**Proceedings Paper:**

Karki, B, Faraj, Y and Wang, M (2016) Electrical Conductivity Based Flow Regime Recognition of Two-phase Flows in Horizontal pipeline. In: WCIPT8 Proceedings. 8th World Congress on Industrial Process Tomography, 26-29 Sep 2016, Iguassu Falls, Brazil. International Society for Industrial Process Tomography . ISBN 9780853163497

# Electrical Conductivity Based Flow Regime Recognition of Two-phase Flows in Horizontal pipeline

B. Karki, Y. Faraj, M. Wang

School of Chemical and Process Engineering, University of Leeds,
Leeds, LS2 9JT, United Kingdom
pmbk@leeds.ac.uk

## ABSTRACT

An experimental method of resolving flow regimes by utilizing the conductivity data measured by Electrical Resistance Tomography (ERT) is presented. The method applies Boolean logic and frequency analysis of the ERT signal in order to identify five typical flow regimes in horizontal pipe namely: bubble, plug, slug, stratified and annular. The relative conductivity signal obtained from the tomograms is converted to binary form in order to perform Boolean logical operation with the binary templates of typical flow patterns. The overall conductivity of the tomogram is used to extract frequency information of the flow. Flow pattern is identified by the statistical analysis of the combination of this information. The recognition method was evaluated using experimental data from horizontal pipeline for different flow conditions. The identification of the flow regimes from the method was verified using the conductivity images from ERT.

**Keywords** electrical resistance tomography, flow regime recognition, multiphase flow

## 1 INTRODUCTION

Multiphase flows are a common phenomenon in various industrial processes such as petroleum, chemical and pharmaceutical sectors. The distribution of liquid and gas phases in the flow give rise to a wide variety of flow regimes whose identification is necessary for the reliability and safe operation of the process. The desirability or harmfulness of flow regimes is different depending on the process they occur in, which make their identification even more important. The flow regimes occurring in multiphase flows of oil, water and gas are also found in two phase gas liquid flows. Hence this study investigates horizontal gas water two phase flows due to its simplicity over three phase flows.

In horizontal co-current gas-liquid flow, the distribution of the liquid phase is influenced by gravity, which acts to stratify the liquid to the bottom of the pipe and the gas to the top. The flow regimes occurring in horizontal gas-liquid flow are generally categorised as bubble, stratified, slug, plug and annular flow (Hoogendorn et al 1959; Spedding et al 1993) as shown in figure 1. In bubble flow, the bubbles are dispersed in the liquid phase with higher accumulation of bubbles at the upper region of the pipe due to their buoyancy. Stratified flow occurs when there is complete separation of the two phases. The gas phase occupies the top and liquid phase the bottom of the pipe, while having an undistributed horizontal interface. Waves can also form on the horizontal interface depending upon the velocity thus giving rise to wavy stratified flow. Plug flow is characterised by existence of liquid plugs, which are separated by elongated gas bubbles. The diameter of these elongated bubbles is smaller than the diameter of the pipe, such that the liquid phase is continuous along the bottom of the pipe below the elongated bubbles. Slug flow is formed when the diameter of elongated bubbles reach almost similar to that of the pipe. The liquid slugs separating each elongated bubbles, can be described as large amplitude waves. Annular flow is characterised by a continuous gas core and an annular liquid film. However, the liquid film is not uniform; it is substantially thicker at the bottom of the pipe.

