A Study on the Characterization of Air-water Two-phase Vertical Flow by Using Electrical Resistance Imaging

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ABSTRACT

The characterization of air-water two-phase vertical flow in a 12 m flow loop with 1.5 m of vertical section is studied by using an impedance image based method of electrical resistance tomography (ERT). The flow patterns of bubbly flow, slug flow and churn flow and their transitions of the vertical flow exit a jet pump in a short distance are imaged by ERT technique. The mixing process, especially the turbulent blending process, of gas and liquid phases is observed and analyzed. By applying a fast data collection to a dual-plane ERT sensor and an iterative image reconstruction algorithm, relevant information is gathered for implementation of flow characteristics, particularly for flow regime recognition. Cross-correlation method is also used to interpret the velocity distribution of the gas phase on the cross section. The paper demonstrates that ERT can now be deployed routinely for velocity measurements and this capability will increase as faster measurement systems evolve.

Keywords ERT, gas-liquid two-phase flow, vertical flow, velocity measurement

1 INTRODUCTION

In petroleum industry, multiphase flow of gas and liquids is commonly encountered in the production and transportation of oil and gas, the need for multiphase flow measurement in the oil and gas production has been evident for many years. Multiphase flow measurement has yet to be established as a separate discipline. The complexity in multiphase flow measurement lies in the simultaneous existence of the gas and liquid phases. The interface between the phases (gas-liquid and liquid-liquid) can be distributed in many configurations which are called flow patterns, demonstrate a very important feature of gas-liquid multiphase flows. In single-phase flow in pipes, the design parameters such as pressure drop can be calculated in a relatively straightforward way, while the existence of other phases presents can difficult challenge in understanding and modeling the flow system. The hydrodynamics of the flow, as well as the flow mechanisms, change significantly from one flow pattern to another.

Process tomography is a discipline which has been a significant growth over the last ten years, and is becoming increasingly promising in the study and application of multiphase flows. This is due to its non-intrusive nature and potential capacity for providing a means of 'looking' inside the detailed local flow information such as volume fraction, the velocity distribution of individual phases and the inter-phase behaviors (Wang, 2001).

In this paper, electrical resistance tomography (ERT) technique is adopted to study the flow pattern and the velocity distribution in a gas-water two-phase vertical flow (Mann, 1999; Wang, 2000). In order to use cross correlation technique to perform component velocity measurement, a fast data collection strategy was applied to the dual-plane ERT sensor and an iterative algorithm was used for image reconstruction (Wang, 2002), and much improved velocity profiles of the gas phase in an air/water flow at different flow patterns were reported.

2 EXPERIMENTAL SET-UP

All the experiments described in this paper were carried out using the multiphase flow loop made of transparent glass at Institute of Particle Science and Engineering at University of Leeds, which is a 12 m gas-liquid flow loop with an inner diameter of 50mm.

The flow loop can run a maximum superficial liquid velocity of 1 m/s with Reynolds number about 58,500, and a superficial gas velocity larger than 30 m/s with Reynolds number above 100,000. The two-phases of gas and liquid, in terms of flow states of laminar to laminar, laminar to turbulent,

turbulent to laminar and turbulent to turbulent, can be performed on this test-loop. By controlling the pressure and flow-rates of the gas phase and the liquid phase, many flow patterns, such as bubbly flow, slug flow, churn flow and annular flow, can be created in this device. A tomographic sensor with two sensing planes is also installed in the flow loop in order to obtain flow patterns of two-phase flow.

The tap-water (conductivity 0.370-0.387mS/cm) was used as the liquid phase, and air was introduced into the flow loop, which was measured by a flow-meter at the range of 1-8Litre/min. Measurements were performed at ambient temperature. By controlling the air flowrate at the air inlet, different flow patterns can be generated in the flow loop.

The experiments were performed under different air flow-rates in regard to the productions of bubbly flow, slug flow, churn flow, and annular flow regimes. The water flows were scaled with an accumulating tank during the experiments to get water flowrate and mean velocity. At the mean time, a number of photographs were recorded as visual presentations of these different flow patterns.

