Proceedings Paper:
Wang, Q, Polansky, J, Wang, M et al. (2016) Experimental Evaluation of Dual-Modality Electrical Tomographic Systems on Gas-Oil-Water Flow 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: 978 0 853 16349 7. ISSN: 2309-3870.

Experimental Evaluation of Dual-Modality Electrical Tomographic Systems on Gas-Oil-Water Flow in Horizontal Pipeline

Qiang Wang[1], Jiri Polansky[1], Mi Wang[1], Kent Wei[2], Changhua Qiu[2], Asaad Kenbar[3], and David Millington[3]

[1] University of Leeds, Leeds LS2 9JT, UK

[2] Industrial Tomography System plc, Manchester M3 3JZ, UK

[3] NEL, Glasgow, G75 0QF, UK

E-mail: m.wang@leeds.ac.uk

ABSTRACT

A variety of dual-modality tomographic systems have been proposed for the characterisation of multiphase flow, but the evaluation of such systems are generally carried out under simplified flow conditions, such as stratified flow and slug flow. This paper reports the evaluation results of a dual-modality electrical tomographic system in an industry-scale gas-oil-water three-phase flow. Experimental conditions include water-to-liquid ratio (WLR) from 0% to 100% in parallel with gas volume fractions from 0% to 100%, which produces a variety of flow patterns, such as stratified-wavy flow, slug flow, plug flow, bubbly flow, and annular flow. Commercialised ITS M3C (ECT) and V5R (ERT) dual-modality systems were applied to perform the measurement. A threshold-based multi-dimensional data fused approach was implemented for the data fusion process. The results demonstrated that the ERT system is able to measure water continuous flow with WLR higher than 40%, which is in good agreement with previous reports. The ECT system is able to measure from 0% to 100% WLR, far beyond its conventional capabilities. Even though the tomograms are distorted when WLR is higher than 90%, this result is much better than the reported 40% limit. Visualisation and mean concentration derived from the tomograms by advanced data fusion verify the capability of the system in the application of gas-oil-water flow characterisation.

Keywords electrical resistance tomography (ERT), electrical capacitance tomography (ECT), dual-modality tomographic system, gas-oil-water flow visualisation, multi-dimensional data fusion

1 INTRODUCTION

In order to provide insights into gas-oil-water flow, many techniques have been commercially applied and scientifically proposed in the past few decades (Thorn et al., 2012), where multi-modality tomographic systems has proved to be effective in several multiphase flow applications, with the advantages of being low cost, non-intrusive/invasive, and robust. (Qiu et al., 2007, York et al., 2011, Wang et al., 2015). In principle, multi-modality tomographic systems integrate different modalities of tomography to overcome the incapability of single-modality tomographic systems when more than two components are engaged in the investigated flow. They usually distinguish different phases or phase combinations by each modality, and later perform data fusion based on the results from both modalities. So far, a variety of multi-modality tomographic systems, beyond ERT-ECT systems, have been suggested for the purpose of three-phase flow measurement and visualisation, such as ECT and gamma-ray tomography (Hjertaker et al., 2011).

Although multi-modality tomographic systems have attracted much attention, they are still at an early stage research and development. Most instruments have not been evaluated thoroughly, where previous the evaluations have been conducted using simulation techniques and simple flow structures, e.g. stratified flow (Qiu et al., 2007, Hjertaker et al., 2011). Although Yue et al. has assessed their ERT-ECT systems for several flow regimes in laboratory-scale flow facilities, for a variety of stratified flow, slug flow, and plug flow, the capability of such systems are still unknown neither for other flow regimes, nor for real-world industrial cases.

This paper reports theoretical and experimental analysis of dual-modality ERT-ECT systems based on the experiments conducted in the industry-scale multiphase flow facility at TUV NEL[1], and further details will be presented at the conference and published elsewhere. The tested flow conditions include WLR from 0% to 100% in parallel with GVF from 0% to 100%, which produces common horizontal flow regimes, including stratified flow, slug flow, plug flow, bubbly flow, and annular flow. The evaluation embraces both qualitative and quantitative outcomes, by means of images and mean concentrations, respectively, which are obtained using the recently developed data fusion approach (Wang et al., 2016). It is worth noting that the quantitative comparison is directly performed between volume fractions by reference values and void fractions by the systems, since the objective of the project was visualisation but not metering.

