Multimodal Tomometry for Slug Detection in two Phase Flow

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ABSTRACT

Electrical Capacitance and Resistance Tomometric (ECTm/ ERTm) approaches are attractive for measurement and control applications in the process industries. By using the time series of raw resistance and capacitance values R(i,j,t) and C(i,j,t) ($i=1, \ldots, N_R$, $j = 1, 2, \ldots, N_R$ and $i \neq j$ for ERT modules with N_R electrodes; $i=1, \ldots, N_C$, $j = 1, 2, \ldots, N_C$ and $i \neq j$ for ECT modules with N_C electrodes), it is shown in this paper (with $N_R=16, N_C=12$) how the intermittent occurrence of slugs in a liquid/gas two phase flow can be detected using the time series data consisting of the measured resistances and capacitances R(i,j,t) and C(i,j,t). In a pipe transporting oil and gas, the slugs can be characterized by their sizes, occurring instants and frequencies. The signal processing employed to estimate these parameters associated with the slugs is based on the analysis of the pulse generated from the ECT/ERT module, both in time and frequency domains. Some measurements are also performed using high speed camera, thus making this effort multimodal. Due to the very much reduced estimation times involved in this process as compared to tomographic image processing, this tomometric method has many advantages in real time measurement and control applications. Signal processing of the volume ratio data of tomography systems and image analysis of high speed camera images can be done to extract various slug parameters. Slug length, velocity and frequency in a slightly inclined upward two phase water/air flow are estimated using fusion of data from the multimodal system. The results obtained are compared to verify the various parameters estimated using different modalities.

Keywords: ERTm, Slug parameters, oil and gas flow, cross-correlation, power spectral density, ECT, ERT

1 MOTIVATION

Electrical Capacitance/ Resistance Tomography (ECT/ERT) is gaining ground in industrial multiphase flow metering (Ismail et al 2005). Some key industrial actors in the oil and gas industries have ECT/ERT systems in their test facilities. In conjunction with multiphase flow metering, the identification of the regions of different phases and hence the flow regimes, is an important application of ECT/ERT. This paper focuses on the detection of slugs very often found in multiphase flow using ECT/ERT. When the slug passes the sensor head containing the resistance/capacitance sensors, a characteristic pulse is formed showing the spatial variations of resistivity or permittivity, given by the raw capacitance/resistance values *C*(*i,j,t*) and *R(i,j,,t)*. Many parameters characterizing the slug can be obtained by studying the characteristic pulse associated with the slug in frequency and time domains.

Slugs in multi-phase flow can lead to hazardous situations involving pressure build-up and blow out as was the case on Deepwater Horizon platform in the Mexican Gulf. Timely detection of slug formation can help the operators in preventing such disasters. Tomometric methods may well be suited for such applications. From raw resistance/capacitance data, sensor level fusion can be performed using inferential methods involving such as fuzzy-logic or neural network based algorithms. Fusion at a higher level leading to features easily assignable to slugs can also be advantageous, but this might need longer time to process. This paper deals with sensor level fusion and addresses some aspects of feature level fusion using inferential methods.

2 MULTIPHASE FLOW FACILITY

A schematic diagram of the multiphase flow facility used for the generation of slug flow is shown in Figure 1. The test section consists of 15m long pipe of 56mm internal diameter with flow meters to monitor water and air flow at the inlet and some pressure and temperature sensors. The ECT/ERT systems are placed about 13 m from the inlet. Pipe inclination is maintained at +1 degree with the horizontal. The outlet pressure is atmospheric due to the storing of the fluids at the outlet in an open tank.

