OIL-WATER FLOWS CHARACTERISTICS IN PIPES OF DIFFERENT DIAMETER

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ABSTRACT

The flow patterns during oil-water flows were investigated in two acrylic pipes that had different diameters, 38 mm ID and 14 mm ID respectively. Water (ρ = 1000 kgm^{-3}, μ = 0.001 kgm^{-1}s^{-1}) and Exxsol D140 oil (ρ = 830 kgm^{-3}, μ = 0.0055 kgm^{-1}s^{-1}) were used as test fluids, while the patterns were recorded with a high speed camera. Dispersed and rivulet flows were seen in the small pipe but not in the large one at the conditions studied. The dual continuous pattern appeared in both pipes but, with different characteristics. Larger drop sizes and smoother interface were seen in the smaller pipe. Double-wire conductance probes were used to collect time-series records of the oil-water interface variation during stratified flow in the pipes. Data was collected at 256 Hz (or 512 Hz) for up to 4 min. Following de-trending and normalisation, the signal was found to be stationary and normal. Power spectra were computed via the auto-correlation function. Low-frequency contributions (due partly to the pumps) were seen in both pipes. In the large pipe, contributions were in the range 20 – 50 Hz and their normalised power increased with the mixture velocity. These higher frequencies were attributed to the fluctuations and roughness of the interface, notorious in the large-diameter pipe during stratified flow. In contrast, the interface in the small pipe was smooth.

***Keywords**: oil-water mixture, stratified flow, flow pattern, double-wire conductance probe, power spectrum, wave characteristics*

Introduction

During the flow of oil and water mixtures, a number of flow patterns can appear depending on fluid properties, input phase flow rates and pipe diameter and inclination. The patterns, in general, change from fully-separated, to partially and fully-dispersed as the mixture velocity increases. It is important to characterise and be able to predict the type of flow pattern and the corresponding phase distribution of the mixture because they determine parameters such as the pressure drop or the mass and heat transfer coefficients, and have an effect on the separation of the two phases.

In research related to oil production and transportation, pipes of large diameter (> 20 mm ID) have been used experimentally (recently, Elseth, 2001; Yao and Gong, 2004; Raj et al., 2006; Al-Wahaibi, 2006; Ngan et al., 2011; etc.). A number of patterns have been identified. The fluid properties -particularly viscosity- and the pipe inclination were found to have a strong effect on the patterns established. Parameters such as pressure drop and the in-situ phase hold-up were measured and experimental results compared against theoretical models, mainly the two-fluid and the homogeneous model.

As opposed to the large diameter pipes, there is limited amount of work available in pipes of small diameter. For example, Beretta et al. (1997) studied oil-water flows in tubes of 3 mm and observed patterns significantly different to those in larger-diameter pipes. In the recent years, the growing importance of miniaturised and micro-scale systems has resulted in a number of studies of liquid-liquid mixtures in channels and capillaries with diameter less than 1mm. This interest arises from the enhanced heat and mass transfer rates achieved in micro-channels due to thin fluidic films that established and enhanced their effectiveness. Such systems have been used in extractive separations (Tsaoulidis et al., 2012), chemical reactions (Kashid et al., 2011) and in miscellaneous applications.

The importance of interfacial forces increases in channels of small diameter and affects the flow patterns developed. It has been suggested that the surface and interfacial forces dominate (the channel is considered small) when Eötvos number, Eo, is larger than 1 (Brauner and Moalem Maron, 1992):

$$\mathrm{Eo} = \frac{(2\pi)^2 \gamma}{\Delta\rho g D^2} \qquad (1)$$

where, γ is the interfacial tension of the two-phase system (i.e. oil-water), Δρ is the density difference between the two fluids, g is the gravity and D is the channel diameter.

In small channels the Eo numbers can be quite large; the flows are in the laminar regime and viscous and interfacial forces dominate. In large pipes, on the contrary, the Reynolds numbers are normally into the turbulent regime and inertial forces are prominent. However, there is an intermediate region of pipe sizes where the contributions of the gravity, interfacial and inertial forces are comparable. Currently, there is very limited work available in this area. Mandal et al. (2006) presented an experimental study of oil-water flow in pipes of two different diameters, 25 mm and 12 mm, using oil with density 787 kgm^{-3} and viscosity 1.2 cp. The Eo numbers were 0.93 and 3.4 for the larger and the smaller pipe, respectively. They found important differences in the flow patterns and the transition boundaries. Rivulet flows, characterized by unsteady meandering paths, were only seen in the smaller pipe.

