my*

ABSTRACT

The spatial distribution of water and oil in horizontal pipe flows was studied experimentally at differing inlet water fractions and mixture velocities. Under most conditions the pattern was oil-continuous in water-dispersed or water-continuous in oil-dispersed and there is entrainment in the form of drops of phase into the other. The investigations were carried out through the cross-sectional phase distribution in the flow of mixtures of water and oil in a horizontal 0.0254 m bore stainless steel section. The phase fraction distribution was determined using a traversing beam gamma densitometer, with the beam being traversed at 0º, 45º and 90º of the vertical line passing through the axis of the tube. Measurements were made at 1.0 m and 7.72 m along the 9.7 m test section length tube. The measurements were made using the **T**wo-phase **O**il **W**ater **E**xperimental **R**ig (**TOWER)** facility, which allows the two fluids to be fed to the test section before separation and return again 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. It was found that the liquids were fully inter-dispersed by the time it reached the end of the test section. The phase fraction distribution was shown to be homogeneously mixed near the outlet of the test section.

Keywords: Water-oil flows, phase distribution, stratified-dispersed flow, inlet water fraction, mixture velocities

INTRODUCTION

Multiphase flow is the simultaneous flow of two or more phases in direct contact in a given system. It is important in many areas of chemical and process engineering and in the petroleum industry, e.g. in production wells and in subsea pipelines. The behavior of the flow will depend on the properties of the constituents, the flow rates and the geometry of the system. There are four combinations of two-phase flows namely, gas-liquid, gas-solid, liquid-liquid and solid-liquid. Liquid-liquid flows, the subject of this study are extremely important particularly in two-phase flow applications in horizontal pipes, for instance in the oil industry. In liquid-liquid flow system, it is important to understand the nature of the interactions between the phases and to observe the ways in which the phases are distributed over the cross section of the pipe or know as flow pattern.

The mean in-situ volume fraction will not normally be the same as the input volume fraction. The flow behavior is also influenced by the density and viscosity of the phases and the diameter of the pipe. Studies of such parametric effects include those of Charles *et al.* (1961), Arirachakaran *et al.* (1989) and Shi *et al.* (1999). Most previous studies have

* Corresponding Author

focused on general flow patterns and their delineation through flow pattern maps. There have been only a few studies focused specifically on dispersed flows in horizontal pipelines. Moreover, the present detailed understanding of the phenomena involved is very limited. In the dispersed flow region, there exist two types of flow configurations, namely oil-in-water dispersions and water-in-oil dispersions.

A number of recent studies on oil-water dispersions have focused on horizontal pipelines and, in particular, on the evaluation of the behavior of the droplets in the system. Extensive studies have been done on the flow patterns and the transition between them resulting in a better understanding of the two-phase flow structure. It is important to understand the nature of the interactions between the phases and how these influence the flow patterns and the resulting flow pattern maps, the droplet behavior and the phase distributions. Arirachakaran *et al.* (1989) and Angeli (1996, 2000) found that dispersed flow for oil-water systems in horizontal pipes occurs when the liquid-liquid mixture is moving at high velocity. In horizontal flow, the flow pattern will inevitably be more complex because the gravitational force acts perpendicular to the direction of flow. Thus, there is a tendency for the dispersed phase to move vertically (i.e. normal to the tube axis) under the influence of gravity (upwards, due to buoyancy, if the dispersed phase is the lighter phase and downwards if the dispersed phase is the heavier). This tendency is affected by the action of turbulent eddies in the continuous phase which act towards making uniform the distribution of the dispersed phase due to turbulent diffusion. The actual distribution is a manifestation of the balance between gravity-induced separation and turbulence-induced mixing.