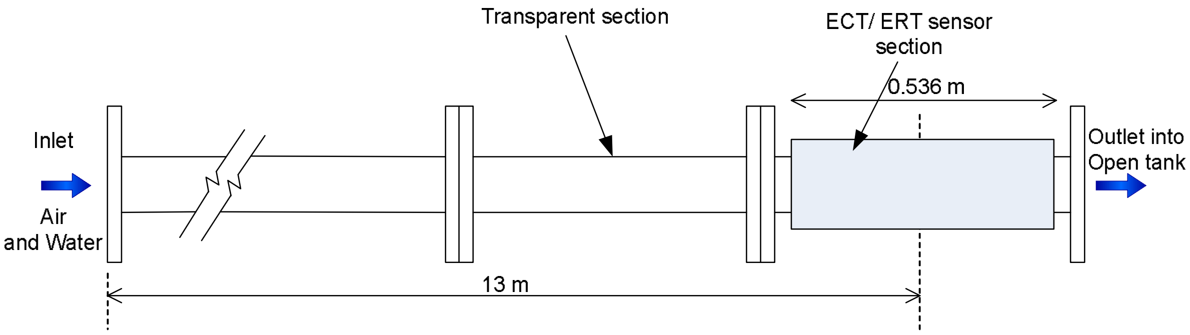


Figure 1. Schematic diagram of the test section with ECT/ERT system

Inter-electrode capacitance and resistance measurements were recorded separately using ECT and ERT systems with the flow loop running under a selected set of inlet conditions. The ECT system used for these experiments is PTL300E. It is capable of measuring up to 100 data frames per second. The current pulse ERT system (Randall et al 2004) developed by the UCT (University of Cape Town) was used and resistance data were acquired at 37 frames per second in the experiments.

A MotionPRO X Digital camera is used to obtain detailed data regarding slug characteristics such as slug frequency, slug lengths and the height of the liquid film. The capture rate used was 40 frames per second.

3 EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

In a typical ERT application, the first set of results are the raw resistance, as well known comprising of $(N_R(N_R\text{-}3)/2)$ measurements for an ERT system with N_R-electrodes using the pulsed current mode of excitation (Daily et al 2000). A schematic of the ERT module is shown in Figure 2. These values are usually processed using rather time consuming algorithms to generate images, called tomograms in the context of process tomography. By focusing on the ERT signal train (shown in Figure 3) obtained during the transit of the slug past the ERT system, and employing signal processing of the pulse generated at the ERT electrodes, we can estimate various parameters associated with this particular slug.

Experiments were performed maintaining volumetric flow rate of water at the inlet of the testing unit at 30kg/min (hence superficial velocity 0.2m/s) while the air flow rate was increased from 0.05 kg/min to 0.5 kg/min in 0.05 kg/min steps (superficial velocity from 0.28m/s to 2.78 m/s). Inclination of 56 mm diameter test pipe was +1◦ to the horizontal plane. Separate ERT, ECT sensors and a high speed camera were also used as indicated in Figure 2.

3.1 Slug velocity

Time series of volume ratio data obtained from twin plane capacitance and resistance sensors were cross-correlated to calculate slug velocity. Figure 2 illustrates how both sensor planes capture the slug flow, assumed to have not undergone any change considerably due to the short distances between the twin planes for ERT and ECT sensors. The time delays between the two signals from the two sets of ERT and ECT sensors are calculated using cross-correlation of signals (Ahmed 2011) as given in equation (1). If $S_{pl_1}(t)$ and $S_{pl_2}(t+\tau)$ are the signals at the sensor planes 1 and 2 at time instant t and $t+\tau$ respectively, then the typical cross-correlation function $\rho_{S_{pl_1}(t),S_{pl_2}(t+\tau)}(\tau)$ is defined by the following equation (Datta 2007):

$$\rho_{S_{pl_1}S_{pl_2}} = \lim_{T\to\infty}\frac{1}{T}\int_0^T S_{pl_1}(t)S_{pl_2}(t-\tau)dt \qquad (1)$$

The time delay τ_{max} corresponding to the maximum value of cross-correlation function gives the transit time of the flow between the two sensors. From the estimate of cross-correlation as given in equation (1), the time delay τ_{max} can be found by finding the correlation peak. Using the time delay τ_{max} and distance L between the two sensor planes, the axial slug velocity, V_s can be evaluated as:

$$V_s = \frac{L}{\tau_{max}} \tag{2}$$

Both ECT and ERT measurements were used in the estimation of the slug velocity. Measured row capacitance and resistance measurements were correlated separately. Flowan software developed by Process Tomography Limited was used to estimate the slug velocities for verifying the results. Flowan software uses pixel correlation for velocity estimation.