3 THE ERT SYSTEM

3.1 ERT Hardware System

A P2000 ERT system (Industrial Tomography System Ltd., Manchester) was used for data collection. The so-called adjacent electrode pair strategy (Brown, 1985) was adopted, using a 10mA injection current at 9.6 kHz for flow regime recognition, and a 50mA current at 38.4 kHz for cross-correlation calculation. Data collection rates were 23.04 frames per second at the signal frequency of 9.6 kHz and 28.3 frames per second at the signal frequency of 38.4 kHz. Both single-plane and dual-plane ERT sensors were used in this study. Each ERT sensing plane consists of 16 titanium-alloy rectangular electrodes (5mm×12mm).

3.2 ERT Sensor Set-up

ERT sensor on conductive ring technique was used in this study. The dual-plane ERT sensor is a core sensing technique in the experiment for implementation of local flow velocities in the two-phase flow. Since the current data collection speed was still limited, we set the distance between the two sensing planes apart to 150mm. To improve the correlation, a dual-plane measurement strategy was applied, which was built in the ITS P2000 ERT system. The principle of the dual-plane strategy is based on a ‘cross measurement between two correlated electrodes on two sensing planes’ instead of ‘plane by plane’ measurement. SBP (sensitivity coefficient weighted back-projection) algorithm was used for on-line flow pattern recognition due to its fast image reconstruction speed. An off-line multi-step algorithm, known as SCG algorithm (the sensitivity theorem based inverse solution using generalised conjugate gradients methods with a method of error vector decomposition) (Wang, 2002), was utilized for the image reconstruction in the velocity implementation in order to reduce the error caused by the point-spread function in the use of the SBP algorithm. The SCG algorithm employs a multi-step approach with the sensitivity theorem based linear approximation and the differences between the relative changes in the measured and simulated boundary voltages at each step to solve the non-linear electric field inverse problem. All images used for implementation of local velocities in the paper were reconstructed with the SCG algorithm.

The dimension of the sensing planes installation is given in Figure 1, and a photograph of the set-up is shown in Figure 2.

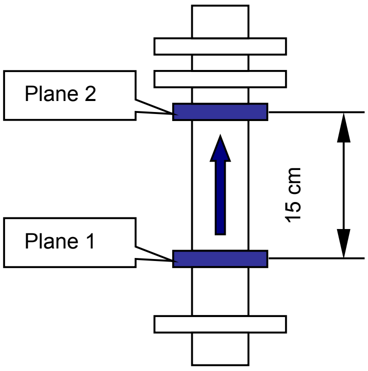


Figure 1: Sensor configuration

Figure 2: The photograph of the sensor

3.3 Flow Parameter Calculation Using ERT

With conductivity data from ERT, the local volume fraction distribution (α_c) can be determined by applying the Maxwell equation:

$$\alpha_c = \frac{2\sigma_1 + \sigma_2 - 2\sigma_{mc} - \sigma_{mc}\,\sigma_2/\sigma_1}{\sigma_{mc} - \sigma_{mc}\sigma_2/\sigma_1 + 2(\sigma_1 - \sigma_2)} \tag{1}$$

where σ_1 is the conductivity of the first phase, σ_2 is the conductivity of the second phase, and σ_{mc} is the local mixture conductivity distribution.

If the second phase is assumed to be non-conductive material, such as air in this study, the above equation can be simplified as following:

$$\alpha_c = \frac{2\sigma_1 - 2\sigma_{mc}}{2\sigma_1 + \sigma_{mc}} \tag{2}$$

The conductivity of the first phase (σ_1) can be found easily with a widely available commercial conductivity meter, while the local mixture conductivity (σ_{mc}) is determined from the pixel conductivity of ERT imagine.