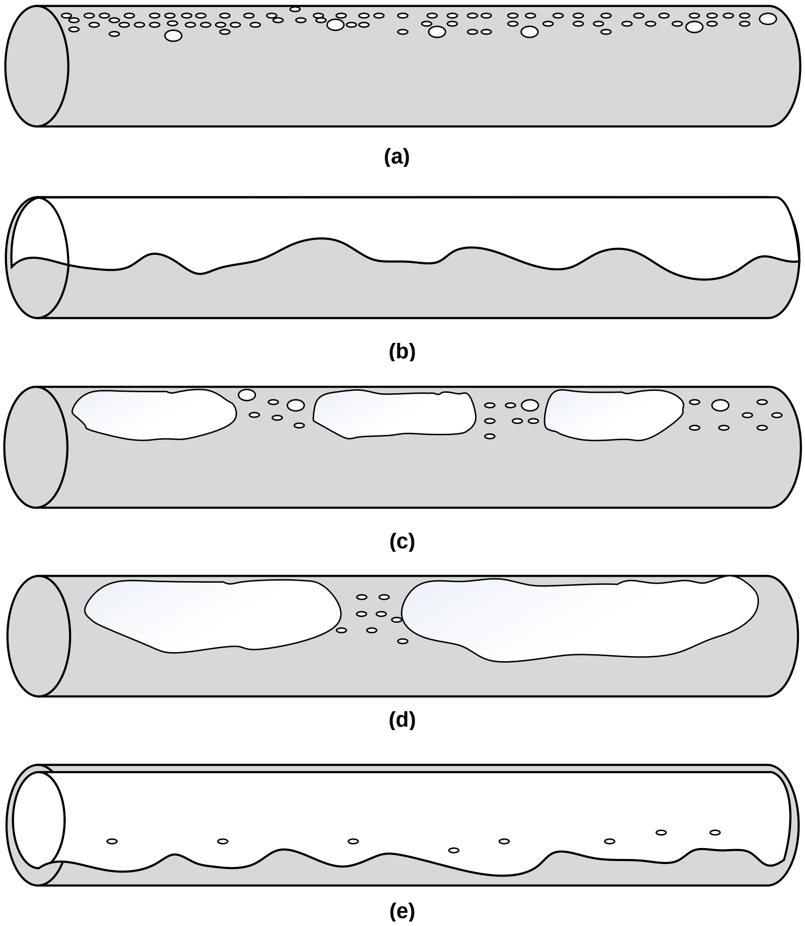



**Figure 1. Gas-liquid flow regimes in horizontal pipes; (a) Bubble flow, (b) Stratified flow, (c) Plug flow, (d) Slug flow and (e) Annular flow**

Flow regime predictions for two-phase horizontal flows can be made based on empirical flow regime maps (Baker 1954; Mandhane et al 1974; Taitel et al 1976). However, these flow regime maps are specific to a certain pipe size, pipe geometry and fluid property. Although attempts have been made by many researchers to generalize these flow regimes, none of the available flow regime maps in the literature is applicable to a wide range of pipe sizes and fluid properties. Therefore, the need for an automated technique is paramount and methods to gauge the flow online during measurement are desirable. Subjective methods such as eyeballing and high speed photography are generally used to determine the flow regimes in real time (Lowe et al 1999; Dong 2001). The subjectivity inherent in these methods render them less accurate than required creating a need for an objective approach. Electrical Resistance Tomography (ERT) is a high speed, non-invasive solution for real time imaging of two-phase flows (Ma et al 2001). ERT produces time difference images based on the conductivity distribution of gas and liquid phase in the domain which depict the state of the flow. The flow can be monitored in real time using ERT images. Flow regime recognition method using Boolean logic analysis of the electrical conductivity information obtained from ERT has been developed (Ramskill et al 2011). The method was based on statistical analysis of the conductivity distribution which enabled quantitative comparison of flow patterns thereby reducing the subjectivity in flow regime recognition. This study proposes an enhancement of the Boolean analysis method with the inclusion of frequency analysis of the two phase flow.

# 2 METHOD

The method of flow regime recognition in horizontal flow is based on the spatial distribution of each constituent phase within the pipe. Based on the physical description of each flow regime, the distribution and structure of gas and liquid differs from one flow regime to another. In the analysis, the tomograms produced by ERT were used to recognise the active flow regime. In order to identify the flow regimes, two distinct approaches were used: i) Signal thresholding based on concentration, and ii) Frequency decomposition. The information obtained from these two methods were utilised to implement the flow regime recognition as demonstrated in figure 2.

