Proceedings of the ASME/JSME 2011 8th Thermal Engineering Joint Conference
AJTEC2011
March 13-17, 2011, Honolulu, Hawaii, USA

AJTEC2011-44239

INVESTIGATING THE EFFECT OF PIPE INCLINATION ON TWO-PHASE GAS-LIQUID FLOWS USING ADVANCED INSTRUMENTATION

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KEY WORDS: PDF, ECT, WMS, void fraction, flow regime

ABSTRACT
Pipes that make up oil and gas wells are not vertical but could be inclined at any angle between the vertical and the horizontal which is a significant technology of modern drilling. Hence, this study has been undertaken to look at the effect of inclination on flow characteristics especially at 10degrees from both horizontal and vertical. Air/silicone oil flows in a 67mm slightly deviated pipe have been investigated using advanced instrumentation: Wire Mesh Sensor Tomography (WMS) and Electrical Capacitance Tomography (ECT). They provide time and cross-sectionally resolved data on void fraction. Both the ECT probes and WMS were mounted on the inclined pipes upstream just at the point where flows were fully developed. By keeping the liquid flow rate constant at 10 litres/min (or liquid superficial velocity of 0.052m/s), gas flow rate was varied from 10 litres/min to 1000 litres/min (or gas superficial velocity from 0.05m/s to 4.7m/s). Then other values of liquid superficial velocity were considered. Visual observations were considered. Time series and void fraction were then measured for WMS while time series and liquid holdup were measured for ECT. The raw data were processed and then interpreted for proper analysis. From an analysis of the output from the tomography equipment, flow patterns were identified using both the reconstructed images as well as the characteristic signatures of Probability Density Function (PDF) plots of the time series of cross-sectionally averaged void fraction as suggested by some authors. Bubbly, slug and churn flows were observed for 10^o from vertical pipe while bubbly, plug as well as slug flow when the *pipe was inclined at 10^o from horizontal. Examples of the PDFs are well illustrated which compares the use of ECT with WMS. In addition, statistical data such as Power Spectral Density (PSD), dominant frequency, mean void fraction as well as the structure velocities from cross correlation of the two planes of ECT have been identified*.

NOMENCLATURE
V_{G} = gas velocity (m/s)
Um = Mixture velocity (m/s)
g = acceleration due to gravity (m/s^2)
D = Diameter of pipe (m)
U_{SG} = gas superficial velocity (m/s)
U_{SL}= liquid superficial velocity (m/s)
B= Bubbly flow
S= Slug flow
P= Plug flow
C= Churn flow
F = frequency (Hz)

INTRODUCTION
This paper emphasizes on gas-liquid flows in inclined pipes at both 10 degrees to the vertical and the horizontal using Electrical Capacitance Tomography and Wire Mesh Sensor. Modern drilling practice means that the pipes which make up oil and gas wells are not vertical as they once were but can be inclined at any angle between the vertical and the horizontal.

Most of the data reported on flow pattern transitions have dealt with either horizontal or vertical tubes with only limited results reported for inclined pipes. Several investigators have considered only one transition for inclined pipes while others have performed experiments only over limited range of inclination angles.

In 1978, Collins [1] developed an approximate solution for the flow in tubes larger than a few centimetres in diameter as given below:

For laminar flow:

$V_G = 2.27U_m + 0.361\sqrt{gD}$.. (1.0)

For Turbulent flow:

$V_G = 1.2U_m + 0.35\sqrt{gD}$.. (1.1)

These have played key roles in determining statistical data in gas-liquid flows

BACKGROUND TO THE WORK

Two phase flow is difficult subject because of the complexity of the form in which the fluids exist inside pipes known flow regimes or flow patterns [2]. So far there is no valid method to identify two-phase flow regimes. In most cases, two-phase flow regimes are determined subjectively. On one hand, two-phase flow is more complex than single-phase flow due to the existence of relative movement and variable interfaces between two phases. On the other hand there is no effective method available to gather the accurate information that can reflect the true flow regimes. The prediction of characteristics such as liquid hold up, gas void friction during two phase gas/liquid flow in pipes is of particular interest to the petroleum, chemical industry. In petroleum industry, the slug flow is a frequently encountered flow regime in multiphase flow pipeline. For pipeline designers, the liquid slug length distribution is important for the proper design of downstream facilities, such as slug catcher and separation system. In 1970, Singh and Griffith [3] investigated slug flow of air and water at small upward inclination angles and developed simple correlations for pressure drop and holdup. In 1985, Barnea et al. [4] examined the effect of the inclination angle on the flow pattern transition boundaries by varying the inclination angle in small steps in the range of 0^O to 90^O.

Small changes in the angle of inclination from the horizontal can have profound effects on the flow patterns that exist. At very small inclination angles, the force of gravity acting in the flow direction can be of the order of the wall shear stress.

On the other hand, small deviations from the vertical have little effect on flow patterns. Kokal and Stanislav [5] show that the uphill-flow regimes were found to be similar to the horizontal-flow regimes except that very limited stratified flow was observed for uphill flows. The downhill-flow regimes on the other hand were found to be very different and more complex.