Earlier work on liquid-liquid flows in horizontal channels (Angeli, 1996; Soleimani, 1999; Siti Aslina, 2006a, 2006b) included studies of the phase distribution. These studies demonstrated the tendency for the dispersed phase to separate to the top or the bottom of the channel depending on its density relative to the continuous phase. The higher the velocity, the more the fluids were well mixed indicating the increasing dominance of turbulence over gravity. In these earlier experiments, the measurements were made in what was expected to be a relatively fully developed flow at the end of the test section (typically 300-400 tube diameters from the inlet). However, it is likely that further insight could be gained regarding the turbulent mixing and gravity separation processes by studying the development of the flow along the channel and this was the underlying theme of this study. The inlet conditions were such that the heavier phase (water) was introduced at the bottom of the tube and the lighter phase (oil) was introduced at the top of the tube. The initial conditions were therefore of well-separated phases though it would be expected that dispersion of the relevant phase would occur quite quickly downstream of the entrance.

The objectives of this study were to investigate the tendency of flow structure to be affected by the action of turbulent eddies in the continuous phase which results in uniform distribution of the dispersed phase due to turbulent diffusion. The current experimental work is natural free flow from mixing equipment at the inlet of the pipe and therefore the actual distribution is a manifestation of the balance between gravity-induced separation and turbulence-induced mixing along the pipe, from partially stratified to fully homogeneous flow.

MATERIALS AND METHODS

Experimental Setup 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 0.0254 m 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 detail by Siti Aslina (2004).

Water and oil were supplied separately from two 0.681m^3 storage tanks to the stainless steel test sections. The test section had an inside diameter of 0.0243m and was made up of six successive pipe section of lengths of 1m, 1m, 1.87m, 1.87m, 3.85m and 0.1m respectively, giving a total length of 9.7m. The pipe sections are linked together with flanged connections designed to give a continuous and smooth inner bore. The final 0.11m 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 a liquid-liquid separator which has 4m^3 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 was 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 (density, 801kg/m^3, viscosity, 1.6 cp and interfacial tension air-oil-water, 0.027 N/m^2, 0.017 N/m^2). The oil was pumped from the supply drums into the oil tank through a special branch in the suction line of the oil pump.

Measurements were taken using an advanced technique known as Gamma Densitometer System. A gamma densitometer system has been developed for use on the TOWER facility. The platform was designed such that the beam could be traversed with the beam in the horizontal (0º), vertical (90º) and inclined (45º) 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 (Soleimani, 1999; Siti Aslina, 2004). The basic equations for gamma densitometry and the factors influencing measurement accuracy are discussed in detail in Soleimani (1999), Siti Aslina (2004) and Siti Aslina *et al* (2006, 2007).

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} are given by the following equations (Siti Aslina, 2004; Siti Aslina *et al.,* 2006, 2007):

$$\varepsilon_{oil} = \frac{\mathrm{In}\left(I / I_{wat}\right)}{\mathrm{In}\left(I_{oil} / I_{wat}\right)} \tag{1}$$

$$\varepsilon_{wat} = \frac{\mathrm{In}\left(I / I_{oil}\right)}{\mathrm{In}\left(I_{wat} / I_{oil}\right)} = 1 - \varepsilon_{oil} \tag{2}$$

In the experiments, I_{oil} , I_{wat} and I were determined, and the errors lead to an error approximately ±0.26 mm corresponding to an error approximately ±1% in phase hold-up (i.e. at the central chord position. 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. For each flow condition, 75 chordal mean phase fraction measurements were

made with 25 at each orientation. 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 any 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 1.0 m and 7.72 m from the inlet. The measurements were taken at 1.8 m/s and 2.76 m/s mixture velocities 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 (Hu and Stewart, 2002).