In this work, the flow patterns seen in two pipes of different diameter (38 and 14 mm ID) at similar oil-water input conditions were analyzed. The Eo numbers are comparable to those of Mandal's work: 0.65 (38 mm ID) and 4.85 (14 mm ID). Further, interfacial characteristics in stratified flow were investigated and compared between pipes, in order to explain the transition to dual continuous flow. Interfacial characteristics were calculated from time-series data of the interface height variation collected with a double-wire conductance probe.

Nomenclature

D	pipe diameter (m)
Eo	Eötvos number (-)
g	gravity (ms^{-2})
Q	flow rate ($Lmin^{-1}$)
r	oil-to-water input ratio (-)
Re	Reynolds number (-)
U_{mix}	mixture velocity (ms^{-1})

Greek letters

α	water fraction (-)
γ	interfacial tension (mNm^{-1})
Δ	change operator (-)
Δp/ΔL	pressure drop per unit of length (Pam^{-1})
μ	viscosity ($kgm^{-1}s^{-1}$)
ρ	density (kgm^{-3})

Subscripts

o	oil
w	water

Materials and Methods

The experiments were carried out in two liquid-liquid flow facilities with test pipes made of acrylic of two different sizes, 14 mm ID (Figure 1) and 38 mm ID, respectively. The test fluids used were tap water (ρ = 1000 kg m^{-3}, μ = 0.001 kg m^{-1} s^{-1}) and ExxsolD140 oil (ρ = 830 kg m^{-3}, μ = 0.0055 kg m^{-1} s^{-1}), where ρ and μ are density and viscosity, respectively. The oil-water interface tension is 39.6 mNm^{-1} (Lovick and Angeli, 2004). The fluids were pumped through Y-inlet sections in order to minimise mixing at the junction. Different oil-water flow rate combinations were studied in both pipes with mixture velocities, U_{mix}, ranging from 0.5 ms^{-1}-1.4 ms^{-1} and input oil-to-water flow rate ratios, r, between 0.5 and 2.5. Flow patterns were identified with a high-speed camera Phantom Miro 4 and images were collected at 1,200 frames per second (fps). Pressure drop was measured with a water manometer in the large pipe and an electronic, hand manometer in the small pipe.

