Characterisation of the mean and time dependent properties of inclined oil-in-water pipe flows using dual-sensor probes

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ABSTRACT

An array of dual-sensor conductance probes, which contains a number of dual-sensor probes equispaced across the diameter of an 80mm pipe, is introduced in this paper for characterizing bubbly oil-in-water pipe flows inclined at angles from 15 degrees to 60 degrees to the vertical. Each dual-sensor probe measures the local axial oil velocity and the local oil volume fraction at the position of the probe. Choosing an averaging interval of 0.05s, values of local oil volume fraction and local oil velocity were measured simultaneously at the different probe positions, enabling the time dependent structure of the two phase flow to be investigated. After data processing, time dependent variations of volume fraction along the pipe were found which are consistent with the presence of intermittent Kelvin-Helmholtz wave structures in the flow. A high speed dual-plane ERT system was used to measure the axial propagation speed of these Kelvin-Helmholtz waves, using cross-correlation. This paper presents results for the measured characteristics of inclined oil-in-water flows including (i) time averaged and time dependent oil volume fraction and velocity distributions and (ii) the Kelvin-Helmholtz wave properties including the wave speed, wave amplitude, wavelength and wave frequency.

Keywords Dual-sensor probe array, high-speed dual plane ERT, Kelvin-Helmholtz wave

1 INTRODUCTION

In the oil industry, horizontal and inclined liquid-liquid flows are frequently encountered. Often, it is required to measure the volumetric flow rate of each of the flowing components and this is particularly true in "Production Logging" applications, where it may be necessary to measure the flow rates of oil and water downhole in inclined oil wells. In an inclined liquid-liquid flow, if the flow is assumed to be steady state, the volumetric flow rate Q_i of the i^{th} component can be obtained using the relationship $Q_i = \int_a \alpha_i u_i da$ where α_i is the local volume fraction of the i^{th} component, u_i is the local axial velocity of the i^{th} component and a represents the cross-sectional area of the flow. In inclined oil-water flows, naturally occurring Kelvin-Helmholtz waves are present which influence both the time dependent and time averaged velocity and volume fraction profiles of the phases. A few techniques such as dual plane Electrical Resistance Tomography (ERT) can be used to measure the time dependent local volume fraction and local axial velocity profiles of the oil (Y.Dai, M Wang *et al.* (2005), Lucas *et al.* (1999)). However few techniques are available to validate the ERT measurement results and to investigate the Kelvin-Helmholtz waves in more detail.

In this paper, dual sensor conductance probes are presented for measuring the local oil droplet axial velocity and the local oil volume fraction. Firstly, a single dual-sensor probe is used to measure time averaged values of these flow properties at different spatial locations in the flow cross section with the aid of a traverse mechanism. Next a novel array of conductance probes is introduced which contains four dual sensor probes positioned along a pipe diameter and which is used to simultaneously measure time dependent values of the local oil axial velocity and the local oil and water volume fractions at different positions in the pipe. This probe array helps to investigate the Kelvin-Helmholtz (K-H) wave phenomenon in inclined oil-water pipe flows and could be used to validate mathematical models of such flows. For the experiments described in this paper, the inclination angle of the pipe varies from 15 degrees to 60 degrees from the vertical. The water flow rate Q_w is from 1.5 $\mathrm{m^3/h}$ to 6.5 $\mathrm{m^3/h}$ and the oil flow rate Q_o is from 0.6 $\mathrm{m^3/h}$ to 3.5 $\mathrm{m^3/h}$. Based on the probe signals, 0.05s was initially used as the time interval over which "time dependent" values of local volume fraction and local axial velocity were measured. Processing the dual-sensor array probe signals also allowed the frequency of the Kelvin-Helmholtz (K-H) waves in the inclined pipe flow to be measured. Finally, a high-speed dual plane ERT system was used to measure the speed of propagation of the K-H waves in the flow. By combining results from the dual-sensor array and the high-speed dual plane ERT system, the K-H wavelength can be calculated for the flow conditions investigated.

2 Operation of dual sensor conductance probe

Conductance dual sensor probes were used to measure the local oil volume fraction and local axial oil velocity in inclined oil-in-water flows. Figure 1 is a schematic diagram of the type of conductance dual sensor probe that was used in the experiments described in this paper.