EXPERIMENTAL FACILITY

In this work, two-phase flow experiments were carried out on an inclinable rig in the Chemical Engineering laboratory of the School of Chemical and Environmental Engineering. Here the experimental facility and procedures undertaken to investigate the two-phase flow behaviour in a pipe inclined at both 10^o from vertical and horizontal using ECT and WMS are outlined. Figure 1(a) presents a schematic diagram of the facility used for carrying out the experiments whereas figure 1(b) shows the actual picture of the rig. The experimental facility consists of an inclinable 6m long rigid steel frame. The test facility is mounted on a frame that can be deviated from 90 degrees to 80 degrees (or 10 degrees from vertical) and from 90 degrees to 10 degrees (or 10 degrees from horizontal). The upward direction of flow will be investigated since it is the most significant in industries. The pipe diameter considered in this case is the 67mm pipe.

In an effort to extract as much information as possible on the complex behaviour of two-phase flows, in this paper a comparison of the performance of different tools available at the University of Nottingham to study gas-liquid flow in pipes is done. The comparison is made based on several two-phase flow parameters such as phase distribution and structures frequency. The tools are capacitance wire mesh sensor (WMS) and electrical capacitance tomography (ECT).

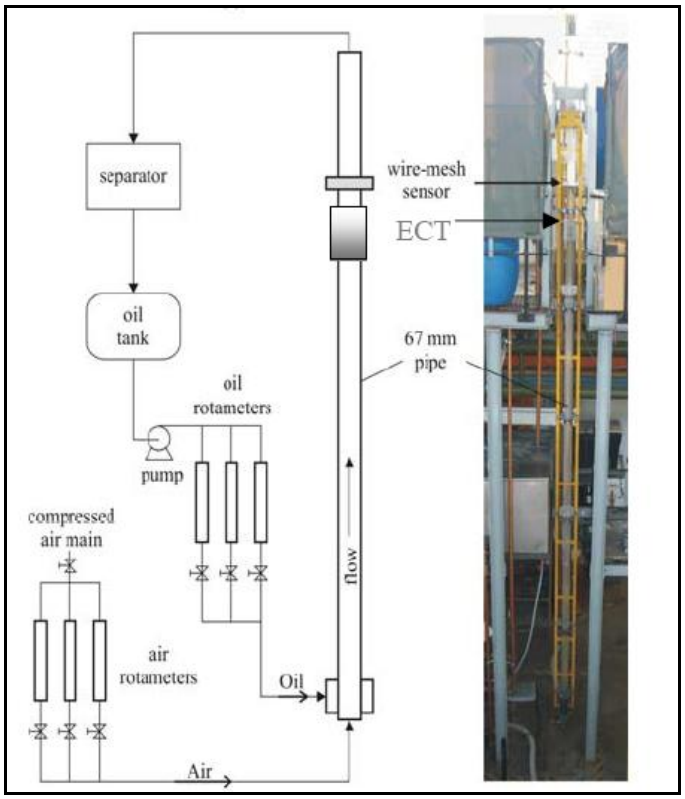


Figure 1: (a) Experimental setup of the flow loop. (b) Image of the inclinable pipe at 10^o from vertical position.

Overview of the Instruments used

The instruments used have been employed previously in a two phase flow in inclinable pipes by Abdulahi [6] and for annular flow studies by Azzopardi [7], Geraci et al. [8], Geraci et al.

[9].The instruments have also been utilised for experiments by Azzopardi et al. [10], Azzopardi et al. [11], Hunt [12], Thiele et al. [13] and Abdulkareem et al. [14]

Electrical Capacitance Tomography (ECT)

Electrical Capacitance Tomography is a non-intrusive measurement technique that exploits the difference in relative permittivity of the two phases present in the pipe. The ECT system (Tomoflow R100) utilized consists of a capacitance sensor, measurement circuitry and a data acquisition computer. Some authors have given detailed description of the theory behind the ECT technology. They include Hammer [15], and Zhu et al. [16].

In addition, ECT has previously been used by Hassan and Azzopardi [17] for liquid-liquid flow and also been applied successfully to gas-solid flows by Azzi et al. [18]. The capacitance sensor comprises a set of equal different diameter. Here, an 8 electrode capacitance sensor has been mounted externally around the pipe, as the pipe wall material is non-conducting. The measurement electrodes are 35 mm long and 26.43 mm wide each. The distance between centres of two measuring planes is 89 mm. Guard electrodes are placed on either side of the measurement electrodes. The probes were calibrated by taking readings with the pipe empty (gas only) and full of silicone oil sized electrodes. They are made using Printed Circuit Board (PCB) technology. It is easy to adapt the instrument to pipes of different diameter.

Figure 2: Electrical Capacitance Tomography (ECT)

Wire Mesh Sensor

Another instrument used is the Wire Mesh Sensor which is sensitive to the capacitance of the fluid. In case of a two-phase flow, the oil phase is non-conducting, while the gas phase is practically an ideal insulator. There are two main intrusive effects of WMS on bubbles in the two-phase flow. The first one is the bubble break-up. The second one is the bubble deceleration. Bubbles passing WMS are broken and decelerated by the sensor.

The sensor comprises of two planes of 24 stainless steel wires with 0.12 mm diameter, 2.8 mm wire separation within each plane and 2 mm axial plane distance. The wires are evenly distributed over the circular pipe cross section. An acrylic frame supports the sensor which allows the sensor to be mounted in the test section. Figure 3 shows a photograph of the sensor. A powerful feature of WMS and its analysis is the quantification of the shapes of the large Taylor bubbles. In summary, WMS can provide details of the distribution of bubble sizes present, both overall and time resolved.