2 EXPERIMENTAL SETUP

The NEL multiphase flow loop is a three component flow facility featuring oil, water and gas. For measurement purposes, Paraflex (HT9) oil is used alongside substitute salt water Magnesium Sulphate (MgSO4) and a dry gas (Nitrogen) is injected externally via a pressurised storage tank. Each component is measured individually using reference turbine flow meters prior to being combined into a multiphase mixture. After passing through the test section, the multiphase flow is then separated via a gravity separation vessel whereby the oil and water is re-circulated and nitrogen is expelled to atmosphere. A graphical representation of the flow facility is shown in Figure 1. The facility can achieve GVF and WLR ranges from 0 to 100%. The target flow patterns are shown in Figure 2, and selected flow conditions are listed in Table 1, in terms of GVF against liquid flowrate. The testing objectives was to evaluate the functional performance of dual-modality ERT-ECT systems in terms of multiphase flow visualisation. Several reference devices were installed in the test section, and the arrangement of the reference equipment is illustrated in Figure 3. In this experiment, ITS dual-modality systems were employed, including V5R ERT (Jia et al., 2010) system and M3C ECT system (Qiu et al., 2007).

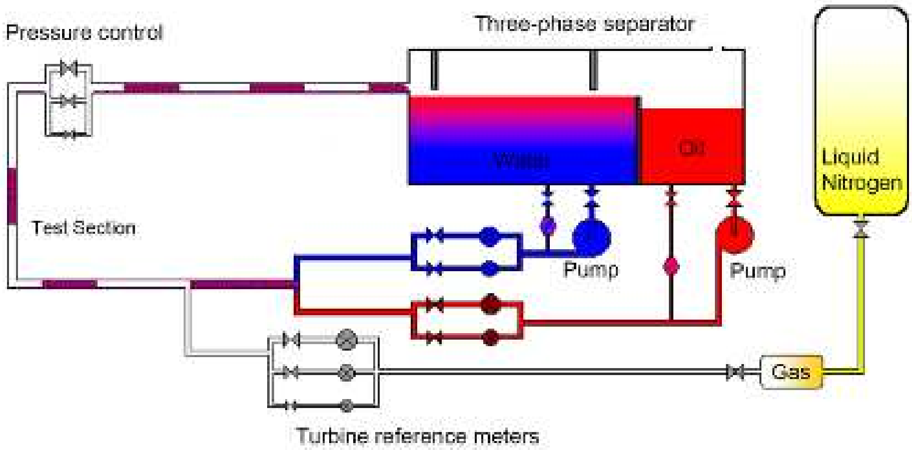

Figure 1: Schematic of NEL multiphase flow facility.

[1] http://www.tuvnel.com

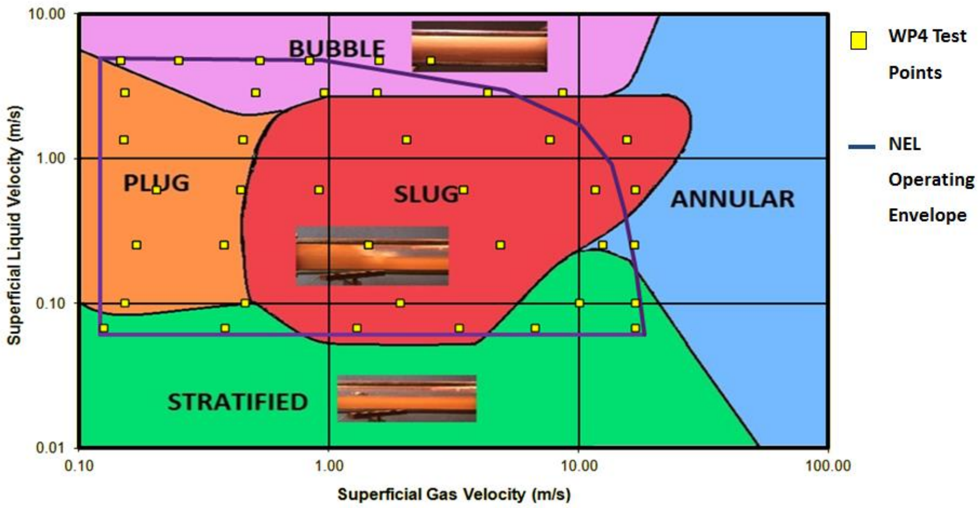

Figure 2: Target flow patterns.