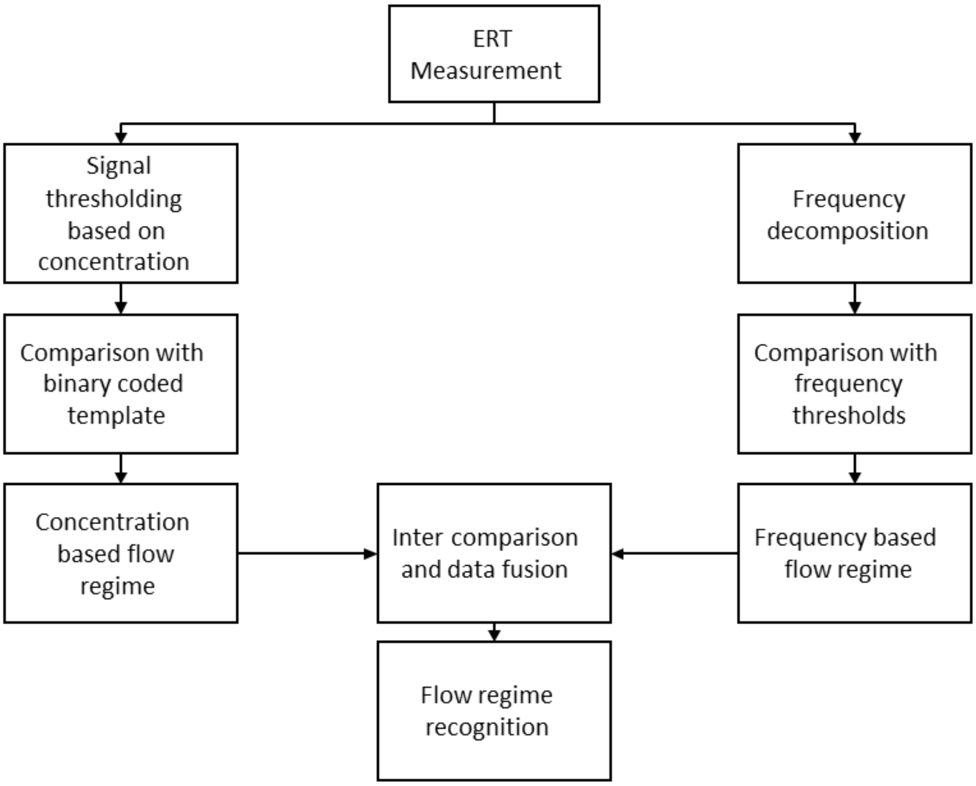



**Figure 2. Simplified Schematic of flow regime recognition**

## 2.1 Signal thresholding based on concentration

Image reconstruction by ERT is possible due to the differences in conductivity of gas and liquid phases in a flow (Wu et al 2005). The air concentration can be derived by using the conductivity distribution obtained from ERT measurement with the application of Maxwell relationship:

$$\alpha = \frac{2\sigma_1 + \sigma_2 - 2\sigma_{\mathrm{m}} - \dfrac{\sigma_{\mathrm{m}}\sigma_2}{\sigma_1}}{\sigma_{\mathrm{m}} - \dfrac{\sigma_2}{\sigma_1}\sigma_{\mathrm{m}} + 2(\sigma_1 - \sigma_2)} \tag{1}$$

Where $\sigma_1$ is the conductivity of continuous phase, $\sigma_2$ is the conductivity of dispersed phase and $\sigma_{\mathrm{m}}$ is the conductivity of mixture of two phases. The concentration tomograms thus obtained were used in the flow regime recognition method. The horizontal two phase flow was considered for this study which is largely influenced by gravity. Thus only the central vertical axis of the concentration tomogram in the 21 cell zone scheme (ITS Ltd 2010) was used to extract the flow features as shown in figure 3.