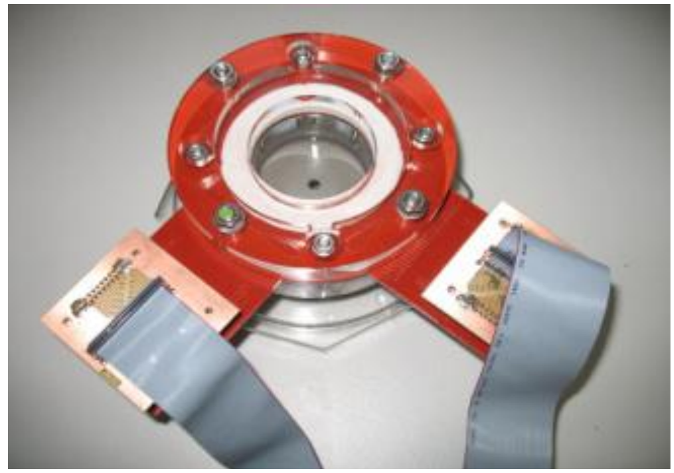


Figure 3: Wire Mesh Sensor

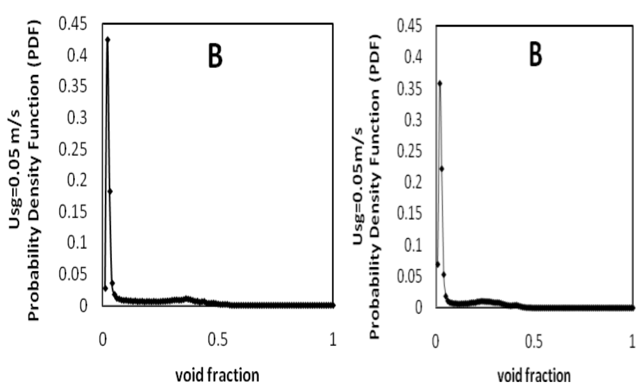
RESULTS AND DISCUSSION

Probability Density Function (PDF)

Discrete random variables can be plotted in a histogram which shows the frequency (on the ordinate) as a function of some measured parameter (on the abscissa for a given class width). The frequency distribution is then a collection of classes which are of equal size and cover the entire range of data without overlapping. A probability density function, (PDF) indicates the probability for a certain void fraction value to exist within a range.

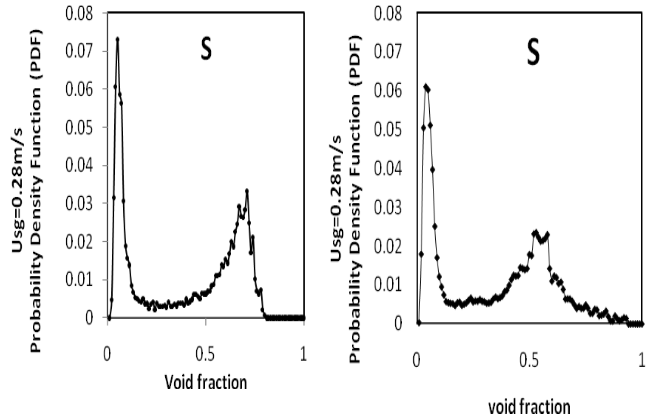
10^o from horizontal

PDF for inclination at 10^o from horizontal are shown in figures 4, 5 and 6 for both ECT and WMS. It shows clearly that they are in the regimes similar to those of perfectly horizontal pipes. The flow regimes observed are bubbly, Slug and Plug flows which are represented by B, S and P respectively.



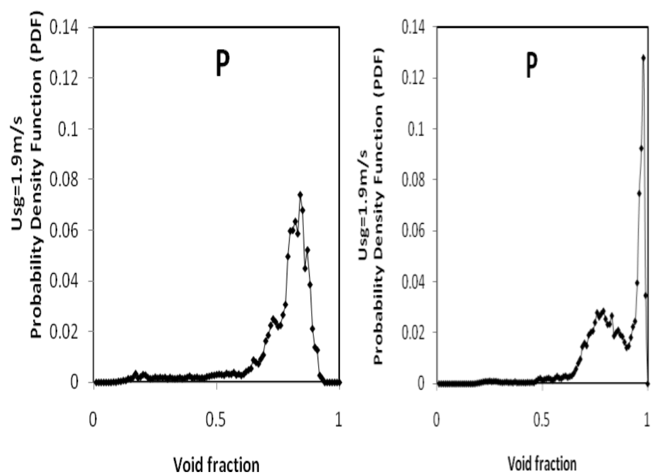
(a) **ECT** (b) **WMS**

Figure 4: PDF for 10^ohorizontal at U_{SL} =0.052m/s (B=Bubbly)



(a) ECT (b) **WMS**

Figure 5: PDF for 10°horizontal at U_{SL} =0.052m/s (S=Slug)