The local axial velocity can be obtained by applying the cross-correlation technique to determine the speed of moving profiles. The basic function of the cross-correlation technique is to find the time offset between two signals where the similarities are most obvious. These signals can be any value and are not limited to quantitative conductivity data. This goal is to find a transition time τ that corresponds to the minimum difference (ε). This can be achieved by using the least square criterion as the following equation:

$$\varepsilon_{xy}^2(\tau) = \min \lim_{T\to\infty} \frac{1}{T} \int_{-T}^{T} [x(t) - y(t-\tau)]^2\, dt \tag{3}$$

where x, y are the original signals of void fraction at each imaging cross section respectively, ε is the error function which gives the transition time τ when the expression take a minimum value. Replacing the integral by partial summation, equation (3) can be expressed in discrete form:

$$\varepsilon_k^2(n) = \sum_{m=0}^{N-n} [x_k(m) - y_k(m-n)]^2 \tag{4}$$

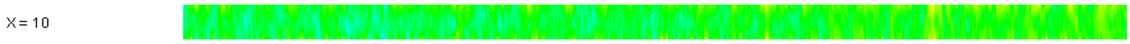
where N is sample length, n is correlated sample ($n = 1,\ldots, N-1$) and k is the number to indicate different pixels on the cross-section.

In the computation, N should be selected according to the distance between the dual-plane ERT sensors and the maximum and the minimum velocity of the flow. In this study, only the axial velocity is considered, and when N is selected properly, there is a strong correlation between planes.

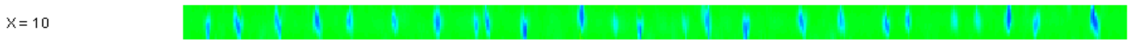
4 EXPERIMENT RESULTS

4.1 Flow Pattern Recognition

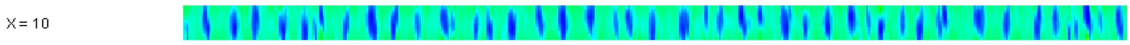
Flow pattern recognition was obtained with data from the single-plane ERT sensor (plane 1 in Figure 1). The data collection speed used in this mode was 23.04 frames/sec, and images were reconstructed by using SBP algorithm. By stacking part of reconstructed tomograms, gas-phase and liquid-phase distribution and their dynamical varying processes (flow processes) in the pipe can be clearly demonstrated. Flow patterns varied with air flowrates are illustrated in Figure 3 resulted from ERT reconstruction.



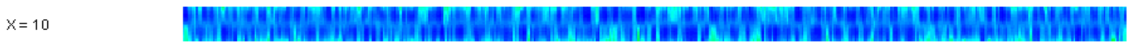
Bubbly flow (superficial water velocity: 0.222m/s, superficial air velocity: 0.017-0.025 m/s)



Slug flow (superficial water velocity: 0.017m/s, superficial air velocity: 0.008 m/s)



Churn flow (superficial water velocity: 0.195m/s, superficial air velocity: >0.068 m/s)

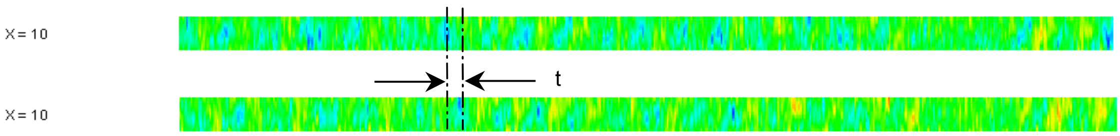


Annular flow (superficial water velocity: 0.536 m/s, superficial air velocity: >>0.068 m/s)

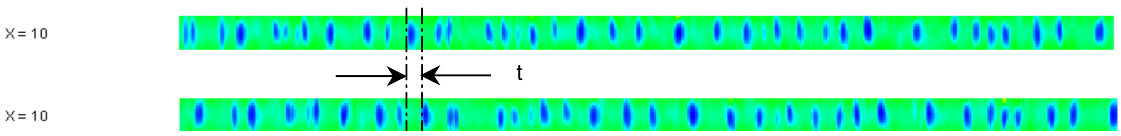
Figure 3: Flow patterns recognition (black denotes air phase and gray denotes water phase)

4.2 Flow Velocity Measurement

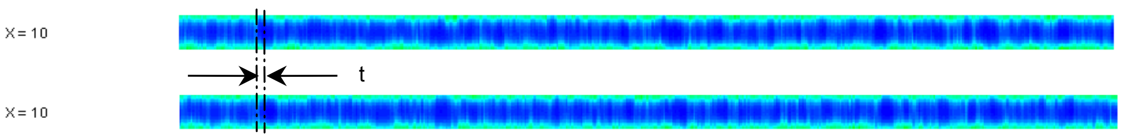
To demonstrate the use of cross correlation in obtaining the velocity profile of a multiphase flow, some stacked images from different air flowrates are given in Figure 4. The correlation between two images taken from different positions is obviously. It demonstrates the dual-plane mode at 28.3 dual-frames/sec is able to manage the velocities at the demonstrated mean air flowrates.