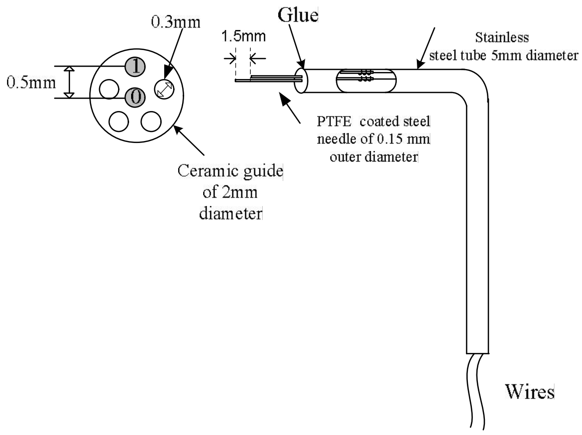


Figure1: The schematic diagram of the single dual sensor probe

The dual sensor probe was made from two PTFE coated steel needles of 0.15mm outer diameter, with the PTFE removed from the very tip of each needle to allow electrical contact with the oil-water two-phase flow. To position the needles, a 2mm diameter ceramic guide which included a number of 0.3mm diameter holes was used to mount the needles. The axial distance between the front and the rear needles was about 1.5mm thus ensuring that the oil bubbles contact the front sensor before contacting the rear sensor. Measurement circuitry used with the probe has been presented in a previous paper (Lucas(2004)). However, when an oil droplet contacts the probe the signals from the front and rear sensors are as shown in Figure 2.

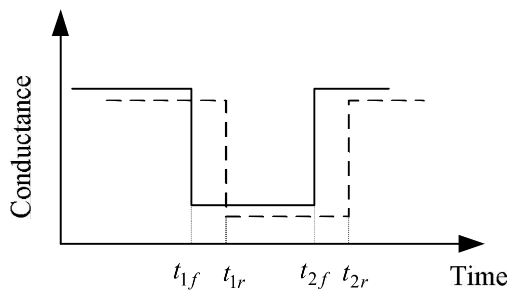


Figure2: Ideal signals obtained from a gas bubble striking a local dual sensor conductance probe

Let us assume that the surface of a bubble makes first and last contact with the upstream (front) sensor at times t_{1f} and t_{2f} respectively. The times at which the rear sensor makes first and last contact with the surface of the droplet are t_{1r} and t_{2r} respectively. Suppose N droplets hit both the front and the rear sensors during a sampling period T . For the i^{th} droplet two time intervals $\delta t_{1,i}$ and $\delta t_{2,i}$ may be defined as follows:

$$\delta t_{1,i} = t_{1r,i} - t_{1f,i} \tag{1}$$

and

$$\delta t_{2,i} = t_{2r,i} - t_{2f,i} \tag{2}$$

The axial distance s between the two needle sensors can be accurately measured using a microscope before and after the probe is mounted in the pipe. The mean local axial oil droplet velocity u_o at the position of the probe is then given by

$$u_o = \frac{2s}{N} \sum_{i=1}^{N} \frac{1}{(\delta t_{1,i} + \delta t_{2,i})} \tag{3}$$

The local volume fraction α of the oil at the position of the probe can be estimated from the conductance signals from the front and rear sensors. If we again assume that in the time T, N oil droplets hit the front and rear sensors then the local oil volume fraction α is given by

$$\alpha = \frac{\frac{1}{T}\sum_{i=1}^{N}(t_{2f,i} - t_{1f,i}) + \frac{1}{T}\sum_{i=1}^{N}(t_{2r,i} - t_{1r,i})}{2} \tag{4}$$

3 The Oil Water Flow Loop

The experiments described in this paper were carried out in the 80mm internal diameter, 2.5m long, vertical, perspex working section of a purpose built oil-water flow loop. The oil and water were stored in a 2.5 m^3 stainless steel separator tank. The water outlet was located close to the base of the tank and the oil outlet was selected using one of three manual valves, dependent upon the position of the oil-water interface. On leaving the tank the oil and water were conveyed through separate flow lines prior to being mixed together in a manifold just upstream of the working section. The oil and water flow lines each contained (i) a pump capable of pumping up to 20 $\mathrm{m^3/h}$ of liquid at 3 bar gauge pressure, (ii) an electro-pneumatic control valve and (iii) a turbine flow meter. For each flow line the liquid flow rate was controlled using a separate Proportional-Integral-Derivative controller so that the oil and water flow rates into the flow loop working section could be individually controlled, for long periods of time, to better than 0.5% of set-point flow rate. A rotation mechanism was used to connect the manifold to the working section so that the working section could be inclined at any angle from 0 degrees to 60 degrees from vertical. On emerging from the flow loop working section the oil-water mixture was piped back to the inlet of the separator tank in the form of a `primary dispersion'. Gravity induced separation of the oil and water in the tank was accelerated with the aid of a coalescer cartridge which spanned the cross-section of the separator tank. The oil used in the experiments described in this paper was Shellsol D70 with a density of 790 kg/m^3 and a kinematic viscosity of about 2 mm^2/s at 20 degrees Celsius.