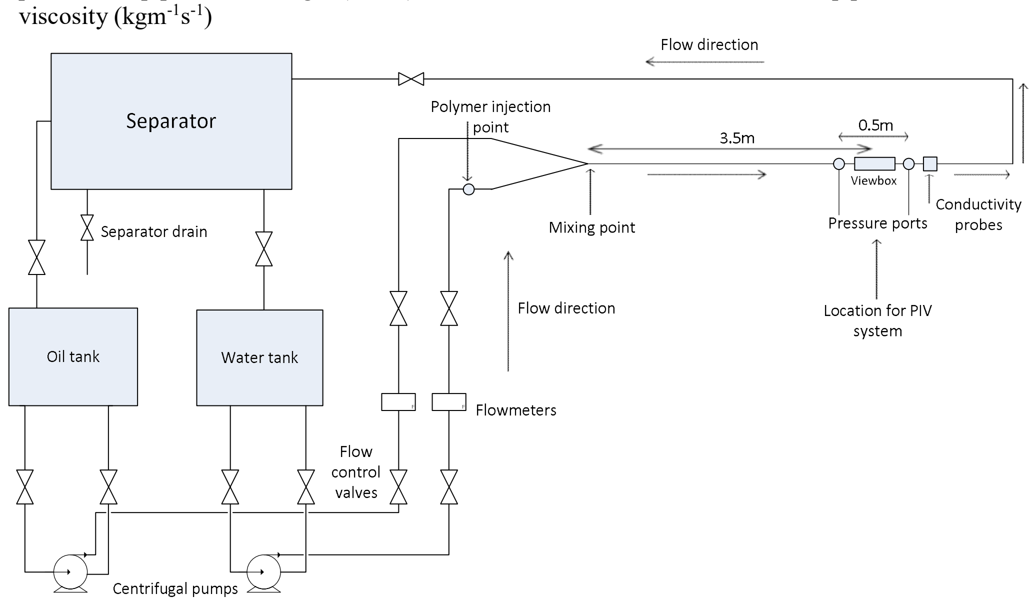


Figure 1: Sketch of 14mm ID flow facility

In order to study the oil-water interface characteristics during stratified flow, two double-wire conductance probes were used, one in each pipe. The instrument consists of two thin, parallel wires of 0.5 mm in thickness, located vertically at the central span of the cross sectional area 2 mm apart. The probes were placed 7 m downstream the inlet in the large pipe (~ 180 D) and 4 m in the small pipe (~ 280 D). An off-line calibration was performed and a linear response was found between interface height and probe signal. The probe signal gives the interface height variation in time. For each set of flow conditions, data was collected during up to 4 min at sampling frequencies of 256 or 512 Hz, which seem to satisfactorily capture periodicities and avoid alias of the record. Prior to any analysis, the signal time series was first de-trended in order to eliminate the low-frequency noise introduced by the data acquisition system and, second, normalised. Normalisation help correct the variation in water conductivity due to changes in salinity and temperature between different experimental campaigns. The time-average interface height was then computed from the signal values over the recording time using the calibration curve. In situ, time-averaged water fraction could then be calculated from the interface height, by virtue of geometrical relations in a cylindrical pipe.

It was found that the probe signal is stationary and Gaussian. Under these conditions, the Fourier Transform of the autocorrelation function of the signal is the power spectrum (Theorem Wiener-Khinchine). The sampling frequencies used (power of 2: 256 = 2^8; 512 = 2^9) allows the computation of Fourier Transform via a Fast Fourier

Transform (FFT) algorithm. In this work, codes were developed in MATLAB ®.

Results and Discussion

Flow patterns. Figure 2 shows the flow pattern boundaries in both size pipes as a function of the oil-to-water input ratio, r and the mixture velocity, U_{mix}.

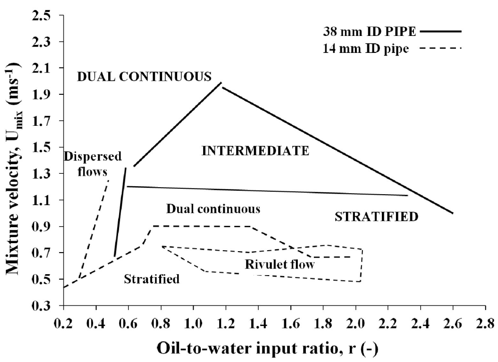


Figure 2: Flow pattern map observed in pipes of different diameter.

In general, it can be seen that the stratified flow persists at higher mixture velocities in the large pipe, whereas dual continuous or dispersed patterns developed in the small one. At low mixture velocities and input ratios close to 1, the flow pattern observed was stratified. As the mixture velocity increases in the 38 mm pipe, an *intermediate* regime appears, characterized by a rough interface and the presence of small and sporadic drops (Figure 3). In contrast, the transition to dual continuous flow in the 14 mm pipe is direct and no intermediate pattern is seen.

Additionally, in the small pipe, mostly within the stratified pattern, rivulet flow is observed at r = 0.8 – 2 and U_{mix} = 0.5 – 0.75, approximately (Figure 4). The pattern is characterized by two continuous faces that *swirl* around the pipe axis and follow a meandering path. It was also observed that the frequency of the swirl is affected by the input phase ratio. The rivulet pattern was not seen in the large pipe at all, where the stratified flows were steady at the downstream location where the measurements were taken.

The water phase is in the turbulent regime for all oil-water combinations investigated in the 38 mm ID pipe, while the oil phase is in transition regime (Re_o = 2000 – 6000). However, in the 14 mm ID pipe oil flows in laminar regime (Re_o = 50 – 2000) and both laminar and turbulent regimes are possible in the water phase (Re_w = 1000 – 15000). This is interesting: even though Re numbers are larger and non-laminar in the 38 mm pipe at comparable mixture velocity, the stratified flow is sustained.

The Eo numbers for the larger and smaller pipes are 0.65 and 4.85, respectively. According to Brauner and Moalem Maron (1992), interfacial forces would be significant in the case of the 14 mm pipe (Eo > 1). The contribution and effect of these forces on the flow pattern would be much less in the larger pipe.