RESULTS AND DISCUSSION

Effect of Inlet Water Fraction

Input water fraction is a very important variable. At the lowest water fraction studied (40%), the water would be expected to be dispersed in the oil and at the highest (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 in the following figures. The effect of input water fraction can be illustrated by considering four examples as follows:

(i) Mixture Velocity 1.8 m/s, Axial Location 1.0 m (*Fig. 1*)

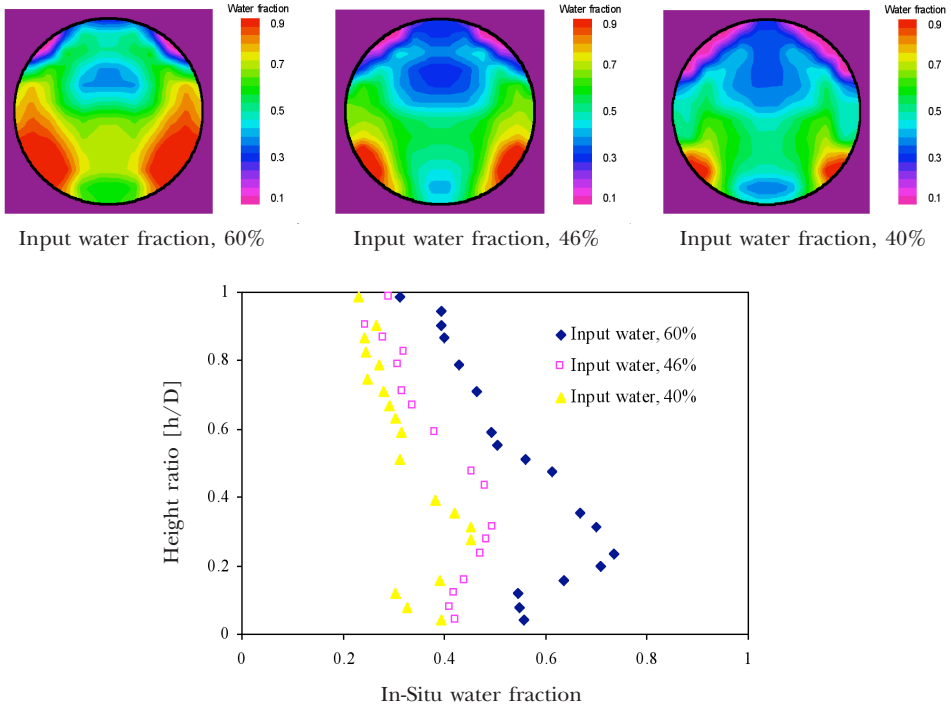


Fig. 1: Cross-sectional phase distributions (obtained by the gamma tomographic method) and vertical water fraction distributions (obtained from the vertical gamma scan) for a velocity of 1.8 m/s and at a position 1m from inlet

At the inlet, the oil is introduced at the top of the channel and the water at the bottom. The phase distribution observed at 1.0 m for a mixture velocity of 1.8 m/s (the lowest velocity studied) may strongly reflect this initial distribution with oil-rich and water-rich zones being seen at the top and bottom of the pipe on either side of a line passing vertically through the axis. Mixing in and around this line may be most intense, leading to the rather unexpected phase distribution observed.

(ii) Mixture Velocity 2.76 m/s, Axial Location 1.0 m (*Fig. 2*)