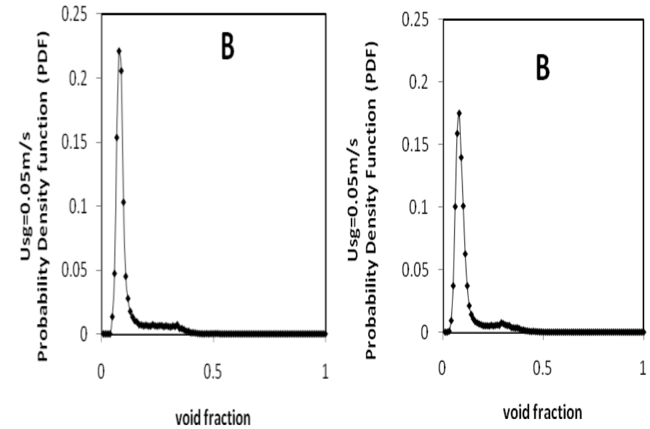


(a) ECT (b) **WMS**

Figure 6: PDF for 10°horizontal at U_{SL} =0.052m/s (P=Plug)

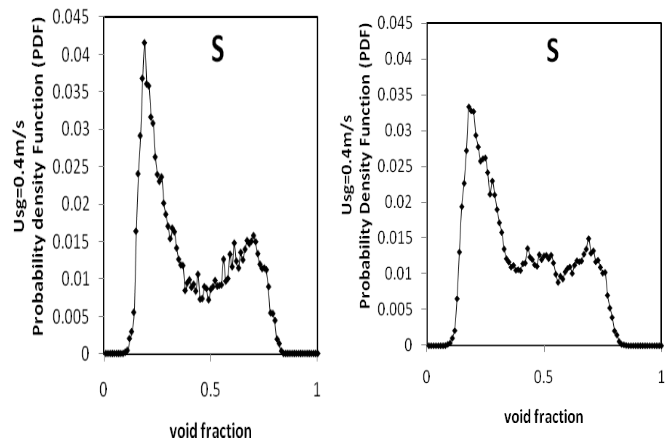
10° from vertical

When the orientation of the pipe was changed to 10° from vertical, the PDFs obtained are as shown in figures 7, 8 and 9. The flow regimes observed are similar for both measurement techniques if both (a) and (b) of the figures are compared. These are bubbly, Slug and Churn flows as depicted by letters B, S and C respectively.



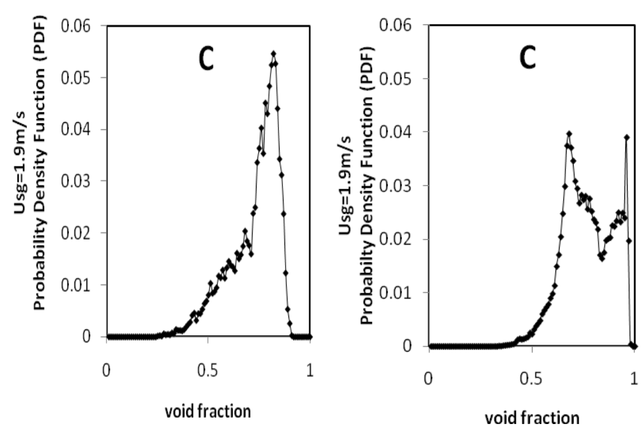
(a) ECT (b) **WMS**

Figure 7: PDF for 10° from vertical at U_{SL} =0.052m/s (B=Bubbly)



(a) **ECT** (b) **WMS**

Figure8: PDF for 10° from vertical at U_{SL} =0.052m/s (S=Slug)



(a) **ECT** (b) **WMS**

Figure 9: PDF for 10° vertical at U_{SL} =0.052m/s (C=Churn)

It could be seen that the concept of PDF of void fraction provides a more objective method by which flow regimes in two-phase flow may be defined. In the bubbly, churn and slug flow regimes the PDFs have the following forms:

- Bubble flow: single peaked PDF occurring at low void fraction.
- Churn flow: single peaked PDF occurring at high void fraction with a long tail at lower void fraction.
- Slug flow: twin-peaked PDF, one peak characteristic of dispersed bubble flow and the other characteristic of annular flow, i.e., the film around the big bullet-shaped bubble. In our case, a stable slug flow was observed as shown in figures 5 and 8

The PDFs have been confirmed by flow pattern maps in Costigan and Whalley [19]

Frequency

Gregory and Scott [20] developed a much used correlation for slug frequency prediction based on the data by Hubbard [21]. The correlation was compared with experimental data by Nydal [22] and he found a good fit within the original data range (U_{SG}<10m/s and U_{SL}<1.3m/s). In our work, the range of U_{SL} considered is lower (0.052m/s <U_{SL}< 0.524m/s)

In our work, the PSD has been used to obtain the frequency. The outputs from the measuring instruments were analyzed and their plots were compared as shown in figure 10 and figure 11 for 10^o from horizontal with both ECT and WMS. It could be observed that the plots show that the instruments were able to produce similar trends. However, scatter in the frequencies at mixture velocity 1m/s for almost all the inclinations considered could be associated with bubbly flow where the structures such as small bubbles and void waves could not be easily identified. This was also observed for inclination at 10^o from vertical as shown in figures 12 and 13.