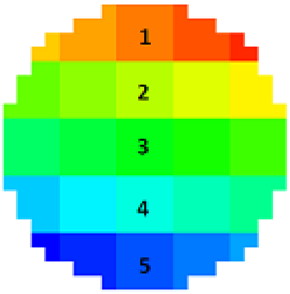



**Figure 3. 21 cell zone scheme (ITS Ltd 2010)**

Since the physical distribution of each constituent phase differs from another, the characteristics of each flow regime can be extracted from five zones shown in figure 3, in which zone 1 represents the top and zone 5 the bottom. The physical distribution of air bubbles within the carrier liquid facilitates the analysis of relative conductivity within each zone. The flow regimes under investigation in this study are: bubble, stratified, plug, slug and annular. Based on the geometric structure of bubble flow regime, high concentration of bubbles are expected at the top of the pipe hence, a change in the relative concentration is observed only in zone 1. Zones 2, 3, 4 and 5 are expected to contain only liquid phase, thus there is no deviation from the reference measurement. Stratified flow involves complete separation of gas and liquid phases separated by a horizontal interface. Therefore, zones 1, 2 and 3 are expected to contain higher concentration of gas, while zone 3 may contain both phases, liquid and gas, but evidently less gas than zones 1 and 2. Similarly, zones 4 and 5 expected to contain only liquid phase. Plug and slug flow regimes are characterised by large amplitude waves containing entrained bubbles intermittently washing the top of the pipe with smaller amplitude waves in between. The top wall of the pipe is nearly continuously wetted by the large amplitude waves and the thin liquid film is left behind. In plug flow, zones 1 and 2 are expected to contain higher concentration of gas, while zones 3, 4 and 5 contain liquid phase with subtle deviation of relative conductivity from the reference. In slug flow, zones 1, 2 and 3 are expected to contain higher concentration of gas, while zones 4 and 5 contain liquid phase with subtle deviation of relative conductivity from the reference. In annular flow, the liquid forms a continuous annular film around the perimeter of the pipe, but the film is thin at the top and thicker at the bottom, and the gas has characteristics of core flow. Based on this feature, zone 1 is expected to contain a liquid film with probably some concentration of gas whereas zones 2, 3 and 4 clearly contain almost 100% gas with a number of small droplets of liquid. On the other hand, zone 5 also contains a liquid film, some gas may also be present, but it can be very small amount in such a way that can be negligible.

The value that defines the threshold was empirically determined as 15% deviation in the relative concentration relative to the reference measurement as it was significant enough to ascertain the existence of air within the zone of interest. The threshold was applied to produce a binary signal of 1s and 0s depending of the magnitude of the deviation from the reference measurement. Therefore, within each zone, a deviation greater than 15% of the reference measurement implied the existence of air and it was given a value of 0. On the other hand, a deviation less than 15% of the reference measurement implied the existence of liquid and it was given a value of 1. Based on the threshold and extracted features of each flow regime, a predicted binary code or template was produced, as shown in table 1. This template was created based on the predicted distribution of each phase or identified flow feature within the five zones along the vertical central line of the ERT tomogram.

**Table 1. Predicted binary code for flow regimes**

| Flow Regime | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 |
|---|---|---|---|---|---|
| **Bubble** | 0 | 1 | 1 | 1 | 1 |
| **Plug** | 0 | 0 | 1 | 1 | 1 |
| **Slug** | 0 | 0 | 0 | 1 | 1 |
| **Stratified** | 0 | 0 | 0 | 1 | 1 |
| **Annular** | 1 | 0 | 0 | 0 | 1 |

Each frame of the ERT concentration tomogram was converted to similar 5 bit binary code based on the mentioned threshold and compared to the templates shown in table 1. A match between the predicted and measured binary codes was registered as presence of the respective flow regime and a mismatch was registered as single phase flow, thus formulating concentration based flow regime recognition.

## 2.2 Frequency Decomposition

The method of utilising concentration based flow regime recognition and Boolean analysis has been implemented successfully for bubble and plug flow (Ramskill et al 2011). This study has advanced the application to include slug, stratified and annular flow regimes as well as included frequency domain analysis of the flow to increase the robustness of the method. The ERT concentration signal thresholding technique is based on generalisation which resulted in slug and stratified flow having the same binary template evident in table 1. The frequency decomposition technique was devised to compensate such deficiency by taking into account the dynamic nature of the flow. Hence a fusion of concentration and frequency information was used to ultimately formulate the flow regime recognition method as shown in figure 4.