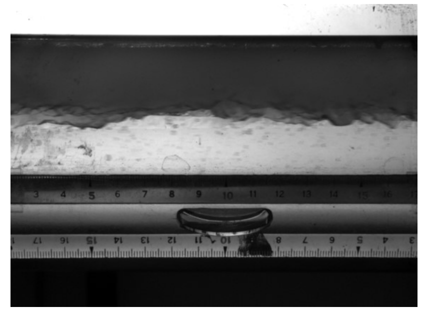


Figure 3: Intermediate flow pattern in the 38 mm pipe.

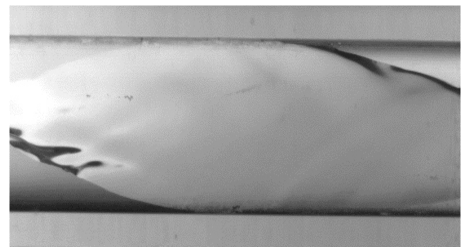
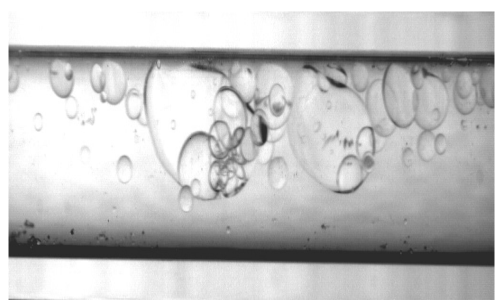
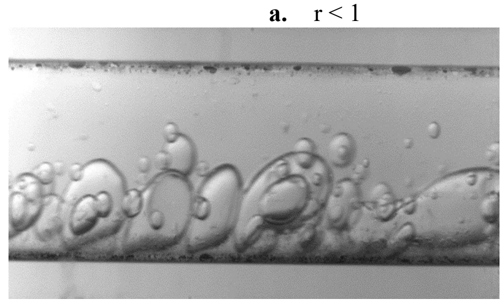


Figure 4: Rivulet flow pattern in the 14 mm pipe.

At input ratios r < 1 or r > 1 the stratified flow in the 14 mm pipe changes to the dual continuous pattern. At even lower ratios dispersed flows establish with large oil drops flowing inside a continuous water phase (Figure 5a) or vice-versa (Figure 5b). The pattern with water as the continuous phase and oil drops was observed at water fractions about 70 %. However, water drops in a continuous phase of oil was only seen at very large input ratios (r > 8) or large oil fractions (90 % or more). It seems that at low or high input ratios, the phase with lower flow rate cannot maintain a continuous layer in the smaller pipe and becomes dispersed.



a. r < 1



b. r > 1

Figure 5: Bubbly flow in the 14 mm ID pipe.

Dispersed oil drops were seen to flow close to the upper wall of the pipe, while water drops flow at the bottom, according to their density (Figures 5a, b). The size of the drops varies, but is considerable compared to the pipe diameter (0.05 – 0.60 D). As the mixture velocity increases the frequency and amount of drops increases. In addition, it was observed that if the flow rate of the dispersed phase is increased (and that of the continuous phase remains constant), drops are larger and travel faster, as a consequence of the slightly-increased mixture velocity.

In contrast, in the larger pipe, dispersed flows were not seen. At $r < 1$, there is a sharp transition from stratified to dual continuous flow in the 38 mm pipe. This pattern is characterised by separated, continuous phases carrying sustained drops of the other phase (entrainment) and has been observed in both pipes. Figure 6 gives an example of dual continuous flow in the smaller pipe: drops distribute around the interface. In the 38 mm pipe, at low mixture velocities, drops also distributed around the interface, but the pattern is different at $r < 1$ and $r > 1$. At $r < 1$, it is similar to that in the smaller pipe, but oil drops are formed, mainly (Figure 7a); at $r > 1$ drops are scarcer and of smaller size (Figure 7b).

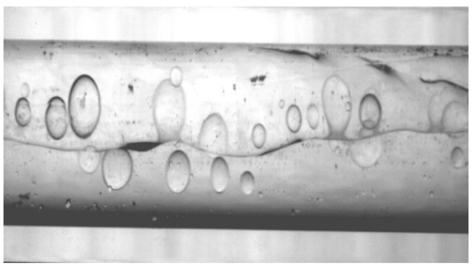
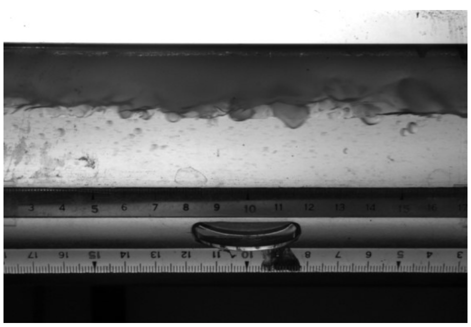
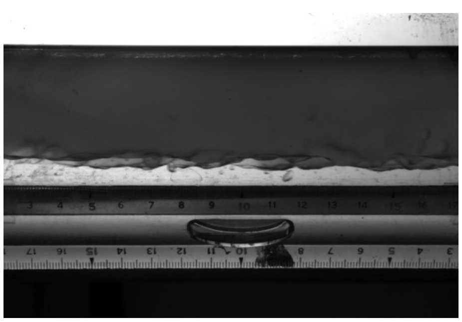