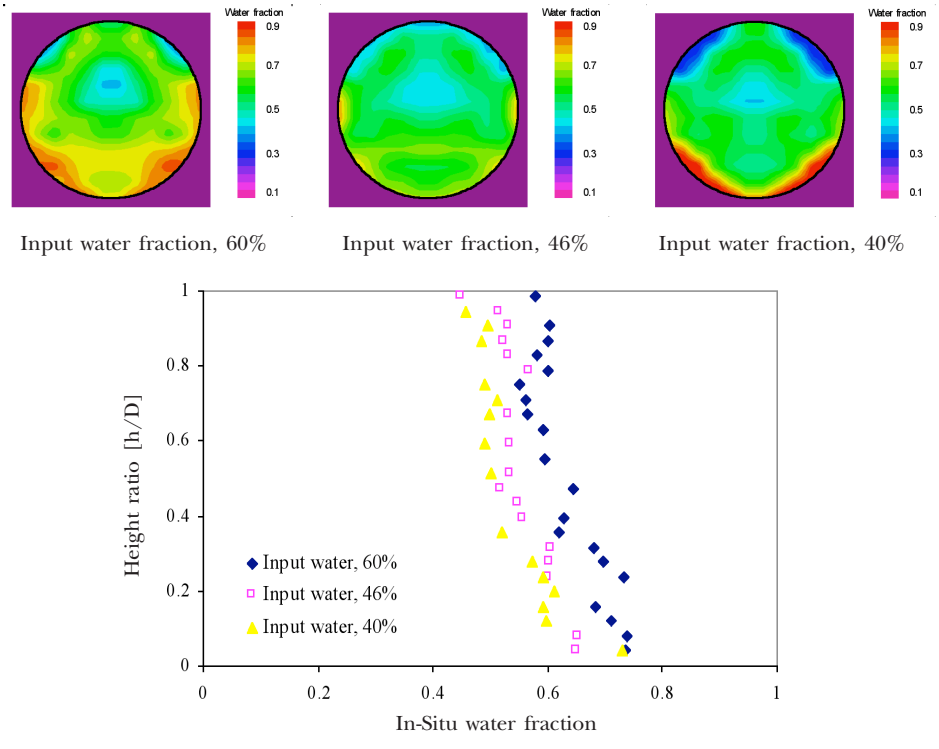


Fig. 2: Cross-sectional phase distributions (obtained by the gamma tomographic method) and vertical water fraction distributions (obtained from the vertical gamma scan) for a velocity of 2.76 m/s and at a position 1m from inlet

In this case, at the highest mixture velocity, 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.

(iii) Mixture Velocity 1.8m/s, Axial Location 7.72 m (*Fig. 3*)

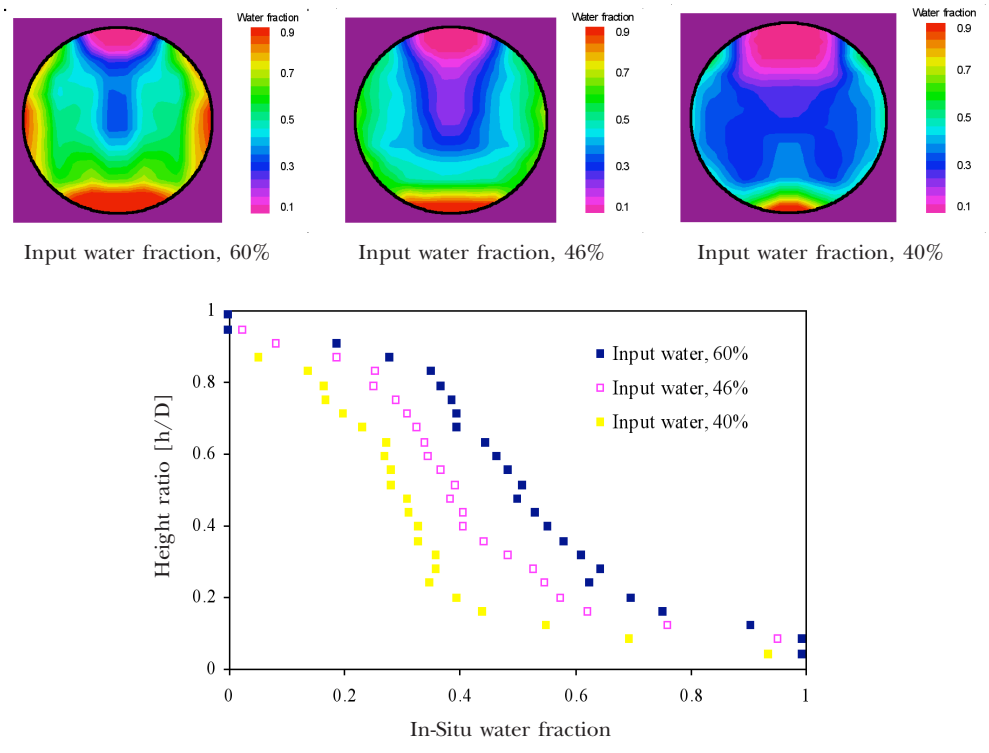
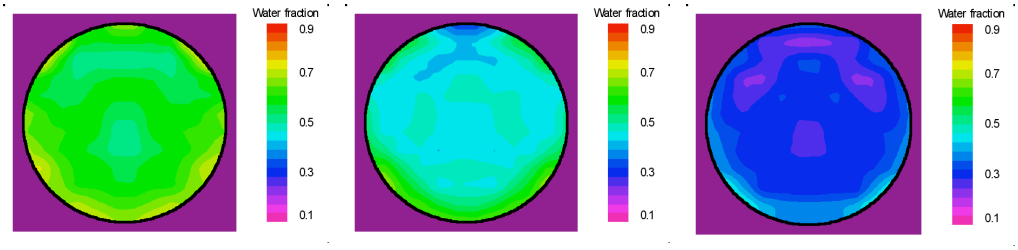