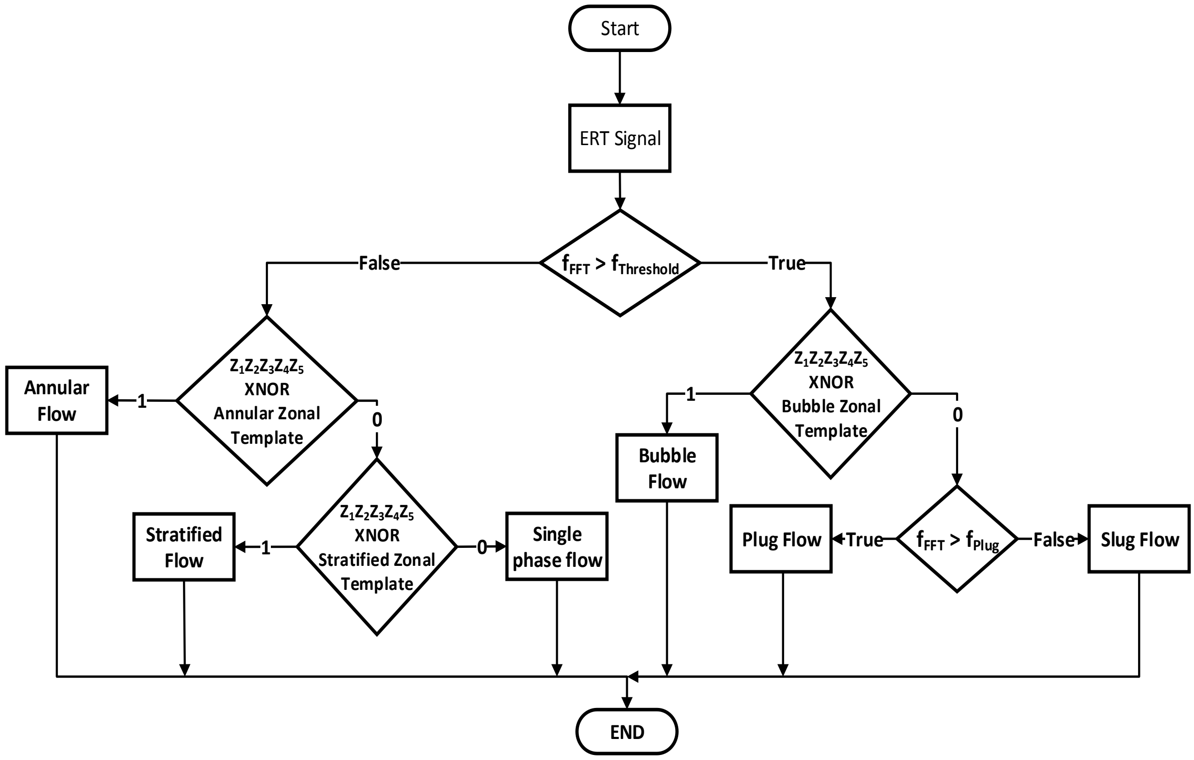



**Figure 4. Flow chart for horizontal flow regime recognition**

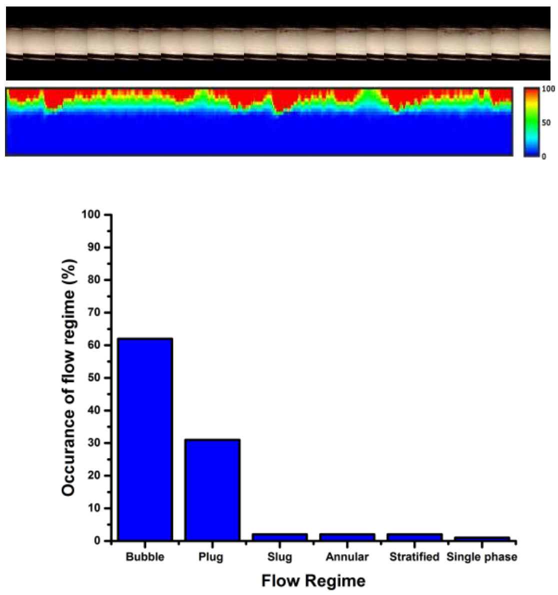
Since frequency is a function of time, ERT tomograms were accumulated over a period of time and mean concentrations of each frame were used to perform Fast Fourier Transform (FFT). The dominant frequency obtained from the FFT ($f_{FFT}$ in figure 3) was compared with a threshold frequency ($f_{Threshold}$ in figure 3) in order to determine the type of flow regime. Bubble, plug and slug flows demonstrate a pulsating nature whereas annular and stratified flow are more or less consistent. Therefore, the characteristic frequency of the flows helped in differentiating the types of flow which was not always possible using just the concentration information. The value of the threshold frequency was determined empirically prior to the measurements.