4 Measuring time averaged values of the local oil volume fraction and the local axial oil velocity using a single dual sensor probe and a traverse mechanism

A single dual sensor conductance probe was used in conjunction with a traverse mechanism to measure time averaged (T = 60s) values of the local oil volume fraction and local oil axial velocity at different spatial location in the flow cross section in the 80mm diameter working section of the flow loop described above. At each spatial location the axes of the needle sensors were parallel to the pipe axis. The traverse mechanism was controlled by two stepper motors and was used to position the probe. For the given flow condition, 60 seconds of data were collected at six radial locations on a given pipe radius. The pipe section containing the probe was then rotated 30° anti-clockwise to take data along the next radius. The same process was repeated for twelve different radii to collect the data at a total of 61 different locations, as shown in Figure 3

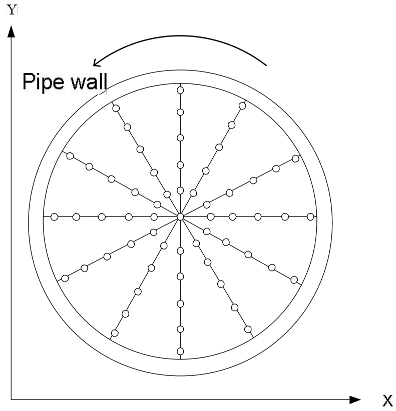


Figure 3: The different measurement positions for the single dual sensor probe in the pipe cross section

Although data was taken for a number of different upward inclined oil-in-water flows, data is only presented here for the flow condition which Q_w =3.5 $\mathrm{m^3/h}$, Q_o =1.0 $\mathrm{m^3/h}$ and the pipe is inclined at 30° to the vertical. For this condition, based on 61 measurement points in the pipe cross section, the interpolated oil volume fraction and the axial oil velocity profiles are shown in figure 4.

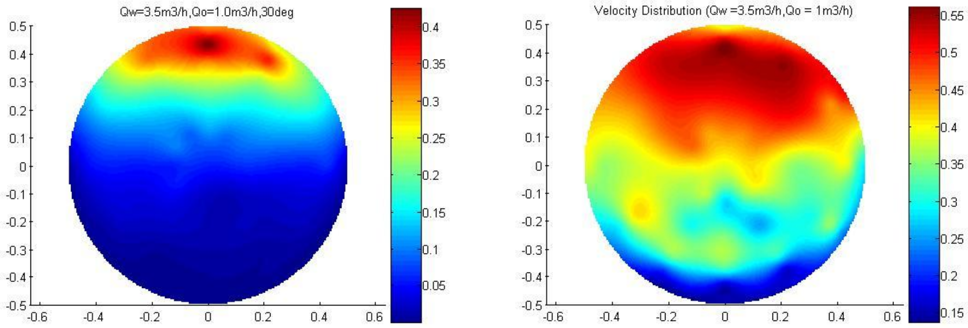


Figure 4: Time averaged local oil volume fraction and local oil axial velocity distributions
(Q_w = $3.5\mathrm{m^3/h}$, Q_o = $1.0\mathrm{m^3/h}$, inclination angle 30 degrees from vertical T = 60s)

For inclined oil-in-water pipe flow, the local oil volume fraction at the top of the pipe is much higher than at the bottom of the pipe and the profile is essentially symmetrical the centreline. The local axial velocity profile shows that the oil bubbles at the top of the pipe travel faster than at the bottom.

Time averaged velocity and volume fraction profiles such as those shown in figure 4 can be useful for characterizing inclined oil-water flow and for validating the mathematical models of such flows but they can reveal nothing of the time dependent structure of such flows. For this reason, a novel array of dual sensor probes was designed and constructed enabling simultaneous volume fraction and velocity measurements to be made in different parts of the pipe as described below.

5 Dual-sensor probe array

One dual-sensor probe only can measure the local flow properties at a single location at a given time. If more measurement points need to be recorded at the same time, it is necessary to put more probes into the pipe test section. To this end, a dual-sensor probe array was designed and built to measure the flow properties at different positions simultaneously.

The dual-sensor probe array consisted of four dual sensor probes positioned along the 80mm long pipe diameter from the upper side of the inclined pipe to the lower side (see figure 5). The four dual sensor probes were supported by an aluminium probe holder held in place by two brass bars located outside of the pipe. The distance from the pipe wall to probe1, along the pipe diameter was 10mm, the distance between adjacent probes was 20mm and the distance between probe4 and the pipe wall was 10mm (as shown in figure 5).

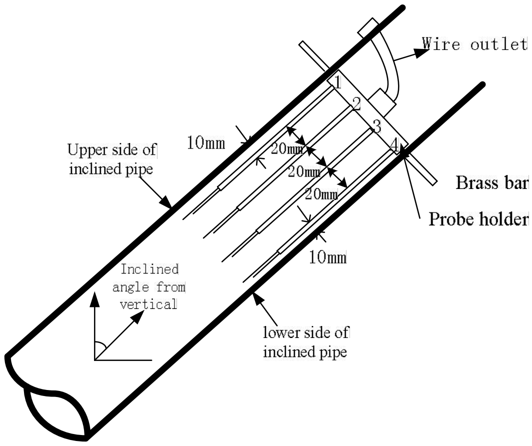


Figure 5: Schematic diagram of the dual sensor probe array

The local oil axial velocity at each probe is denoted $u_{o,1}$, $u_{o,2}$, $u_{o,3}$, and $u_{o,4}$ for the probes 1 to 4 respectively. The local oil volume fraction at each probe is denoted α_1, α_2 α_3 and α_4 for probes 1 to 4 respectively.