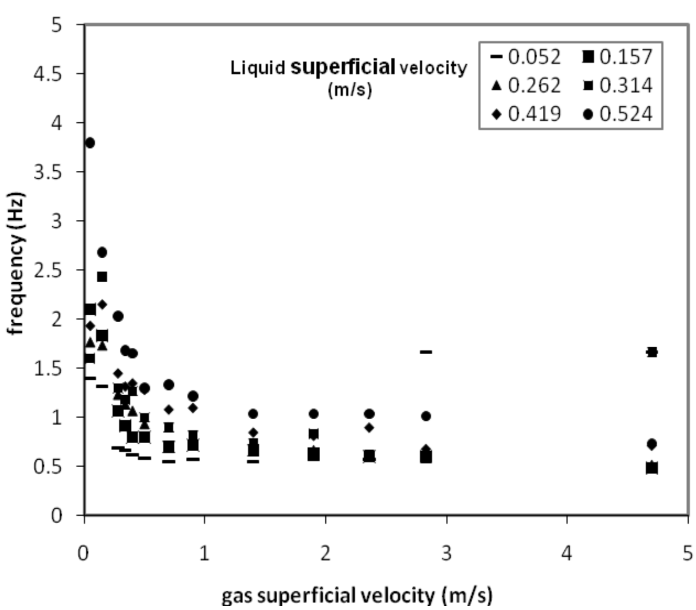


Figure 10: Frequency for 10^o from horizontal with ECT

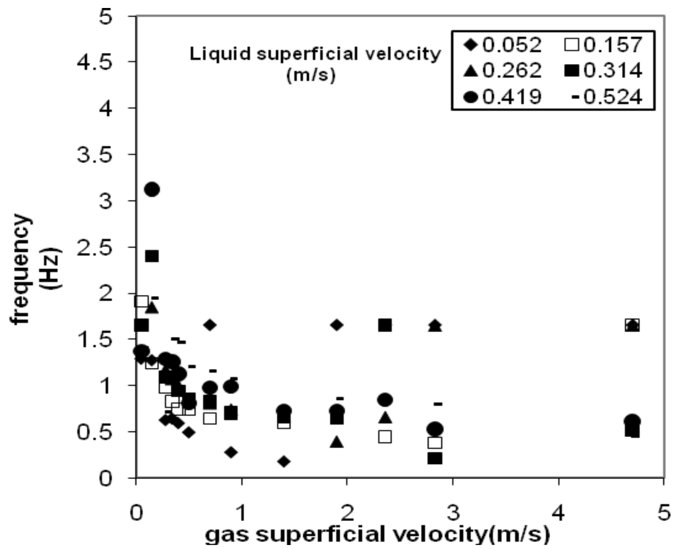


Figure 11: Frequency for 10^o from horizontal with WMS

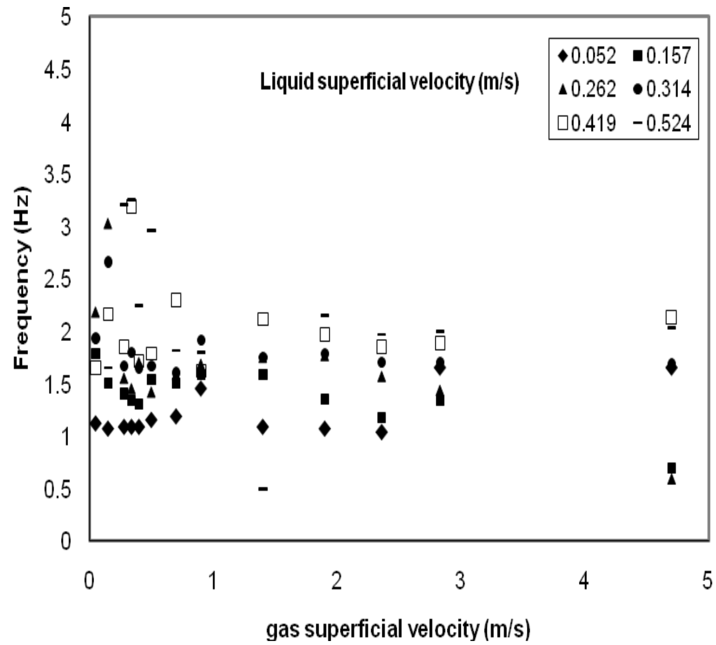


Figure 12: Frequency for 10^o from vertical with WMS

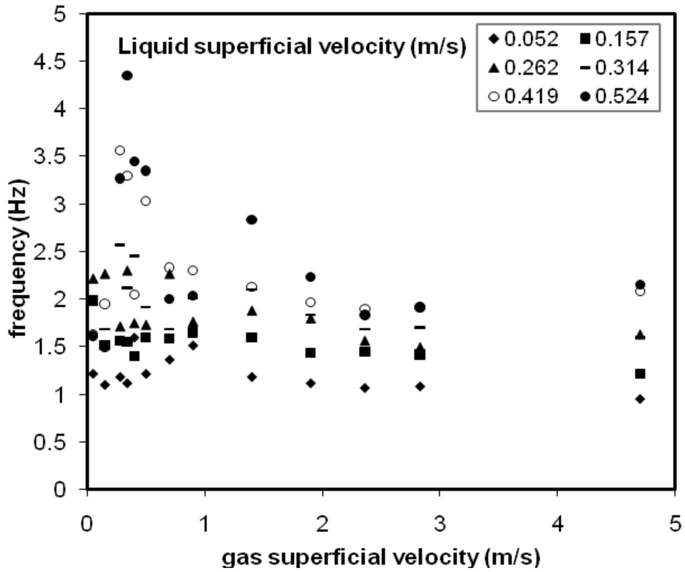


Figure 13: Frequency for 10^o from vertical with ECT

Power Spectral Density (PSD)

Hubbard and Duckler, [23] found in their work that all of the spectral distributions fall into three broad categories, characterized by the manner in which the energy in the wall pressure fluctuation was distributed among the frequencies observed. They classified horizontal air-water flow into three regimes: separated flow, intermittent flow and dispersed flow. Shou and Leu [24] have utilized the PSD function to describe the dominant frequency. In their work, a wide band spectrum is considered to signify an increase in the number of bubbles, while a narrow band with sharp peaks either signifies a single bubble or slugging bed behaviour. In our work, the peaks shown in figures 15 and 16 are for bubbly flow. This occurs at low liquid and gas superficial velocities at both inclinations.