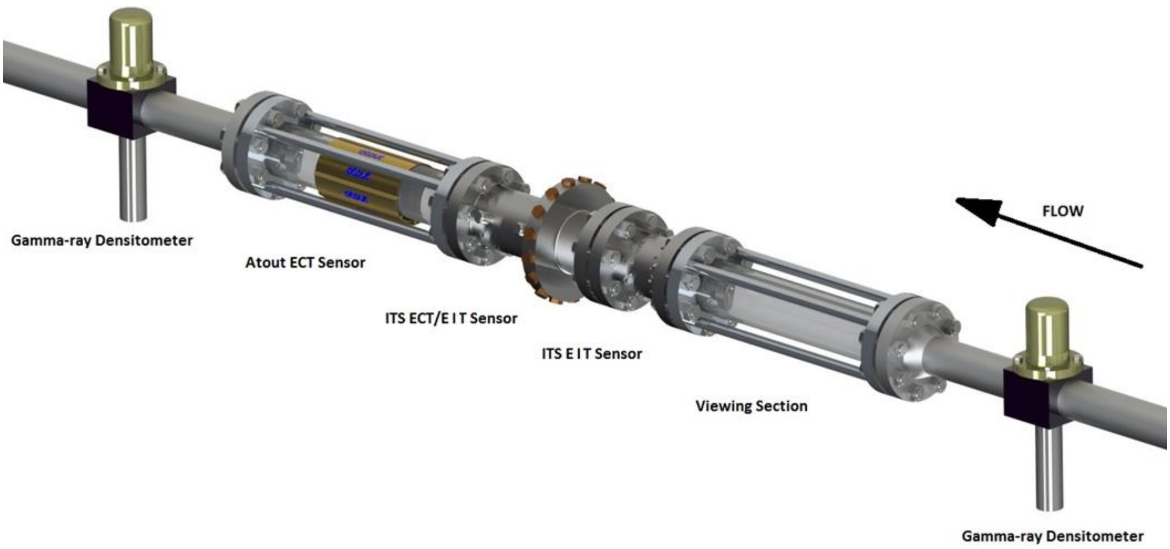

Figure 3: Test section line build schematic.

Table 1: Selected test conditions of liquid flowrate vs GVF.

Liquid flowrate (m^3/hr)	GVF (%)																
	3	5	10	15	25	35	40	42	60	75	82	85	92	95	96.5	98	99
2												x		x		x	99.6
3											x			x			99.4
7.5							x	x				x		x		98.5	x
18					x							x		x	x		
40					x							x	x				
85		x		x	x	x				x	x						
140	x	x	x	x	x	x											

3 EXPERIMENTAL RESULTS

The results are presented in the format of axially-stacked tomograms, along with the images from high-speed video logger as a visual reference, and also mean concentrations of gas and/or water. Due to the considerable amount of flow conditions, only the results at WLR 50% are chosen for the demonstration purpose, and for five common flow conditions, representing different flow regimes, namely stratified flow, slug flow, plug flow, annular flow, and bubbly flow. On the other hand, quantitative results are compared in terms of water and gas mean concentration. The primary objective of the project is visualisation, instead of measurement, of gas-oil-water flow using ERT-ECT systems, volumetric fraction values, i.e. WLR and GVF, are utilised directly as references for mean concentration. For water concentration, three values are presented, including reference values by Equation (1), mean concentration from ERT using Equation (2), and water concentration from data fusion results in (Wang et al., 2016).

$$\overline{\alpha}_w^{ref} = \frac{(100 - GVF) * WLR}{100} \tag{1}$$

$$\overline{\alpha}_w^{ERT} = 100 - \overline{\alpha}^{ref} \tag{2}$$

Where $\overline{\alpha}^{ERT}$ is the mean concentration by ERT. For gas concentration, four results are compared, namely GVF as a reference, mean concentration derived from gamma-ray densitometer, ECT results, and the one based on data fusion results in (Wang et al., 2016). The mixture density by gamma-ray is as below:

$$\rho_m = \rho_g * \alpha_g + \rho_w * \alpha_w + \rho_o * \alpha_o \tag{3}$$

Where ρ_x is the density for each phase or the mixture, and α_x is the volume fraction of each phase. Compared to ρ_w and ρ_o, the ρ_g is so small that it can be ignored. In addition, ρ_w and ρ_o are approximated using density of liquid ρ_l, of which the value is replaced by water density ρ_w. Consequently, Equation (3) is changed to:

$$\rho_m \approx \rho_w * \alpha_l \Rightarrow \alpha_l \approx \frac{\rho_m}{\rho_w} \tag{4}$$