## 2.3 Experimental Evaluation

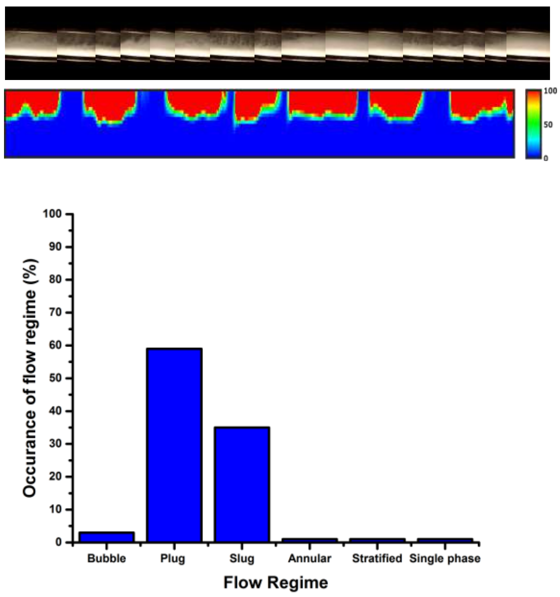
The experiments were carried out at the flow loop facility in University of Leeds. Water was used as continuous phase and air was used as dispersed phase flowing in the loop with 12 m length and 0.05 m diameter. Flow rates of the water and air were manipulated to produce different flow regimes. ERT measurements were taken in the horizontal section of the pipeline using a 16 electrode system (V5r) (Wang et al 2015). For each of the flow regimes 10000 frames of ERT were collected.

# 3 RESULTS AND DISCUSSION

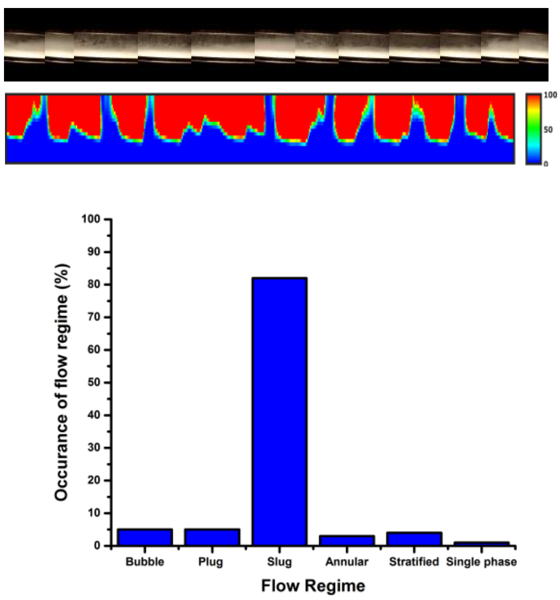
The result of the flow regime recognition method is shown in figure 5 along with stacked photos and stacked images from the ERT tomogram for comparison. The axial images above each flow regime recognition result are comprised of 1000 frames stacked together which represent the respective flow regimes. The flow regime recognition results are displayed graphically as percentages of occurrence of different flow regime within the duration of the measurement. The output from the recognition method is accumulated over time for each block of measurement to provide a true representation of the entire duration of the flow. Figure 5 (a) shows the result of bubble flow regime with superficial liquid velocity ($v_L$) of 1.067 $ms^{-1}$ and superficial gas velocity ($v_G$) of 0.026 $ms^{-1}$. Bubble flow was represented as the major flow regime i.e. 62% with plug representing 31% for the duration of the flow. Similarly, for plug flow shown in figure 5 (b), $v_G$ = 0.085 $ms^{-1}$ and $v_L$ = 0.878 $ms^{-1}$. Plug flow represented 59% and slug flow represented 35% of the total measurement for the plug flow regime.