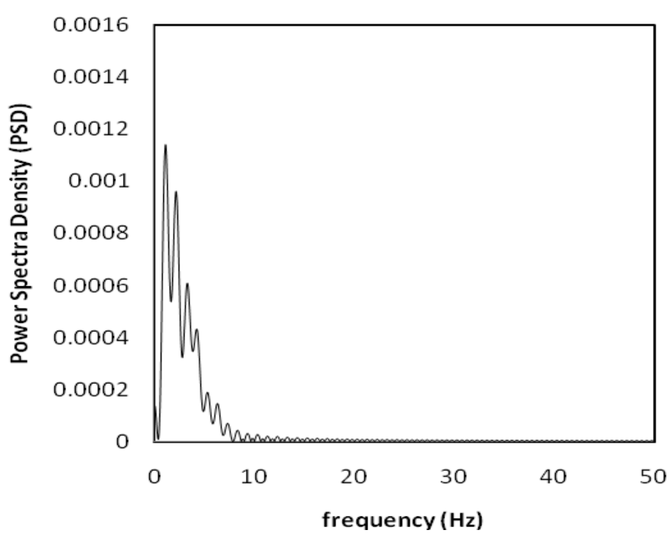


Figure 14: PSD for 10^{0}horizontal with WMS at U_{SL}=0.157m/s and U_{SG}=0.060m/s

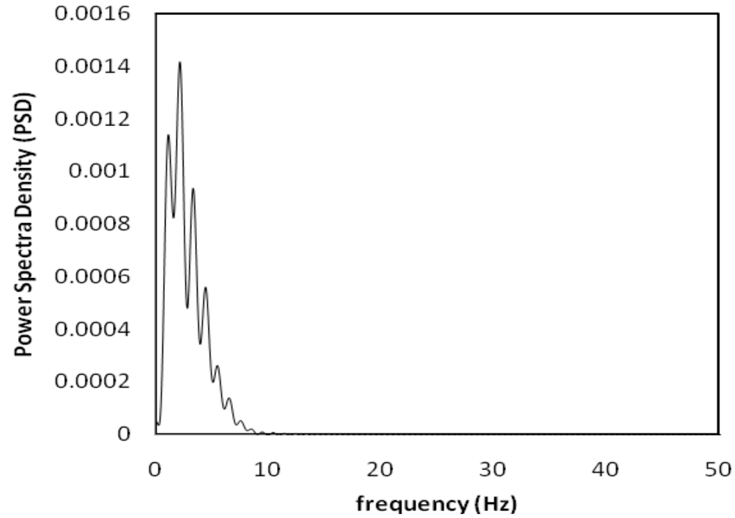


Figure 15: PSD for 10^0 horizontal with ECT at U_{SL}=0.157m/s and U_{SG}= 0.060m/s

The obvious peaks in both figures 14 and 15 indicate the range of the dominant frequency. It can be seen that most peaks for the plots occur just slightly above zero frequency, i.e. 0<f<10.

Structure Velocity

We derived structure velocities from cross correlation between two planes of Electrical Capacitance Tomography (ECT) probes. The graphs of structure velocity plotted against mixture velocity (where Um= U_{SL} + U_{SG}) are shown in figures 16-18. As can be seen, the line on figure 8 shows the prediction by Nicklin [25] correlation for a vertical pipe. Since the pipe in our case is inclined at 10^o from vertical, the difference could be as a result of slight inclination. In addition, at lower mixture velocity the results fall within bubbly-slug region with few points deviating from Nicklin correlation. This deviation agrees with the experimental slug to churn transition boundary.

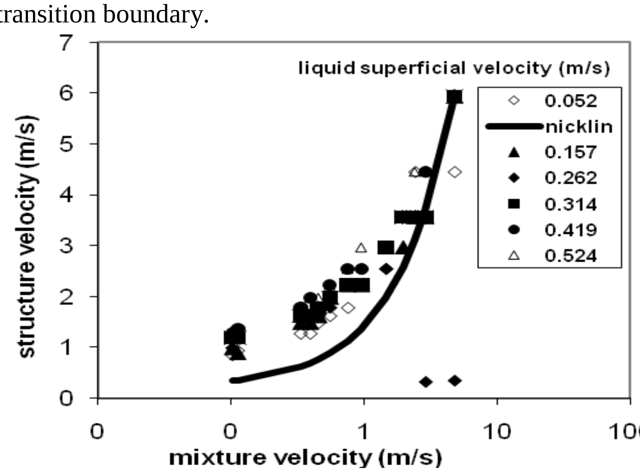


Figure 16: Structure velocity for 10^o from vertical with ECT compared with Nicklin correlation

Mean Void fraction

In this case, mean values of void fraction were obtained and plotted against gas superficial velocities for all liquid superficial velocities considered in each case of inclination under consideration for both WMS and ECT as shown in figures 19-22.