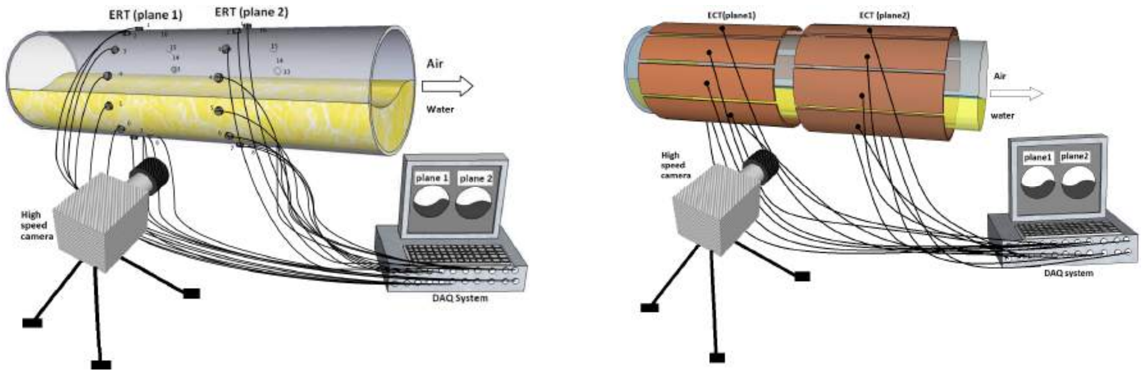


Figure 2. Resistance and Capacitance sensors on the periphery of a pipe distributed in two different planes with water and air delivering capacitance values *C(i,j,t)* with *i= 1, 2, ..12, j=1, 2, …12* and resistance values *R(i,j,t)* with *i= 1, 2, ..16, j=1, 2, …16* in this case

3.2 Slug frequency

Counting the number of slugs moving past these two sets of sensors placed in the two different planes pl_1 and pl_2 within the observation period can be used to calculate the slug frequency as given in equation (3). A threshold value has to be defined to decide the existence of slug (Al-Lababidi 2006).

$$f_s = \frac{n_s}{T} \tag{3}$$

Where f_s is the slug frequency, n_s is the number of slugs passed during the observation period T .
Average of the ECT/ERT measurement signals was used. The averaging process helps to identify the boundaries of the slug bodies. Images captured from the high speed camera were also run frame by frame to count the number of slugs to verify the results.

3.3 Mean Slug body length

As indicated in Figure 3, time window t_s associated with the slug body is calculated. Then with the estimated slug flow velocity, each slug length L_s can be calculated.

$$L_s = t_s V_s \tag{4}$$

The threshold selected in the algorithm used in the slug frequency calculation is used here to find the time window of the slug body. Typical slug front and tail images produced by the High speed camera, are shown in Figure 4. ECT and ERT signals used in the analysis of slug frequency are shown here to see some clear boundaries of slug fronts and tails.

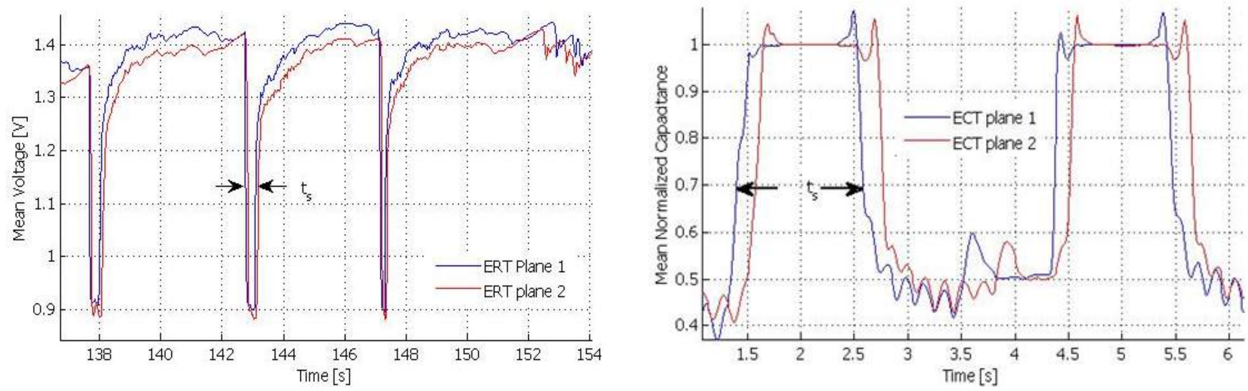
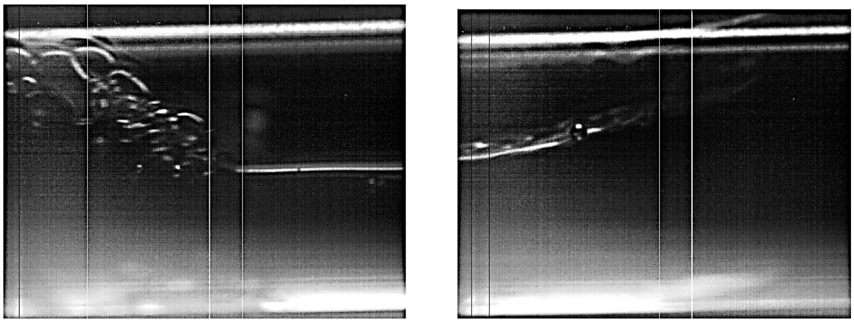


Figure 3. Typical Slug pulse as obtained from ERT and ECT time sequences



(a) (b)

Figure 4. Images of slug front (a) and tail (b). Bottom part of the slug is water and top part air.