Further, gas volume fraction can be calculated by Equation (5):

$$\alpha_g \approx 1 - \alpha_l = 1 - \frac{\rho_m}{\rho_w} \tag{5}$$

3.2 Water-Liquid-Ratio 50%

There are 28 flow conditions with a 50% WLR. The selected flow conditions are listed in Table 2, and the associated images are presented in Figure 4. Since ERT is fully operational at 50% WLR, the visualisation results are presented using the tomograms by ECT, ERT, and a data fusion approach (Wang et al., 2016), along with the images by high-speed video logger as a reference. Figure 4 illustrates the results. From visualisation perspective, the figures demonstrate a promising capability of the systems for imaging gas-oil-water flow at WLR 50%. There are small deviations from conditions as seen by the reference video logger, as in Figure 4d, where the top liquid film is very thin, ECT fails to detect it, and ERT also unable to recognise its thickness. The system struggles to image bubbly flow in Figure 4e, due to the incapability of both ERT and ECT systems to identify small bubbles. It is worth noting that bubble flow is notoriously difficult to measure for all levels of commercially developed multiphase measurement systems. This limitation has been realised and further work is being conducted to address the inability to display very small features on a tomogram display (Wang et al., 2016).

Figure 5 explains the quantitative results in terms of water and gas concentrations by different approaches. The results provided by ERT-ECT systems show good agreement with reference values providing WLR and GVF. It is also noticeable that the quantities are also in accordance with the visualisation. That is, the deviation of gas concentration from the references becomes significant for bubbly flow, which in turn affects the accuracy of water concentration.