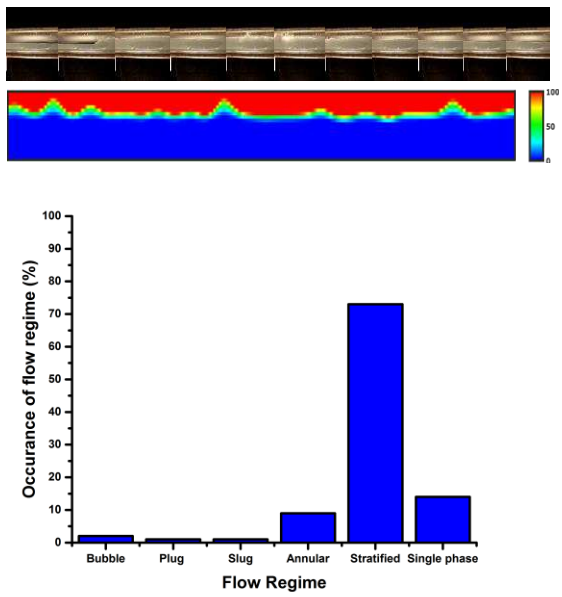

(a)



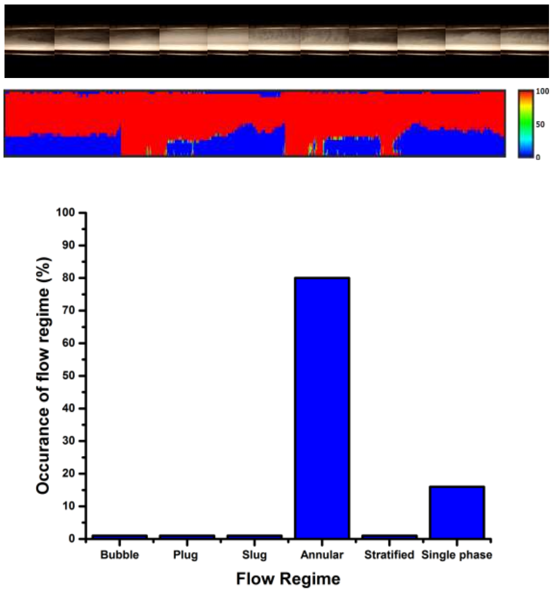

(b)




(c)




(d)




**(e)**

**Figure 5. Results of flow regime recognition for (a) Bubble flow, (b) Plug flow, (c) Slug flow, (d) Stratified flow and (e) Annular flow. Flow direction for the axial stacked images is from left to right.**

Figure 5 (c) is the depiction of slug flow regime where $v_G = 0.68$ ms$^{-1}$ and $v_L = 1.01$ ms$^{-1}$. Slug flow was successfully able to represent 82% of the total measurement. Stratified flow is shown in figure 5 (d) where $v_G = 0.043$ ms$^{-1}$ and $v_L = 0.27$ ms$^{-1}$. Stratified flow represented 73% of the measurement for stratified flow regime. Lastly, figure 5 (e) depicts the annular flow regime with $v_G = 13.46$ ms$^{-1}$ and $v_L = 0.073$ ms$^{-1}$. The measurement was represented by annular flow as the dominant flow regime with 80% occurrence.

The flow regime recognition method was successfully able to represent the dominant flow regimes in each of the measurements. The representation was higher for slug, annular and stratified flow whereas it was slightly lower for bubble and plug flow. Plug flow was also represented in the measurement for bubble flow as the smaller bubbles could coalesce to form elongated bubbles during a few instances in the measurement. Representation of slug flow was found for plug flow measurement due to the indistinguishability of the bubbles sizes and flow frequency in some instances. The frequency analysis contributed in distinguishing characteristic features of the flow regimes investigated.