4 RESULTS

Estimates of slug velocity, slug frequency and slug length are given in Figures 5, 6 and 7. It can be seen in Figure 5, that all three curves show an increase in slug velocities with increasing superficial gas velocities. Compared to the ECT and Flowan based calculations, ERT measurements show an increase of slug velocity about 0.1m/s at 0.8 m/s superficial gas velocity and decrease of about 0.13 m/s at superficial gas velocity 1.1 m/s. At superficial air velocity 2.2 m/s the highest velocity difference of 0.35 m/s is observed.
To see whether these estimation differences are due to different data capturing rates of ECT and ERT systems, uncertainty of the slug velocities due to the data capturing rate of each ECT and ERT systems were tested. There is $\pm$ 0.005 s uncertainty to the time delay, τ_{max} in the ECT, since its data capturing rate is 100 frames per seconds. The corresponding uncertainty associated with ERT is $\pm$ 0.013 s.

When τ_{max} increases, slug flow velocity decreases and hence uncertainties of the calculated slug velocities also decrease. When the time delay τ_{max} decreases, slug velocity and uncertainty increase. Figure 8 shows the uncertainty increase in the velocity range considered of this work. This may be one of the reasons for higher velocity estimates resulting from ERT data.

Slug frequency decreases when the superficial gas velocity increases as explained by Kang et al (1999). Results show slight decrease in slug frequency. It can be easily seen that results based on the image data are showing higher slug frequencies compared to the ECT and ERT based calculations even though they follow similar trends. An offset of about +0.05 Hz is observed compared to the other ECT/ERT based calculations. Limitations in the memory storages in the camera restrict the possibilities of capturing data to 40s. The increase of one slug increases the slug frequency by 0.025 Hz due to the limited observation time period. The ECT and ERT measurements were made for 4 min. Maximum difference in frequency calculations between ECT and ERT is about 0.01 Hz at superficial air velocity of 1.1 m/s.