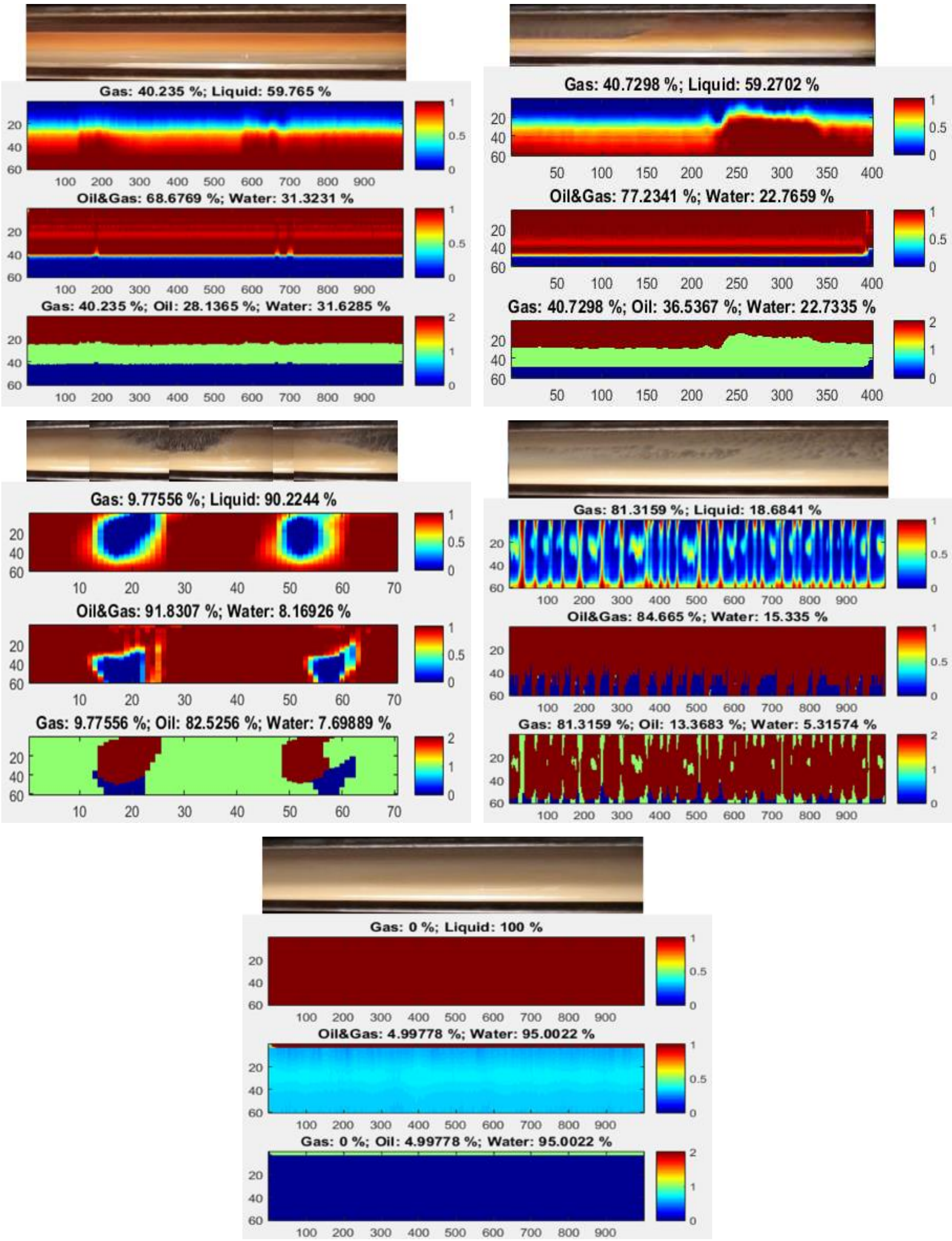

Figure 4: Visualisation results of WLR 50% for (a) stratified flow; (b) slug flow; (c) plug flow; (d) annular flow; and (e) bubbly flow.

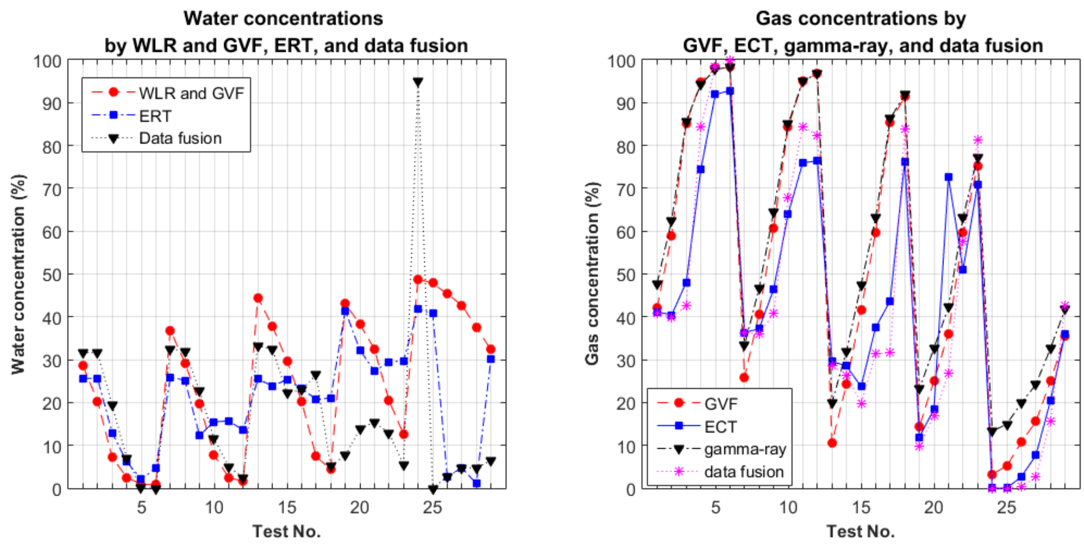

Figure 5: Water and gas concentrations from different approaches at WLR 50%.

Table 2: Selected flow conditions for the visualisation at WLR 90%.