Fig. 3: Cross-sectional phase distributions (obtained by the gamma tomographic method) and vertical water fraction distributions (obtained from the vertical gamma scan) for a velocity of 1.8 m/s and at a position 7.72 m from inlet

For this axial distance, there was time for the two phases to partially separate with an oil "rivulet" at the top of the pipe and a water "rivulet" at the bottom of the pipe. The region between is mixed with some separation of the heavier and lighter phases observed.

(iv) Mixture Velocity 2.76m/s, Axial Location 7.72 m (*Fig. 4*)

At this higher velocity, partial separation is also observed. However, the shape of the regions with near-pure fluid is much more complex. At 46% and 60% input water fractions, the water layer is seen to be spreading around the tube. For 40% input water fraction (water-in-oil dispersion) a region of high oil concentration also appears half way along the circumference from the bottom as shown in *Fig. 4* (water fraction 60%) and (water fraction 46%). This is consistent with the behavior seen in stratifying annular gas-liquid flows (Badie, 2000). Water is constantly separating from the core mixture and forms a downstream-draining layer near the wall which thickens near the bottom of the tube. Re-entrainment of the draining layer may occur near the wall which thickens near the bottom of the tube. Re-entrainment of the draining layer may then occur preferentially from this layer, as well as in the region near the bottom of the tube. The distributions seen in *Fig. 4* (water fraction



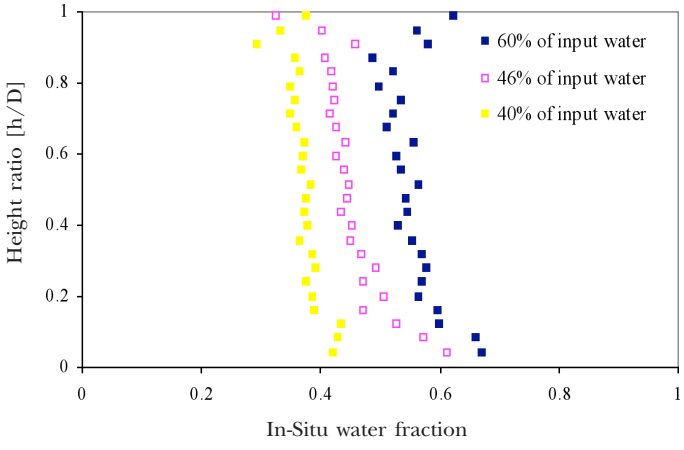


Fig. 4: Cross-sectional phase distributions (obtained by the gamma tomographic method) and vertical water fraction distributions (obtained from the vertical gamma scan) for a velocity of 2.76 m/s and at a position 7.72 m from inlet

40%) indicate that there is a tendency for the phases to mix as they pass along the channel.