Figure 6: Dual continuous flow in the 14 mm pipe.



a. $r < 1$



b. $r > 1$

Figure 7: Dual continuous flow in the 38 mm pipe.

In the 38 mm pipe it has been observed that the interface oil-water is relatively smooth during the transition to dual continuous flow at $r < 1$. It becomes rougher as the mixture velocity increases. In contrast, flows with large input ratios display stratified patterns with rougher interfaces before transition to dual continuous occur.

Water fraction and pressure-drop. The in situ water fraction calculated from the time-averaged interface height is shown in Figure 8 for both pipe diameters. All results are for stratified patterns and can be compared with the predictions of the standard two-fluid model (Brauner and Moalem Maron, 1989). In both cases, there is a strong dependence with the input ratio, r. In the larger pipe, the in situ water fraction depends only on r, while in the smaller pipe, there is a small dependence on the mixture velocity, and the water fraction increases slightly as the mixture velocity increases. Pressure drop was also measured and was found to increase only with mixture velocity in both pipes (Figure9), although the increase and values are larger in the case of the 14 mm pipe.

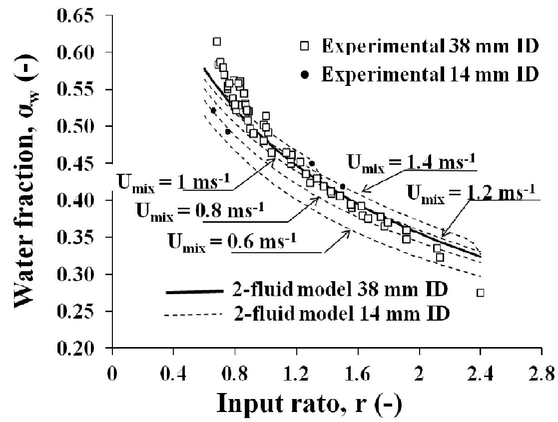


Figure 8: Experimental and predicted in situ average water fraction against oil to water flow-rate ratio.

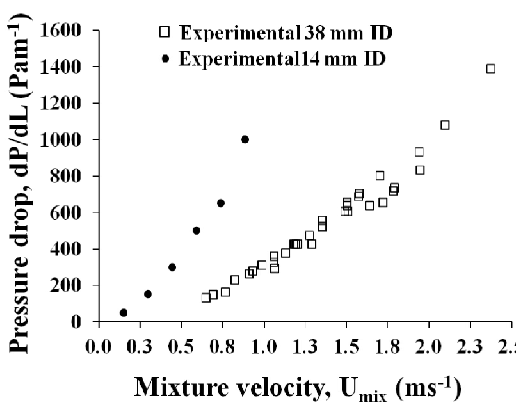
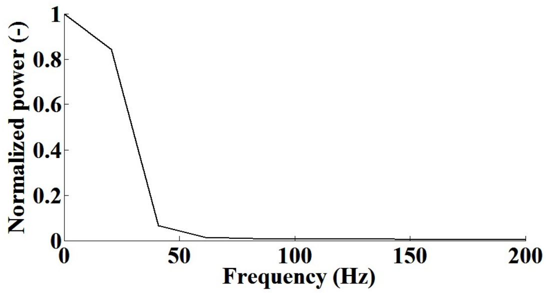
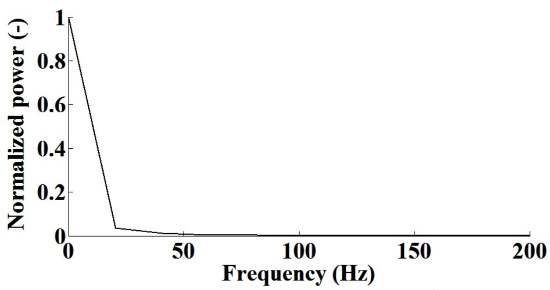


Figure 9: Experimental pressure drop against mixture velocity.