	Qwater (m^3/hr')	*Qoil* (m^3/hr)	*Qgas* (m^3/hr)
Stratified flow	3.790	3.860	10.978
Slug flow	9.031	9.030	27.896
Plug flow	42.520	40.626	27.841
Annular flow	42.451	40.974	254.034
Bubbly flow	70.327	69.061	7.606

4 Discussion and Conclusion

ECT system

The results in previous Section (Section 3) demonstrate the capability of the applied ECT system to visualise multiphase flow in a horizontal pipeline. Compared to the reported suitability of ECT system for the flow with WLR less than 40%, i.e. oil-continuous flow (Li and Yang, 2009), the results clearly prove the capability of the ECT system to at least 90 % WLR, with appropriate taking of reference. When flow structure is relatively simple, i.e. stratified flow and slug flow, and flow is with relatively low or moderate flowrate, i.e. water and oil are not fully mixed, ECT can detect the interface between gas and liquid, with great accuracy. As for annular flow, ECT is still able to image it with certain accuracy. It is also able to detect the thickness change of the top liquid film. Nevertheless, it has to be pointed out that when the thickness is below the resolution of ECT system, the film is undetectable. Moreover, there are some ECT tomograms that depict a strange phenomenon, i.e. some liquid is at the centre of the pipe, which might be caused by the liquid droplets at the centre. As far as bubbly flow is concerned, when gas is fully dispersed in liquid, ECT fails to extract tiny bubbles due to the size is below ECT's resolution, whereas the quantitative results present that gas concentration can be extracted by ECT.

ERT system

For examined WLR values, ERT system has a good agreement with the report (Li and Yang, 2009). That is, it is capable of handling gas-oil-water flow with WLR above 40%, i.e. water-continuous flow. Nonetheless, it was inspected that the applied ERT system was functional to image stratified and slug flow when WLR is at 25%, although the measured quantities had a large discrepancy to the reference values. Within the effective WLR range, ERT produces similar results compared with the ones by ECT. That is, when flow structure is simple and total flowrate is relatively low, the interface between conductive (water) and non-conductive (gas and oil) is clearly addressed. For stratified, slug, and plug flow, the boundaries are quite sharp and reasonable, compared with relating video log; whereas when water and oil are mixed together, the performance of ERT deteriorates. ERT is unable to image the top liquid film for engaged annular flow, due to the limitation of ERT with respect to resolution. It is also noticed that there is an overestimate of the thickness of bottom liquid film, which may result from the disturbance of oil phase since oil phase is supposed to be fully dispersed in water phase for annular flow. Similar to ECT, ERT has no ability to identify dispersed tiny bubbles in bubbly flow, and hence no bubble is shown in ERT tomograms for bubbly flow. But it still presents water concentration even though tiny bubbles disappear in the images.

Dual-modality electrical tomographic systems

On the basis of the performance of ERT and ECT, a general conclusion can be drawn in regard to ERT-ECT systems: dual-modality ERT-ECT systems are an effective method when characterising gas-oil-water horizontal flow of WLR between 40% and 90%. Within this range, single-modality electrical tomography struggles to provide sufficient and accurate flow features, whereas the integrated systems complement the limitations of either system. In contrast, either of single modality in the dual-modality systems will malfunction if WLR is out of range, thereby the systems cannot provide complementary information by fusing the data from each modality.

By applying threshold-based data fusion approach in (Wang et al., 2016), individual phases are distinguished, and therefore visualised using different colours. In principle, the gas concentration by the fusion is determined by ECT result, whereas the water concentration by the fusion depends on ERT results. In consequence, the accuracy of the data fusion relies on the resolution of ECT and ERT. When total flowrate is relatively low, i.e. stratified flow and slug flow, both qualification and quantification are in great agreement with references. In contrast, the performance of data fusion deteriorates when either of modality cannot perform well, especially in terms of visualisation. A typical example is bubbly flow, in which both ERT and ECT are incapable of locate tiny bubbles, and hence the fused images provide little clues about tiny bubbles, although concentration information is presented.

Overall, the application of dual-modality electrical tomography results in more accurate quantities of phase concentrations within its functional range, compared to that of each single modality. However, it is also noted that at some extreme conditions, e.g. bubbly flow, data fusion results are not as good as those by individual modality. As for gas concentration, the results by data fusion outperforms that by ECT alone, except on bubbly flow. This is essentially because of the limit of ECT in this flow. On the other hand, the comparisons of water concentrations by different approaches indicate that ERT results are not always as good as expected, especially at lower WLR, which reflects the negative effect of oil phase as an additional non-conductive phase on ERT. The quantities, however, become better after data fusion, despite there being extreme cases where ERT outperforms data fusion, such as bubbly flow.