Local Volume Fractions Results with Previous Studies

Measurements of the vertical distributions of chordal mean void fraction were made by Soleimani (1999, 2000) for conditions similar to those used in current experiments. Comparisons between the results of this study and that reported by Soleimani are shown in *Figs. 5* and *6*. For the highest velocity (2.76 m/s here and 3.0 m/s for the data of Soleimani), there is reasonable qualitative agreement between the two data sets. Soleimani (1999, 2000) found that there is a transition of phases and therefore at 46% of input water as in *Fig. 5*, there is a higher oil concentration at 0.58, height ratio. The current data shows greater phase separation with lower water concentration at the top of the pipe and higher at the bottom. This is probably accounted for by the fact that a static mixer immediately downstream of the inlet was used in Soleimani's study resulting in good agreement where the phases distributed well across tube area. This may explain the mixing instability and internal forces with higher input velocity that appear in the fluid system.

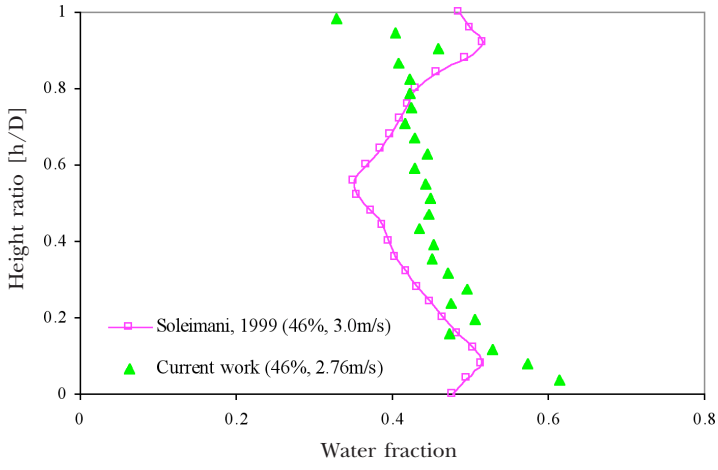


Fig. 5: Comparison of present data for vertical distribution of water phase fraction across the cross section for an input water fraction of 46% and at 7.72 m from the inlet with that of Soleimani (1999)

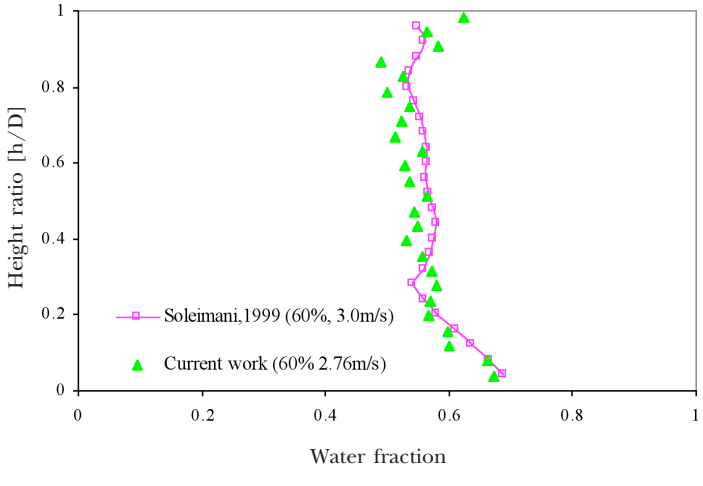


Fig. 6: Comparison of present data for vertical distribution of water phase fraction across the cross section for an input water fraction of 60% and at 7.72 m from the inlet with that of Soleimani (1999)

CONCLUSIONS

The experimental results reported here serve mainly to illustrate the complexity of the processes in liquid-liquid flows. If flow pattern is regarded as a characteristic type of phase distribution then it has been demonstrated that this depends not only on phase flow rates but also on the axial position. Pressure gradient (not reported here) passes through a maximum pressure point 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).