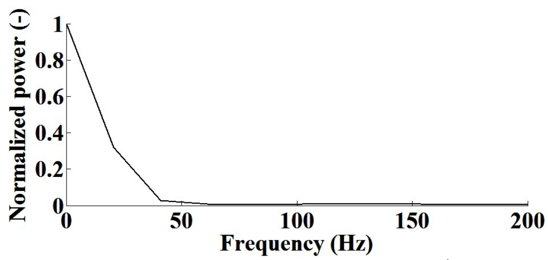
Power spectrum of the probe signal. The power spectra of the time series of the interface heights obtained by the probe in stratified flows were computed via the Fourier Transform of the auto-correlation function of the probe signal. This procedure is valid because of the Wiener-Khinchine theorem, which states that the power spectrum is the Fourier Transform of the auto-correlation function if the record is stationary and Gaussian. (Bendat and Piersol, 2010).



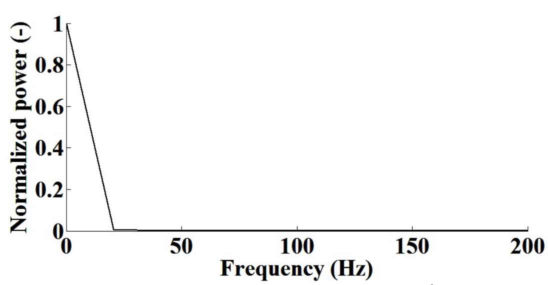
a. r = 1; U_{mix} = 0.441 ms^{-1}



b. r = 1; U_{mix} = 0.735 ms^{-1}



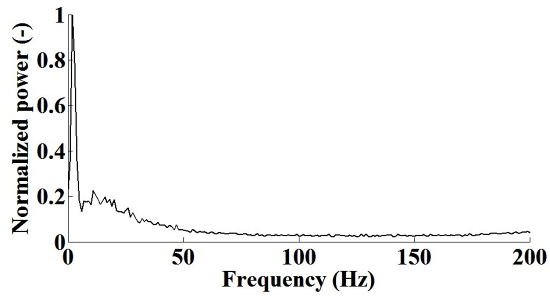
c. r = 0.75; U_{mix} = 0.441 ms^{-1}



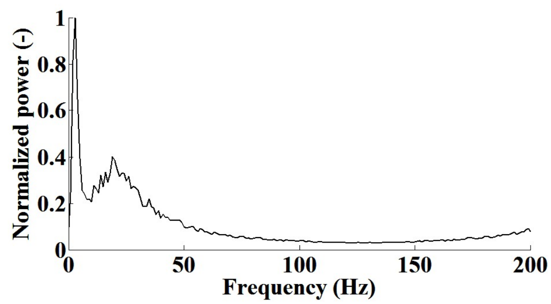
d. r = 2; U_{mix} = 0.735 ms^{-1}

Figure 10: Power spectrum of the conductance probe signal in the 14 mm pipe.

It was found that the spectrum of the probe signal collected in the small pipe had similar characteristics for all flow conditions investigated regardless of the input ratio and the mixture velocity (see Figure 10 a-d). There is only a band of frequencies up to 45 Hz, while the highest contributions are seen up to 20 Hz. The operation of the pumps contributes to some extend to the low frequencies seen. This frequency band is also seen during stratified flow in the 38 mm-pipe. However, in this case, the width is narrower: the band contains mainly the lowest frequencies up to 5 Hz, which is attributed mostly to the operation of the pumps. Higher frequencies (20 – 50 Hz) appear in the spectrum, and their amplitude depends on the flow rates. The normalised power of the frequencies in this band increases with the mixture velocity (Figures 11 a-b). Some contributions can also be seen in the high-frequency end of the spectrum (> 50 Hz).



a. U_{mix} = 1.20 ms^{-1}



b. U_{mix} = 1.63 ms^{-1}

Figure 11: Power spectrum of the conductance probe signal in the 38 mm pipe diameter at r = 1.

The presence of a band at high frequencies in the larger-diameter pipe reflects the fluctuating nature of the oil-water interface, which was also captured with the high speed imaging (Figure 12). In contrast, it was observed that the interface in the small diameter pipe is significantly smoother than that in the 38 mm pipe.