6 Dual-sensor probe array experimental results and analysis

The dual sensor probe array described above was positioned at a distance of 1.8m from the inlet of the working section of the flow loop described in section 3. For the dual sensor probe array experiments, for each flow condition investigated, 100 seconds of data were collected continuously from 8 channels (each dual sensor probe has 2 channels and four dual sensor probes were used). This data was collected using a sampling rate of 40KHz for each channel. The pipe inclination angle was varied from 15 degrees to 60 degrees relative to the vertical. The water volumetric rate Q_w took values in the range 2.5$\mathrm{m^3/h}$ to 5.5$\mathrm{m^3/h}$ and the oil volumetric flow rate Q_o took value in the range 0.6$\mathrm{m^3/h}$ to 2.0$\mathrm{m^3/h}$.

6.1 Dual sensor array test results

Prior to analysing the data from the dual sensor probe array some initial work was undertaken, involving the use of high speed cameras, to determine the optimum sampling interval T. The high speed camera was used to record the oil-water inclined pipe flow with a frame rate of 60 frames/s. Figure 6 is a single frame showing the oil-water flow structure in an oil-water flow inclined at 30° to the vertical and where Q_w=3.5$\mathrm{m^3/h}$, Q_o=1.0$\mathrm{m^3/h}$.

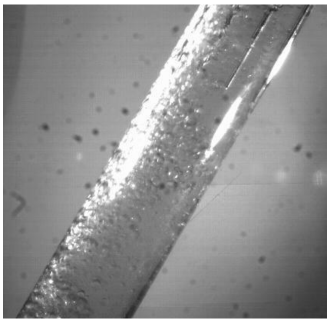


Figure 6: Oil-water inclined pipe flow structure (inclination angle =30 degrees from the vertical $Q_w = 3.5\mathrm{m^3/h}$, $Q_o = 1.0\mathrm{m^3/h}$)

For the flow conditions investigated, a K-H wave structure could take as little as 0.15 seconds to pass the needle probes (as observed using the high speed video) although in many cases the structures took longer than this to pass the probes. However it was also found that if a sampling interval T of less than 0.05 seconds was used for the dual sensor probes, then an insufficient number of oil droplets hit the probe to enable satisfactory estimates of α_i and $u_{o,i}$ to be made at the i^{th} probe during the time interval T. Therefore in order to satisfy the requirements of (i) determining the time dependent variations in oil volume fraction and oil velocity brought about by the passage of individual K-H wave structures and (ii) ensuring that the oil volume fraction and oil velocity measurements were of sufficient accuracy, a sampling interval T equal to 0.05s was used.

6.2 Presentation of data from the dual-sensor probe array

The local oil volume fraction and the local oil axial velocity data obtained from the four dual sensor probes, using a sampling interval T of 0.05s (as described above), can be presented using consecutive sequences of grids of 4×16 pixels.

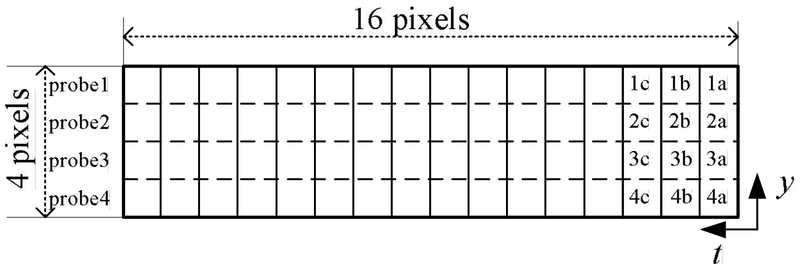


Figure 7: The local oil volume fraction distribution presented by using the global mean velocity

As shown in figure 7, on each grid the centre of each pixel in the y direction represents the distance of the corresponding probe from the lower side of the inclined pipe (along the pipe diameter from the lower side of the pipe to the upper side of the pipe). The centre of each pixel in the increasing t direction represents the time at which the local oil volume fraction or local oil axial velocity data was taken. Note that data in pixels 1a, 2a, 3a and 4a in figure 7 was taken 0.05seconds before the data in pixels 1b to 4b. Similarly, the data in pixels 1b to 4b was taken 0.05s before the data in pixels 1c to 4c *etc*.

An initial approach to plotting the local oil volume fraction data in order to visualise the K-H wave structures was to use the global mean oil velocity $\overline{u_o}$ of the oil in the pipe to convert the horizontal axis of the grid to a distance d where $d = 16 \times \overline{u_o} \times T$ where T is the probe sampling interval of 0.05s. In this way the grid can now be said to represent a 2-D plane of the pipe of axial length $16 \times \overline{u_o} \times T$, which contains the pipe diameters joining the upper side of the inclined pipe to the lower side (see Figure 5). [Note that another way of visualising this plane is that it is the plane which contains the four dual-sensor probes]. Values of local oil volume fraction contained within the pixels can now be said to represent a snapshot (or frame) of the instantaneous local oil volume fraction distribution within this 2-D plane. If the k^{th} frame of data shows the local oil volume fraction distribution in the 2-D plane at the time t, then the $(k+1)^{th}$ frame of data represents the local oil volume fraction distribution within the 2-D plane at time $t+T$. By creating a 'movie' from a number of such successive frames of data it is possible to visualise how the local oil volume fraction in the 2-D plane varies with time as the oil-water flow enters from the left hand side of the grid and leaves at the right hand side (see figures 7 and 8).