The results for the vertical distributions of chordal mean volume fraction are in reasonable qualitative agreement with those obtained by Soleimani (1999, 2000). The key results are shown in *Fig. 4* and show the tendency of the phase to mix and approach uniform distribution as the flow proceeds along the channel. In general, the tomography results illustrate the great complexity of liquid-liquid dispersed flows, reflecting the many competing processes (turbulence, gravitational separation, droplet break-up and coalescence) which are occurring in the channel.

REFERENCES

Angeli, P. (1996). Liquid-liquid in horizontal pipes (Ph.D thesis, Imperial College, Imperial College of Science, Technology & Medicine, London, England, 1996).

Angeli, P. and Hewitt, G.F. (2000). Flow structure in horizontal oil-water flow. *International Journal Multiphase Flow, 26,* 1117-1140.

Arirachakaran, S., Oglesby, K.D., Malinowsky, M.S., Shoham, O. and Brill, J.P. (1989). An analysis of oil/water flow phenomena in horizontal pipes. SPE paper 18836. In *SPE Prod. Operating Symposium*, March 13-14 (p. 155-167). Oklahoma.

Badie, S. (2000). Horizontal stratifying/annular gas-liquid flow (Ph.D thesis, Imperial College of Science, Technology & Medicine, London, England, 2000).

Charles, M.E, Govier, G.W. and Hodgson, G.W. (1961). The horizontal pipeline flow of equal density oil-water mixture. *Can. J. Chem. Eng., 39,* 27-36.

Hu, B. and Stewart, C. (2002). XrayCT 1.1 calculation principle and user's manual. Three Plex Project, MPS/188. Department of Chemical Engineering and Chemical Technology, Imperial College of Science, Technology & Medicine, London, England.

Rashmi, W., Siti Aslina, H. and Thomas, C.Y.S. (2006). Analysing liquid holdup for dispersed flow using CFD. In *11th Asian Pacific Confederation of Chemical Engineering (APCChE Congress 2006)*, 28-30 August. Kuala Lumpur.

Shi, H., Cai, J.Y. and Jepson, W.P. (1999). Oil-water distributions in large diameter horizontal pipelines. Multiphase flow and heat transfer. *Proc. of the Fourth International Symposium* (p. 73-80). Xi'an China.

Siti Aslina, H. (2004). Experimental and computational studies of liquid-liquid dispersed flows (PhD Thesis, Imperial College of Science, Technology & Medicine, London, England, 2004).

Siti Aslina, H., Siti Mazlina, M.K. and Wan Hassan, M.J. (2006). *In-situ* phase fractions for oil and water occupied in pipe channel. *International Journal of Engineering and Technology, 3(2)*, 248-256.

Siti Aslina, H. and Siti Mazlina, M.K. (2006). *In-situ* phase fractions for oil and water occupied in pipe channel. *Seminar on Engineering and Technology (SET 2006)*, 4-5 September. Kuala Lumpur.

Siti Aslina, H. (2006a). Local volume fraction on liquid-liquid dispersion. *The Eleventh Asian Congress of Fluid Mechanics*, 22-25 May. Kuala Lumpur.

Siti Aslina, H. (2006b). Experimental investigation of two-phase local volume fraction using gamma densitometer system technique on liquid-liquid dispersion. *11th Asian Pacific Confederation of Chemical Engineering (APCChE Congress 2006)*, 28-30 August. Kuala Lumpur.

Siti Aslina, H., Siti Mazlina, M.K. and Wan Hassan, M.J. (2007). Influence of oil and water holdup on mixture velocity in horizontal flows. *Journal of Chemical Engineering of Japan* (In Press).

SOLEIMANI, A. (1999). Phase distribution and associated phenomena in oil-water flows in horizontal tubes. (Ph.D Thesis, Imperial College of Science, Technology & Medicine, London, England, 1999).

SOLEIMANI, A. (2000). Spatial distribution of oil and water in horizontal pipe flow. *SPE Journal, 4*(5), 394-401).