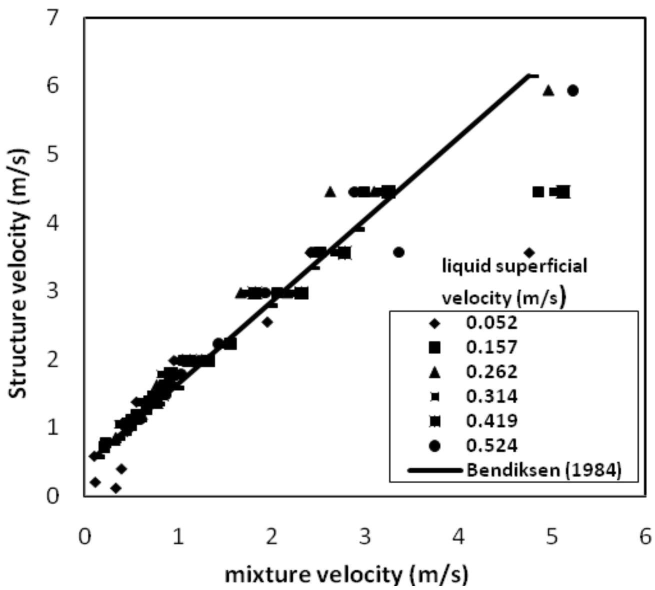


Figure 17: Structure velocity for 10° from horizontal with ECT compared with Bendiksen correlation

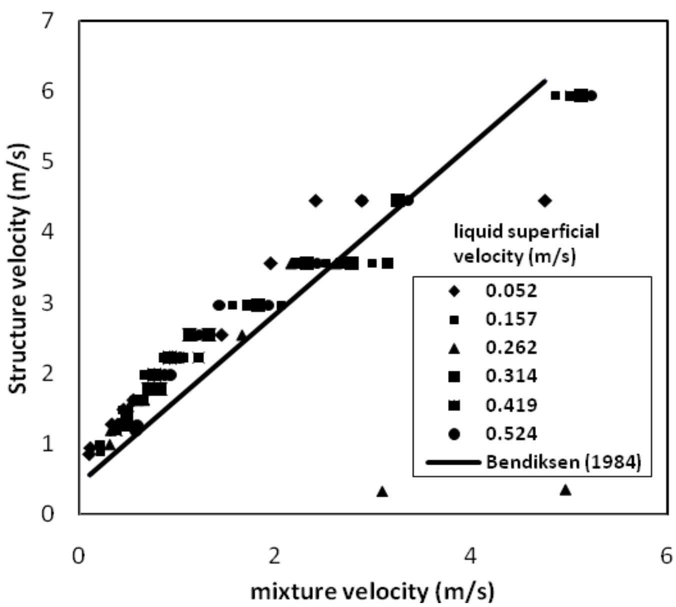


Figure 18: Structure velocity for 10° from vertical with ECT considering Bendiksen (1984) correlation

However, the correlation by Bendiksen [26] is able to have a good comparison with our work since this correlation considers all pipe orientations. Figures 17 and 18 show the comparison between our work and Bendiksen correlation