Bubbly flow (superficial water velocity: 0.547m/s, superficial air velocity: 0.025 m/s)



Churn flow (superficial water velocity: 0.223m/s, superficial air velocity: >0.068 m/s)



Annular flow (superficial water velocity: 0.743 m/s, superficial air velocity: >>0.068 m/s)

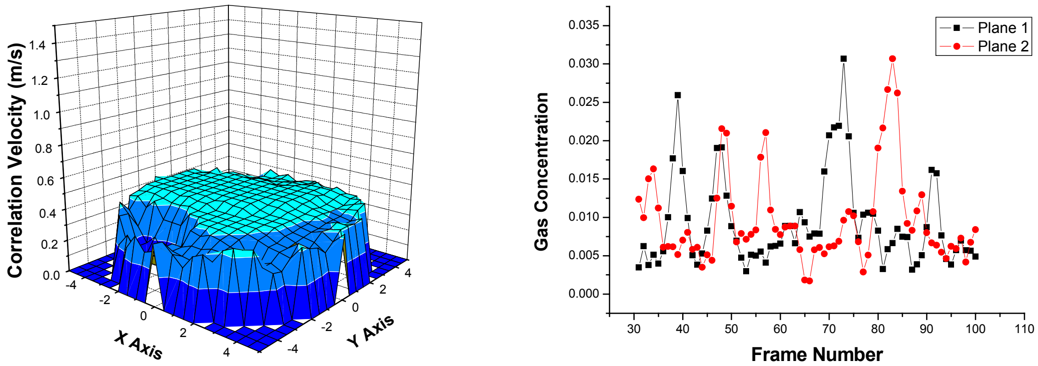
Figure 4: Cross-correlation between two images obtained from dual-plane ERT sensor

The gas-phase velocity converted from the cross-correlation results can be calculated by:

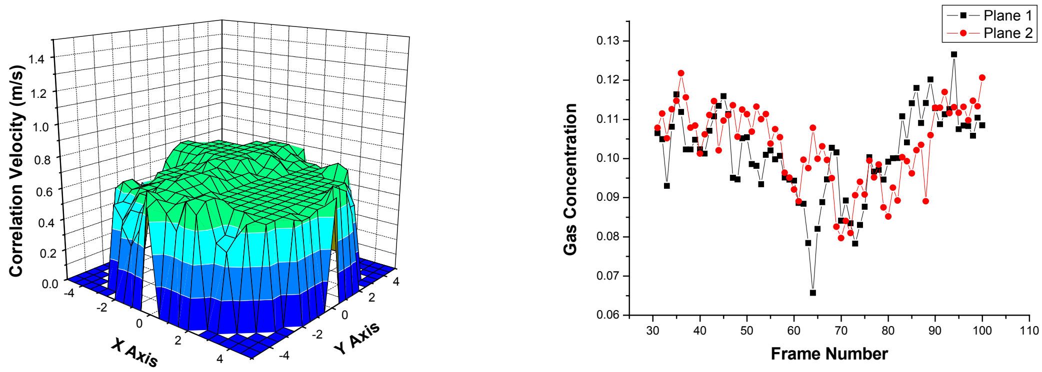
$$v = \frac{\Delta s}{\Delta t} = \frac{L}{(n_k - 1)/F_s} \tag{5}$$

where L is the distance between two sensor planes, n_k is the number of n when it makes equation (3) or (4) take the minimum value, F_s is the sampling frequency.