Figure 8 shows the local oil volume fraction distribution in the 2-D plane at a given value of t for which the flow conditions are $Q_W = 3.5\text{m}^3/\text{h}$, $Q_O = 1.0\text{m}^3/\text{h}$, the inclination angle from the vertical is 30 degrees and the global mean oil velocity $\overline{u_o}$ is 0.4m/s. Consequently this data frame can be interpreted as showing the instantaneous local oil volume fraction distribution, in the 2-D plane described above, along an axial pipe length of 320mm.

The method of data presentation described above relies upon the unrealistic assumptions that (i) the oil velocity is the same for all values of the y coordinate shown in Figure 7 and (ii) that the oil volume fraction α measured at time t at a given value of y propagates downstream, at the same value of y, for a distance $16 \times \bar{u}_o \times T$ without the value of α changing.

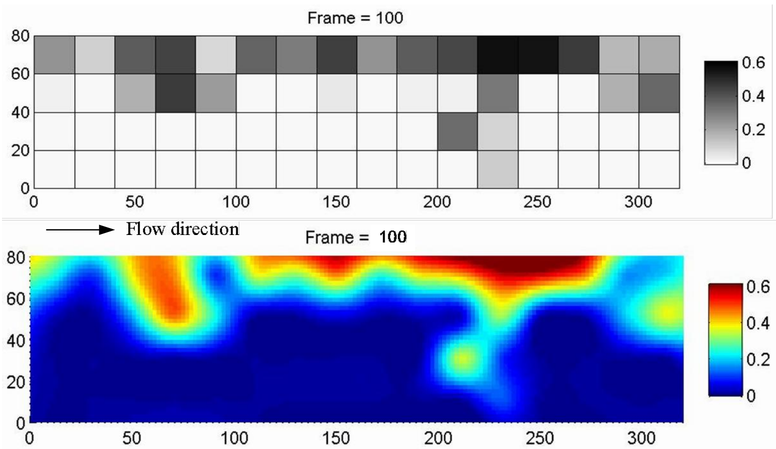


Figure 8: Black-white pixel volume fraction and the interpolated data (Frame 100) (inclination angle =30 degrees from the vertical $Q_w = 3.5\text{m}^3/\text{h}$, $Q_o = 1.0\text{m}^3/\text{h}$)

To overcome the first of the unrealistic assumptions described above, the data presentation method was extended to account for the fact that, for the inclined oil-water flows investigated, the mean axial oil velocity averaged over the 100s sampling period was different for each of the four probes, with the measured oil velocity being higher towards the upper side of the inclined pipe and lower towards the lower side of the inclined pipe. For a given flow condition suppose that for the i^{th} probe ($i = 1$ to 4) the mean axial oil droplet velocity averaged over a 100 second time period is $\bar{u}_{o,i}$. In the sampling interval T (equal to 0.05 seconds) the oil droplets at the i^{th} probe travel a distance $T \times \bar{u}_{o,i}$. Therefore a more realistic method of representing the 'instantaneous' local volume fraction distribution in the (80mm by 320mm) 2-D plane described above is to set the pixel length associated with the i^{th} probe to be equal to $T \times \bar{u}_{o,i}$. Each successive frame of data can now be said to give a more realistic representation of the 'instantaneous' local oil volume fraction distribution that would be observed in the 2-D plane at time intervals of 0.05s. For this method of defining pixel lengths, which takes the local oil velocity at the position of each probe into consideration, it is not always possible, at some probe locations, to incorporate an integer number of pixels into the 320mm axial plane length under consideration. This can result in the presence of 'partial pixels' in the 2-D plane as seen in figure 9 below.