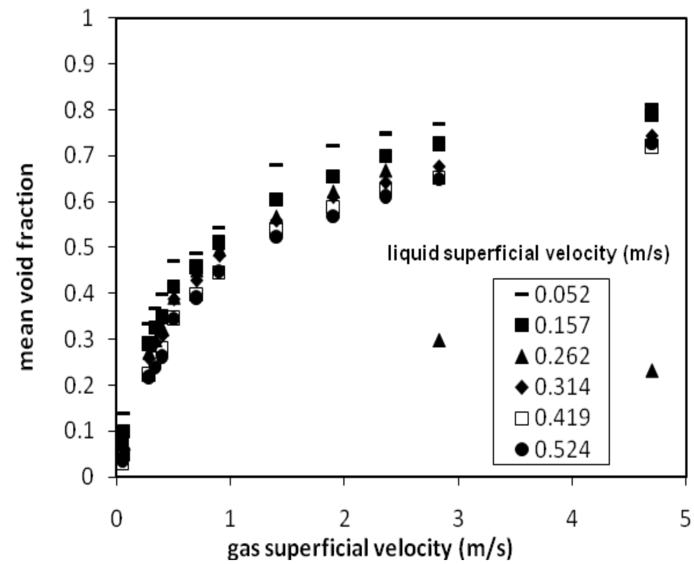


Figure 19: Mean void fraction for 10° from vertical with ECT

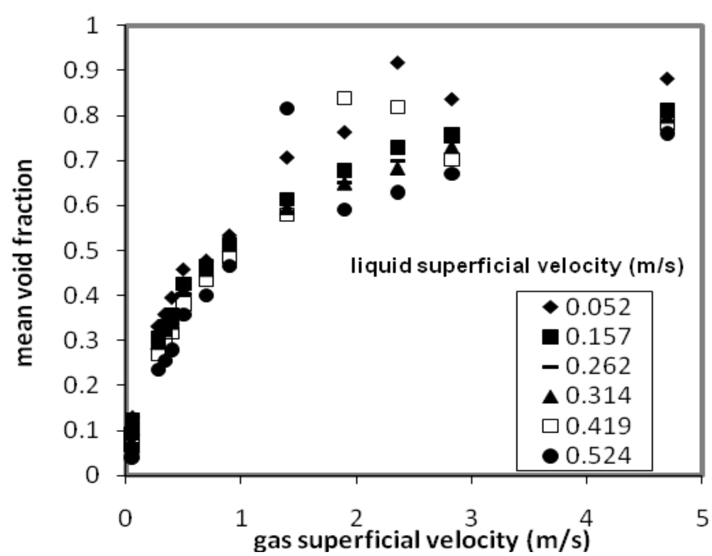


Figure 20: Mean void fraction for 10° from vertical with WMS

The time average void fraction versus gas superficial velocity at $0.052<U_{SL}<0.521$ of silicone oil from the results by Electrical Capacitance Tomography (ECT) and Wire Mesh Sensor (WMS) at the similar axial distances (75 *Dt*) as shown in Figures 19-22 indicate an increasing void fraction with increasing gas superficial velocity. The data from both sensors show very good agreement between them; hence, these results are useful and necessary for many engineering calculations

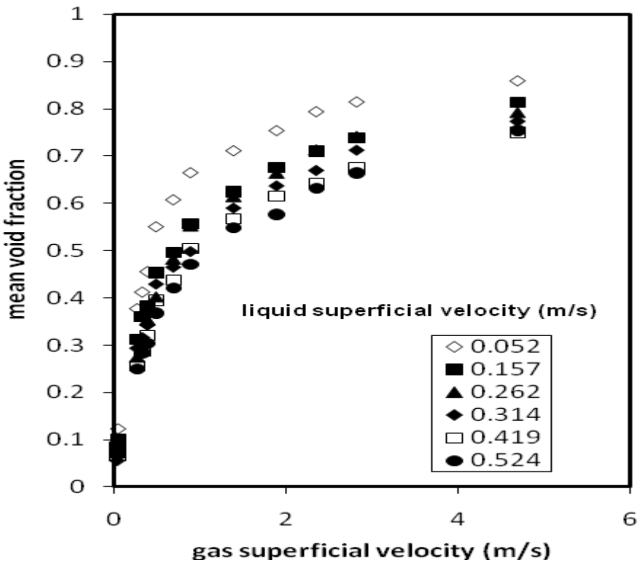


Figure 21: Mean void fraction for 10^o from horizontal with ECT

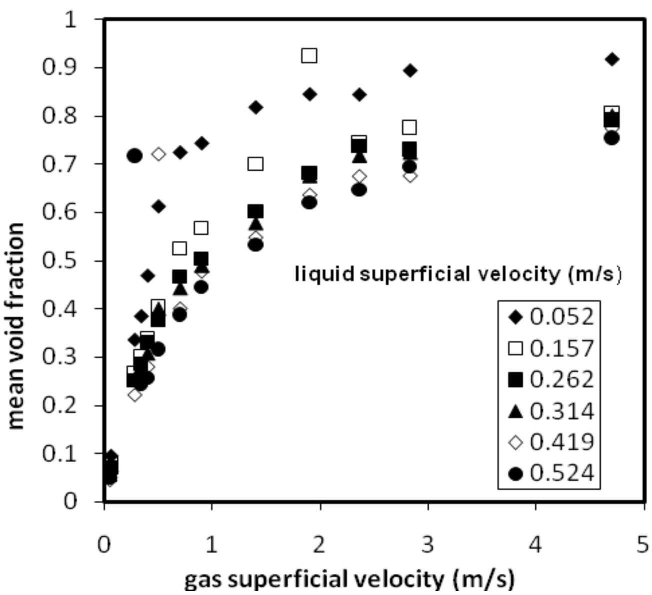


Figure 22: Mean void fraction for 10^o from horizontal with WMS

CONCLUSION

The effect of pipe inclination has successfully been investigated using advanced instrumentation. From the above it can be concluded that the Electrical Capacitance Tomography as well as Wire Mesh Sensor employed has great capability for interrogating gas liquid flow parameters. Even from just the cross-sectionally averaged time series of void fraction, there are many features of the flow that can be identified. We have found that the following apply:

(a) Inclinations have some effects on the gas-liquid flows

(b) Electrical Capacitance Tomography and Wire Mesh Sensor are good for study of flow characteristics since they have been able to give output signals/results that are corroborated by literature

(c) The flow pattern transitions can be identified from analysis of the output of the measurements techniques.

(d) Structure velocity shows a trend with mixture velocity when compared with the correlation of Nickin et al.[25] and the work carried out by Bendiksen [26]

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ACKNOWLEDGEMENT

Abdulahi Abolore and Abdulkadir Mukhtar would like to express sincere appreciation to the Nigerian government through the Petroleum Technology Development Fund (PTDF) for providing the funding for their MSc and PhD studies respectively. Lokman A. Abdulkareem would also like to thank the Iraqi Ministry of Higher Education for supporting his PhD study.

This work has been undertaken within the Joint Project on Transient Multiphase Flows and Flow Assurance. The Authors wish to acknowledge the contributions made to this project by the UK Engineering and Physical Sciences Research Council (EPSRC) and the following: - Advantica; BP Exploration; CD-adapco; Chevron; ConocoPhillips; ENI; ExxonMobil; FEESA; IFP; Institutt for Energiteknikk; Norsk Hydro; PDVSA (INTERVEP); Petrobras; PETRONAS; Scandpower PT; Shell; SINTEF; Statoil and TOTAL. The Authors wish to express their sincere gratitude for this support.

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