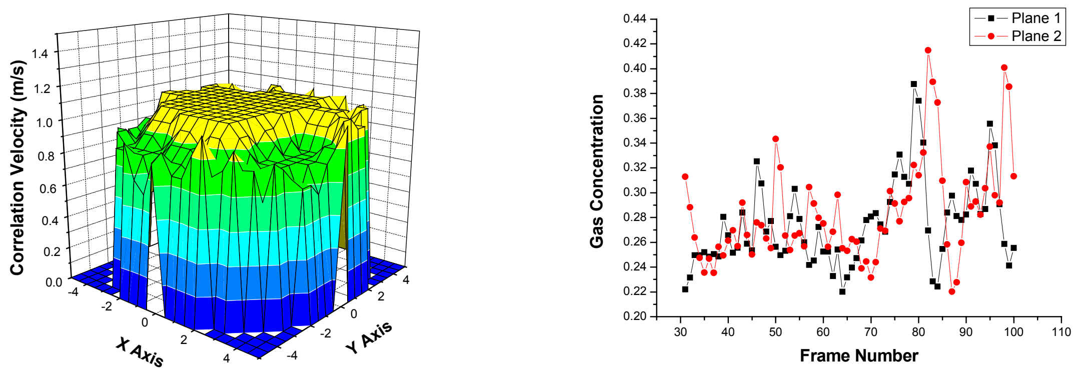
By applying the cross-correlation procedure to a data set of 1000-frame of tomographic images, that were acquired from the air/water two-phase vertical pipe flow, an evident correlation was found for the similar flow information at some corresponding pixels of the dual-sensing rings. Figure 5 shows the velocity distribution, resulted from the cross-correlation implementation, for a bubbly flow and a churn flow. The superficial velocities estimated in the experiments are 0.141 m/s, 0.419 m/s and 0.463 m/s for water.



(a) Bubbly flow (superficial water velocity: 0.141 m/s, superficial air velocity: <0.008 m/s)



(b) Churn flow (superficial water velocity: 0.419 m/s, superficial air velocity: >0.068 m/s)



(c) Churn-annular flow (superficial water velocity: 0.463 m/s, superficial air velocity: >>0.068 m/s)

Figure 5: Correlation local velocity distributions and mean cross-section gas concentration at different flow patterns

5 DISCUSSIONS AND CONCLUSIONS

From the main results of Figures 3, 4 and 5, some useful information and interesting phenomena can be found for both gas-liquid two-phase flows in a vertical pipe and ERT technique, viz.:

First, the ERT technique is a suitable means for detecting the flow patterns of gas-liquid multiphase flow in a vertical pipe. With a fast data collecting protocol and an effective iterative image reconstruction algorithm, gas-phase and liquid-phase distribution and their dynamic variations in the pipe can be clearly quantified (Figure 3).

Secondly, the time of cross-correlation can reveal the velocity magnitude of the interface of the gas-phase and liquid-phase. The cross-correlation time interval of bubbly flow is longer than that of churn flow, and much longer than that of annular flow (Figure 4). Based on the time interval (ERT data frames), the mean velocity of gas-liquid two-phase can be estimated. This may be important in the on-situ monitor of industrial processes.

Thirdly, we can see that as gravity acts in the axial direction giving symmetry across the pipe cross-section. Flow patterns tend to be somewhat more stable, but with slug and churn flows, oscillations and bubble roll in the flow can occur to destroy the symmetry. The degree of the cross-correlation of the flow state is good for bubbly flow and annular flow, but not so good for churn flow (Figure 5). This can also be proven during the cross-correlation procedure. In a bubbly or an annular flow, the cross-correlation graphics can be obtained almost on every pixel, but only partially for churn flows.

Fourthly, the velocity on the central part of the pipe is larger than that on the edge of the pipe at any flow pattern. For a churn flow (Figure 5.b), large air bubbles rise upwards asymmetrically, which causes the distribution of velocities on a section of the flow loop also to be asymmetrical. While for a bubbly flow or an annular flow, it is almost symmetrical. As the amount of gas is increased the coalescence of smaller air bubbles forming larger bubbles gradually concentrates on the core of the pipe to transit to an annular flow at the end of the pipe.

Lastly, for a churn flow or an annular flow, as the velocity is relatively high, the sampling frequency should be high, otherwise large errors will arise in the measured data. More noise points occur on the edge of the pipe with increasing gas content. For obtaining accurate value of flow parameters, much more care should be taken both on ERT hardware and software improvement, such as increasing the sampling frequency, reducing noise influence, developing better correlation algorithm to describe the three-dimensional velocity distribution of the flow field.

6 ACKNOWLEDGMENTS

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