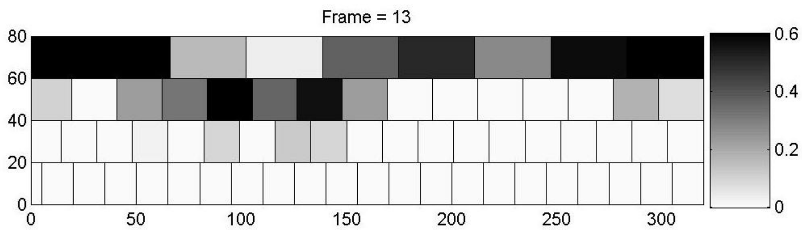
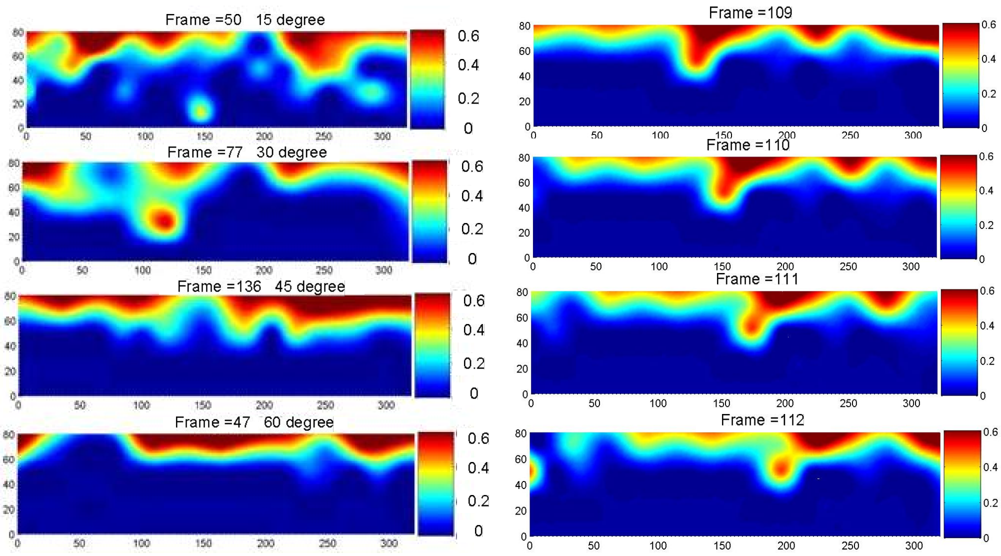


Figure 9: Greyscale representation of the local oil volume fraction distribution measured using the dual sensor probe array (inclination angle = 45 degrees from the vertical $Q_w = 5.5\text{m}^3/\text{h}$, $Q_o = Q_o = 1.5\text{m}^3/\text{h}$)

In figure 9, the greyscale colouration in each pixel represents the local oil volume fraction and the different pixel lengths at the different probe positions arise due to the different mean oil velocities as described above. For the 100 seconds of data collected at each flow condition a new frame of data can be created every 0.05 seconds allowing a possible 2,000 consecutive frames of local volume fraction data to be created. The local volume fraction information in each frame of data (such as that shown in figure 9) can be interpolated using a MATLAB interpolation algorithm to give a smoother, more realistic representation of the local oil volume fraction distribution in the 2-D plane. Figure 10(a) shows the local oil volume fraction distribution for different pipe inclination angles from the vertical at the same water and oil flow rates ($Q_w = 3.5\mathrm{m}^3/\mathrm{h}$; $Q_o = 1.0\mathrm{m}^3/\mathrm{h}$). It can be seen clearly from Figure 10(a) that the oil is more concentrated at the upper side of the pipe for inclination angles of 45 degrees and 60 than is the case for inclination angles of 15 degrees and 30 degrees. Figure 10(b) shows successive frames of data (each frame separated by 0.05 seconds) for the local oil volume fraction distribution in an oil-water flow inclined at 45 degrees to the vertical for which $Q_w = 4.5\mathrm{m}^3/\mathrm{h}$ and $Q_o = 1.5\mathrm{m}^3/\mathrm{h}$. The flow direction in each frame (109-112) is from left to right and there is a clear suggestion of a K-H wave in the flow forming and then breaking.



(a) (b)

Figure 10: Interpolated oil volume fraction profiles for inclined oil-water flows.

10(a) Local oil volume fraction distributions for different inclination angles to the vertical (15^o 30^o 45^o **and** 60^o **).** $Q_w = 3.5\mathrm{m}^3/h$ **;** $Q_o = 1.0\mathrm{m}^3/h$ **).**

10(b) Successive frames of local oil volume fraction distribution data separated by 0.05s. $Q_w = 4.5\mathrm{m}^3/h$ **;** $Q_o = 1.5\mathrm{m}^3/h$ **;** 45^o **inclination angle to the vertical**

6.3 Dual-sensor probe signal analysis

Figure 11, shows the measured local volume fraction versus time data from the four dual sensor probes for water and oil flow rates of $3.5\mathrm{m}^3/\mathrm{h}$ and $1.0\mathrm{m}^3/\mathrm{h}$ respectively and for an inclination angle of 15^o from the vertical. Each value of volume fraction in the graphs was calculated over a sampling interval T of 0.05 seconds as described in section 2. Data is shown for a 64 second time period. Data for probe 1 is at the top and for probe 4 at the bottom. The positions of the four probes is the same as that given in Figure 5.