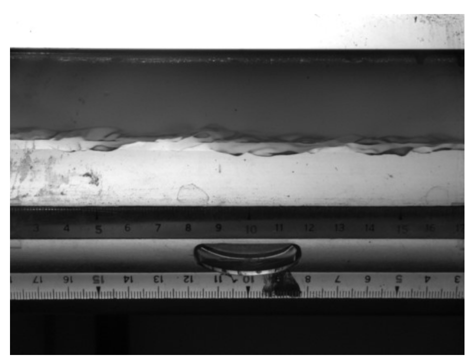


Figure 12: Interface roughness of stratified flow in 38 mm pipe at r = 1.2 and U_{mix} = 1 ms^{-1}.

Conclusions

Different flow patterns have been identified in two test pipes of different size (14 mm ID and 38 mm ID) during horizontal oil-water flow. In the 14 mm ID pipe, Eo number was found to be greater than 1 and hence, interfacial phenomena was significant A spiral, rivulet and dispersed flows patterns were seen in the 14 mm pipe. Although dual continuous flow appears in both pipes, there are qualitative differences depending on the pipe size.

The interfacial characteristics during stratified flow were studied with double-wire conductance probes. The time series probe signal data was found to be stationary and Gaussian, which allows the calculation of its power spectrum via the auto-correlation function of the signal. The spectra from both pipes had characteristic low frequency contributions, attributed to the pumps. Variable higher-frequency contributions (above 20Hz) appeared in the larger pipe but not in the smaller one and reflect the fluctuating interface observed in the large pipe. Their normalised power increases with the mixture velocity in agreement with the increase in interface roughness.

Acknowledgements

The authors are grateful to Chevron Technology Company and UCL, on one side, and to the Nigerian Petroleum Technology Development Fund (PTDF), on another, for their financial support of these projects. Special acknowledgments go to Dr. Simon Barrass for assisting technically with the conductance probe and instrumentation. The authors would also like to acknowledge UK EPSRC for the loan of the high-speed camera Phantom Miro 4.

References

Al-Wahaibi, T. K. *Investigations on the transition between stratified to non-stratified horizontal oil-water flows*, Ph.D. Thesis, University College London (2006).

Bendat, J. S. & Piersol, A. G. *Random data: analysis and measurement procedures*, Wiley series in probability and statistics, New Jersey, 4th edition (2010).

Beretta, A. et al. Oil-water flow in small diameter tubes: flow patterns, International Communications in Heat and Mass Transfer, 24 (2), 223-229 (1997).

Brauner, N. & Moalem Maron, D. Two phase liquid-liquid stratified flow, Physical Chemical Hydrodynamics, 11, 487-506 (1989).

Brauner, N. & Moalem Maron, D. Identification of the range of small diameters conduits regarding two-phase flow pattern transitions, International Communications in Heat and Mass Transfer, 19, 29-39 (1992).

Elseth, G. et al. Measurement of velocity and phase fraction in stratified oil/water flow, In: *2nd International Symposium on Multiphase Flow and Transport Phenomena*, Antalya, Turkey, 333-340 (2001).

Kashid, M. et al. Micro-structured reactors and supports for ionic liquids, Chemical Engineering Science, 66(7), 1480-1489 (2011).

Lovick, J. A. & Angeli, P. Experimental studies on the dual continuous flow pattern in oil-water flows, International Journal of Multiphase Flow, 30, 139-157 (2004).

Mandal, T. K. et al. Oil water flow through different diameter pipes: similarities and differences, Chemical Engineering Research and Design, 85(A8), 1123-1128 (2007).

Ngan, K. H. et al. Effect of glycerol addition on phase inversion in horizontal dispersed oil-water pipe flows, Experimental Thermal and Fluid Science, 35, 628-635 (2011).

Raj, T. S. et al. Liquid-liquid stratified flow through horizontal conduit, Chemical Engineering and Technology, 28(9), 899-907 (2005).

Tsaoulidis, D. et al. Dioxouranium (VI) extraction in micro-channels using ionic liquids, Chemical Engineering Journal, DOI: 10.1016/j.cej.2012.08.064.

Yao, H. Y. & Gong, J. An experimental investigation on flow patterns and pressure gradients of heavy oil-water flows in horizontal pipes, In: *3rd International Symposium on Multiphase, Non-Newtonian and Reacting Flows*, Hangzhou, China (2004).