# 4 CONCLUSION

A method of flow regime recognition in horizontal gas-liquid flow was implemented. The statistical analysis of the ERT measurement and frequency analysis of the flow enabled a quantitative comparison of flow regimes, thus reducing the subjectivity associated with flow regime recognition. The proposed method was implemented into an algorithm which was tested and utilised for the evaluation of the proposed method. The proposed method was able to identify prevalent flow regimes from the measured data. Visualization of the axial stacked images provided a qualitative comparison and reference for the recognition method.

The method utilised the five zones from the central vertical axis of the tomogram to prepare 5 bit binary codes. The distinguishability between similar flow patterns such as plug and slug can be increased by increasing the number of zones. For instance, same template was predicted for slug and stratified flow regime, which can be avoided by increasing the zones and thus increasing the accuracy of the method. The threshold value of 15% deviation in the concentration from the reference measurement has been used in the study which can be optimised in the future. Further study is necessary in order to determine the effects variables such as pipeline geometry, number and types of phases in the flow may have on the threshold value. Inclusion of frequency analysis helped in enhancing the accuracy of the method. It is a requisite to measure the frequency threshold beforehand for the application of frequency information as it is affected by the flow velocity. This poses a limitation in industrial settings where it may not always be possible to perform such prior measurements. Velocity information of the flow can be obtained for ERT measurements of suitably high temporal resolution. There is room for further research towards inclusion of velocity analysis of the flow in the recognition method to enhance its accuracy.

The capacity of the method for two phase flow regime recognition has been demonstrated. This method can be extended to three phase flow recognition in its current form.

**Acknowledgement:** The authors acknowledge the support by European Metrology Research Programme (EMRP) project Multiphase flow metrology in the Oil and Gas production jointly funded by the European Commission and participating countries within Euramet and the European Union.

## REFERENCES

BAKER O., (1954), Simultaneous flow of oil and gas, Oil Gas J., 53 185.

DONG F., (2001), Identification of two-phase flow regimes in horizontal, inclined and vertical pipes, Meas. Sci. Technol., 12, 1069–75.

HOOGENDORN C.S., (1959), Gas-Liquid Flow in Horizontal Pipes, Chem. Eng. Sci., 9, pp. 205-217.

Industrial Tomography Systems Ltd 2010 P2+ Electrical Resistance Tomography System—*User's* Manual (Manchester: Industrial Tomography Systems Ltd).

LOWE D. C. AND REZKALLAH K. S., (1999), Flow Regime Identification in Microgravity Two-phase Flows Using Void Fraction Signals, Int. J. Multiphase Flow, 25, pp 433–457.

MA Y., ZHENG Z., XU L., LIU X. AND WU Y., (2001), Application of electrical resistance tomography system to monitor gas/liquid two-phase flow in a horizontal pipe, Flow Meas. Instrum., 12, 259–65.

MANDHANE J. M., GREGORY G. A. AND AZIZ K., (1974), A Flow Pattern Map for Gas-Liquid Flow in Horizontal Pipes, Int. J. Multiphase Flow, 1(4), pp 537-554.

MAXWELL J. C., (1881), A Treatise on Electricity and Magnetism, (Oxford: Clarendon Press).

RAMSKILL N. P. AND WANG M., (2011), Boolean Logic Analysis for Flow Regime Recognition of Gas-liquid Horizontal Flow, Meas. Sci. Technol., 22, 1-9.

SPEDDING P. L. AND SPECE D. R., (1993), Flow regimes in two-phase gas-liquid flow. Int. J. Multiphase Flow, 19, pp 245–280.

TAITEL Y. AND DUKLER A. E., (1976), A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow, AIChE Journal, 22, pp 47-55.

WANG M., JIA J., FARAJ Y., WANG Q., XIE C., ODDIE G., PRIMROSE K., QUI C., (2015), A new visualisation and measurement technology for water continuous multiphase Flows. Flow Measurement and Instrumentation, 46(Part B), pp. 204-212

WU Y., LI H., WANG M. AND WILLIAMS R. A., (2005) Characterization of air-water two-phase vertical flow by using electrical resistance imaging, Can. J. Chem. Eng. 83, pp 37–41.