For a given flow condition and at a given probe position, if the time dependent local oil volume fraction changes from being higher than the average value to lower than the average value this represents a ‘zero-crossing’ event. Transition from a ‘lower than average’ value to a ‘higher than average’ value also represents a ‘zero-crossing’ event. For a given flow condition if, at the i^{th} probe position, the number of zero crossing events is N_i in a time period P then a ‘volume fraction fluctuation frequency’ f_i can be defined as

$$f_i = \frac{N_i}{2P} \tag{5}$$

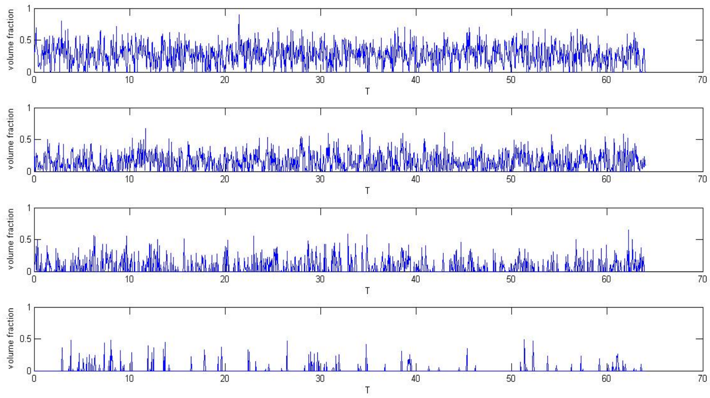


Figure 11 local oil volume fraction variations different inclination angle
(inclination angle to vertical = 15°; $Q_w = 3.5\mathrm{m}^3/\mathrm{h}$; $Q_o = 1.0\mathrm{m}^3/\mathrm{h}$)

This fluctuation frequency is representative of the frequency of 'volume fraction' waves occurring at the i^{th} probe. Kelvin-Helmholtz (K-H) waves in the flow represent one such type of volume fraction wave and, as can be seen from Figure 10(b), K-H waves can have relatively large amplitudes which may even span the entire cross section of the pipe. These volume fraction waves arise a result of shear at the water-oil 'interface' towards the upper side of the inclined pipe. Consequently the volume fraction fluctuations at probe 1 (at the upper side of the inclined pipe) are principally due to low amplitude fluctuations, where in this context, 'amplitude' refers to the wave height parallel to the y direction shown in Figure 7. Volume fraction fluctuations seen at probes 2, 3 and 4 are principally due to waves of increasingly large amplitude due to the greater distances of these probes from the upper side of the inclined pipe where the waves are initially formed. Those volume fraction fluctuations seen at probe 4 are almost certainly due to large scale K-H wave structures present in the flow. Figure 12 shows a plot of volume fraction fluctuation frequency f_i , on the vertical axis of the graph, against the position of the i^{th} probe, on the horizontal axis of the graph for a flow inclined at 15 degrees to the vertical for which the water and oil flow rates are $3.5\mathrm{m}^3/\mathrm{h}$ and $1.0\mathrm{m}^3/\mathrm{h}$ respectively The horizontal axis of figure 12 can therefore be said to be representative of the amplitude (in mm) of the volume fraction fluctuations. It follows that the graph in figure 12 can be said to represent the relationship between the amplitude and frequency of volume fraction waves in inclined oil-water flow at the given flow conditions. For the largest amplitude volume fraction fluctuations in the flow, which are almost certainly associated with the presence of K-H waves, the wave frequency f_4 is approximately equal to 1.3Hz.

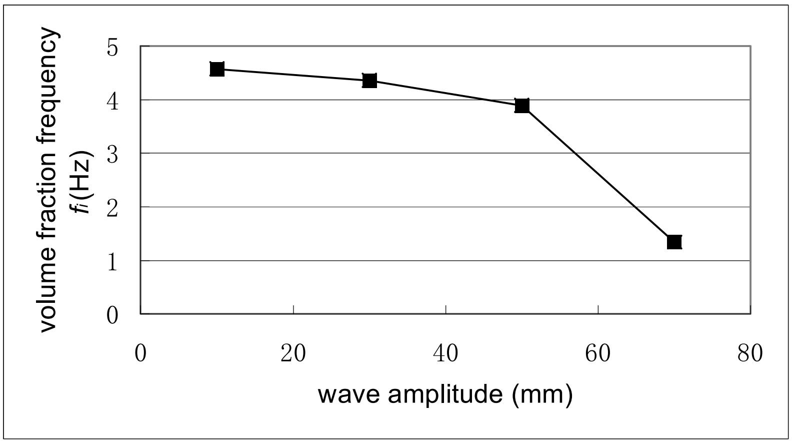


Figure 12: K-H wave frequency versus the K-H wave amplitude
(inclination angle = 15 degrees from the vertical $Q_w = 3.5\mathrm{m}^3/\mathrm{h}$, $Q_o = 1.0\mathrm{m}^3/\mathrm{h}$)

7 High speed dual-plant ERT experiments

An important parameter of K-H waves is their axial propagation speed and this can be measured using a dual-plane Electrical Resistance Tomography (ERT) system. Such a system with a frame rate of 1000 dual frames per second was installed on the test loop at the same position at which the array of dual-sensor probes had previously been installed. For each inclination angle of 15, 30, 45 and 60 degrees from the vertical, data was collected from the ERT system at ten different flow conditions for which Q_w was in the range $1.5 \text{ to } 6.5\mathrm{m}^3/\mathrm{h}$ and Q_o was in the range $0.6 \text{ to } 3.5\mathrm{m}^3/\mathrm{h}$. For each flow condition, 10 sets of data were recorded and then averaged. The distance between the two planes of the ERT system was 5cm. Fluctuations in the overall mixture conductance at each plane were cross correlated to give a characteristic flow velocity u_{cc}. Figure 14 shows u_{cc} plotted against the mixture superficial velocity (or homogeneous velocity) u_h for the range of flow conditions investigated. Lucas(1997) and Lucas and Jin(2001) have previously demonstrated that the measured cross correlation velocity u_{cc} corresponds to the axial speed of propagation of the largest coherent structures in the flow which in this case are large amplitude K-H waves.