Despite the error caused by above data fusion, however, it is worth noting that measurement uncertainty plays an important role. The measurement uncertainty mainly comes from two sources: one is systematic error, and the other is random noise. It is usually believed that about 5% of systematic error comes from hardware (Wang et al., 1999), which could be introduced by the imprecision of sensing electronics and A/D conversion, improper compensation to temperature and/or ionic concentration changes, etc., and also the artificial error from imaging reconstruction. Consequently, ERT-ECT systems could introduce up to 10% systematic error. Random noise, on the other hand, is generally as the consequence of uncontrollable and unrepeatable factors, such as the flow instability, electricity crosstalk, and so on. The uncertainty due to random noise could be 5%, but can be reduced with the cost of creasing sampling number. Together the potential systematic error with the random noise, the final uncertainty of the measurements could be up to 10-15%.

Future work

Despite the advantages, there still have some aspects to be addressed in the future. First of all, further experiments should be carried out to make the evaluation more thorough. For example, WLR between 30% and 50% should be covered to determine the lower bound of the effective range for the systems. Moreover, cross-correlation method should be applied to quantify the flowrate of each phase, so that the comparisons with GVF and WLR are more meaningful and accurate. The quantification of velocity would also contribute to study slip characteristics between each phase. Since the performance of ERT-ECT systems totally depend on the tomograms by each individual modality. The systems utilised in this study have low resolution due to the application of single-step linear back-projection (LBP) (Kotre, 1994), advanced iterative reconstruction algorithms could be applied to improve the resolution of the tomograms, which in turn improves the final results, especially as the data-processing speeds develop over time. Last but not least is the improvement of the data fusion methodology, although a threshold-based approach is effective, few efforts have made on a comprehensive evaluation of the impact of the selected threshold values on the final fused results. In addition, advanced fusion algorithms requires more computational power. Data fusion may mature into a process that can support the development, operation and optimisation of multiphase flow measurement technology.

Acknowledgments

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

CORNELIUSSEN, S., COUPUT, J.-P., DAHL, E., DYKESTEEN, E., FRYSA, K.-E., MALDE, E., MOESTUE, H., MOKSNES, P. O., AND LEX SCHEERS, H. T. (2005). Handbook of multiphase flow metering.

HJERTAKER, B., MAAD, R., AND JOHANSEN, G. A. (2011). Dual-mode capacitance and gamma-ray tomography using the landweber reconstruction algorithm. Measurement Science and Technology, 22(10):104002.

JIA, J., WANG, M., SCHLABERG, H. I., AND LI, H. (2010). A novel tomographic sensing system for high electrically conductive multiphase flow measurement. Flow Measurement and Instrumentation, 21(3):184 - 190. Special Issue: Validation and Data Fusion for Process Tomographic Flow Measurements.

KOTRE, C. J. (1994). Eit image reconstruction using sensitivity weighted filtered back-projection. Physiological Measurement, 15(2A):A125.

LI, Y. AND YANG, W. (2009). Measurement of multi-phase distribution using an integrated dual-modality sensor. In Imaging Systems and Techniques, 2009. IST '09. IEEE International Workshop on, pages 335-339.

QIU, C., HOYLE, B., AND PODD, F. (2007). Engineering and application of a dual-modality process tomography system. Flow Measurement and Instrumentation, 18(56):247 - 254. Process Tomography and Flow Visualization.

THORN, R., JOHANSEN, G., AND HJERTAKER, B. (2012). Three-phase flow measurement in the petroleum industry. Measurement Science and Technology, 24(1):012003.

WANG, M., DICKIN, F.J. and MANN, R. (1999) 'ELECTRICAL RESISTANCE TOMOGRAPHIC SENSING SYSTEMS FOR INDUSTRIAL APPLICATIONS', Chemical Engineering Communications, 175(1), pp. 49–70.

WANG, Q., JIA, X,. Wang, M. (2016). Bubble Mapping: A Novel Approach for Three-Dimensional Visualisation of Gas-Liquid Flow by Electrical Tomography. International Journal of Multiphase Flow. Submitted.

WANG, Q., WANG, M., WEI, K., AND QIU, C. (2016). Visualisation of gas-oil- water flow in horizontal pipeline using dual-modality electrical tomographic system. Measurement Science and Technology. Submitted.

YORK, T., MCCANN, H., AND OZANYAN, K. B. (2011). Agile sensing systems for tomography. IEEE Sensors Journal, 11(12):3086-3105.