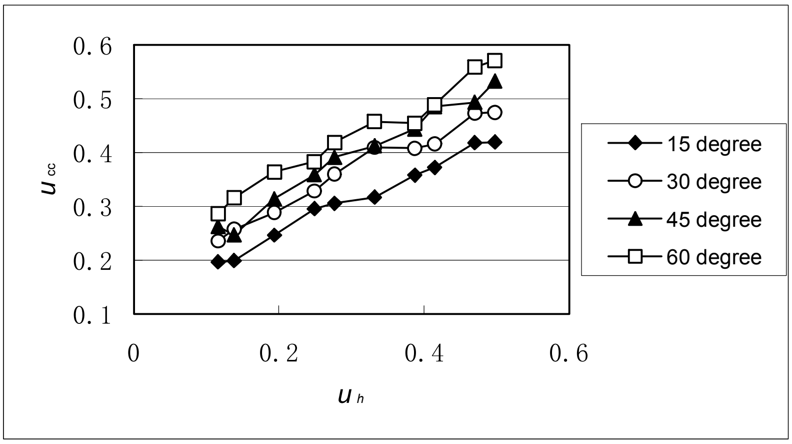


Figure 14 K-H wave propagation speed versus the homogenous velocity

If both the axial speed of propagation of the K-H waves u_{kh} (where $u_{kh} = u_{cc}$) and their frequency f (where $f = f_4$ as defined in section 6) are known then the K-H wavelength λ can be calculated from

$$\lambda = \frac{u_{kh}}{f} \tag{6}$$

For the flow condition where $Q_w = 3.5\mathrm{m}^3/\mathrm{h}$, $Q_o = 1.0\mathrm{m}^3/\mathrm{h}$ and the pipe inclination angle to the vertical is equal to 15° the 'volume fraction wave' frequency f_4 at probe 4 was 1.3Hz (as described above), u_{kh} was found to be $0.2808\mathrm{m/s}$ and therefore the K-H wave length was calculated from equation 6 to be equal to 0.216m. This agreed with the mean K-H wavelength observed at these flow conditions using high speed filming techniques.

8 Conclusions

In this paper, a dual-sensor conductance probe has been introduced to measure the local oil volume fraction and the local oil axial velocity in inclined oil-in-water pipe flows. A newly designed dual-sensor probe array which can measure the local information of oil phase simultaneously at different spatial locations in the flow cross section has also been introduced in this paper. This probe array was used to measure the time dependent local oil volume fraction and the local oil axial velocity variations and enabled Kelvin-Helmholtz (K-H) wave phenomena to be studied in inclined oil-water pipe flows. The local oil volume fraction data was presented using a 2-D, 16×4 grid of fixed length pixels, the pixel length being determined using the global mean oil velocity $\bar{u}_o$ at the given flow conditions. Subsequently, a more realistic method of presenting the local oil volume fraction data was introduced using a 2-D grid in which the pixel length, at a given probe position, was based on the mean axial oil velocity at that probe position. Using this second method of data presentation, K-H void fraction waves were observed forming and breaking. After processing the dual-sensor probe array data, characteristics of the K-H waves such as their frequency and amplitude were investigated. Combining wave frequency information with K-H wave propagation speed information obtained from a dual-plane high speed ERT system enabled the K-H wavelength to be measured.

9 References

Y.Dai, M Wang, N. Panayotopoulos, G. Lucas and R. A. Williams (2005), 3-D Visualisation of a swirling flow using electrical resistance tomograph,*4th World congress on industrial process tomography, Aizu,Japan, 2005.*

G.P.Lucas, J.Cory, R.C.Waterfall, W.W.Loh, F.J.Dickin, (1999), Measurement of the solids volume fraction and velocity distributions in solids-liquid flows using dual-plane electrical resistance tomography, *Flow Measurement and Instrumentation*, 10 249-258

G.P.Lucas, R. Mishra, N. Panayotopoulos,(2004), Power law approximations to gas volume fraction and velocity profile in low void fraction vertical gas-liquid flow, *Flow Measurement and Instrumentation*, 15 271-283.

Lucas G P and Walton I C,(1997), Flow rate measurement by kinematic wave detection in vertically upward, bubbly two-phase flows, *Flow Measurement and Instrumentation*, 8 133–43.

G.P. Lucas and N D Jin,(2001), Measurement of the homogeneous velocity of inclined oil-in-water flows using a resistance cross correlation flow meter, *Measurement Science and Technology*, 12 1529–1537