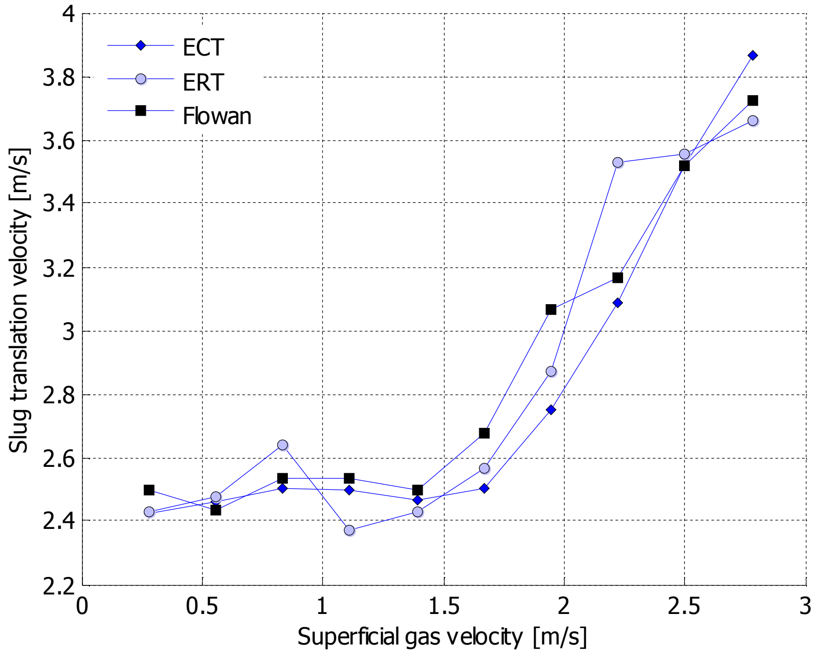


Figure 5. Slug velocity with water superficial velocity at 0.2 m/s

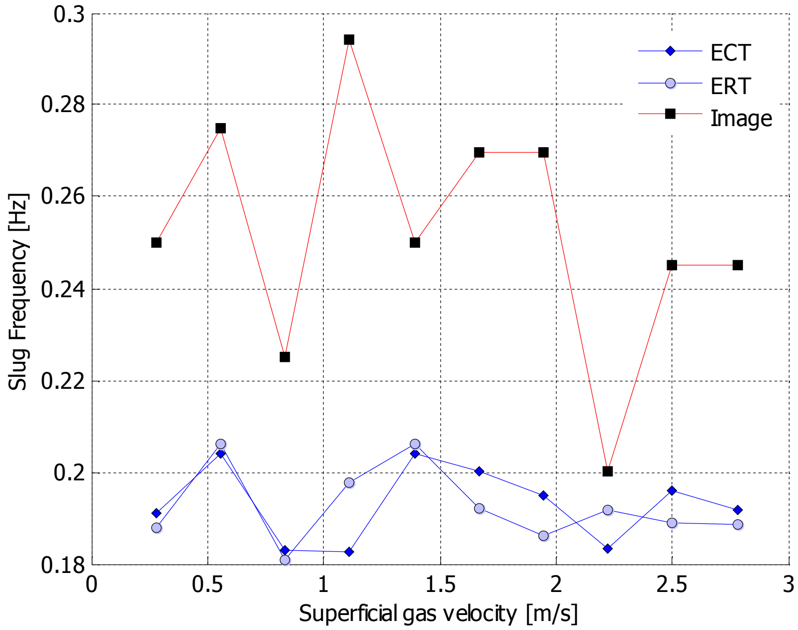


Figure 6. Slug Frequency with water superficial velocity at 0.2 m/s

Slug length calculations were made using equation (4) and calculated velocities given in Figure 5. Lower gas velocities should result in a shorter slug but higher gas velocities should show increases in slug length as explained by Cai et al (1999). All 3 curves in Figure 7, show decrease in slug lengths with increase in superficial water velocities. At superficial gas velocity 2.2 m/s, image data based calculation gives 1.7m for the mean slug length. Difficulties involved in estimating exact time window of the slug is one of the reasons for the variations in image based approach. The slug velocity V_s used in the calculation was from the ERT system and it might also be the reason for getting some higher and lower slug length values. To see whether the trend observed exists with different flow conditions, another two sets of experiments were performed varying superficial water velocities to 0.27m/s and 0.33 m/s. Results after the ECT measurement based calculations are given in Figure 9. It can be seen clearly in Figure 9 that the mean slug length decreases with increase in superficial gas velocity.

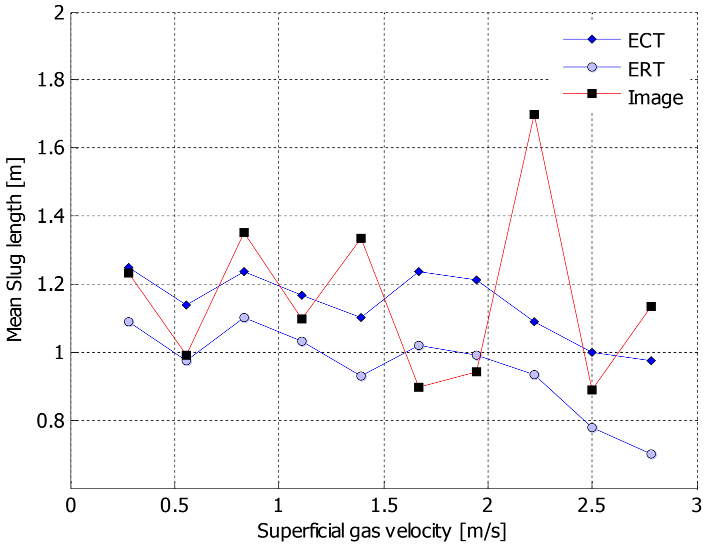


Figure 7. Slug Length with water superficial velocity at 0.2 m/s

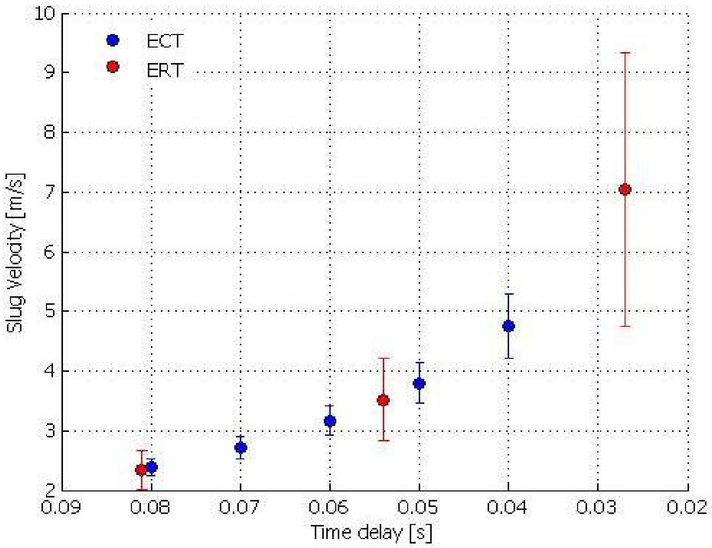


Figure 8. Estimated uncertainties for different slug velocities

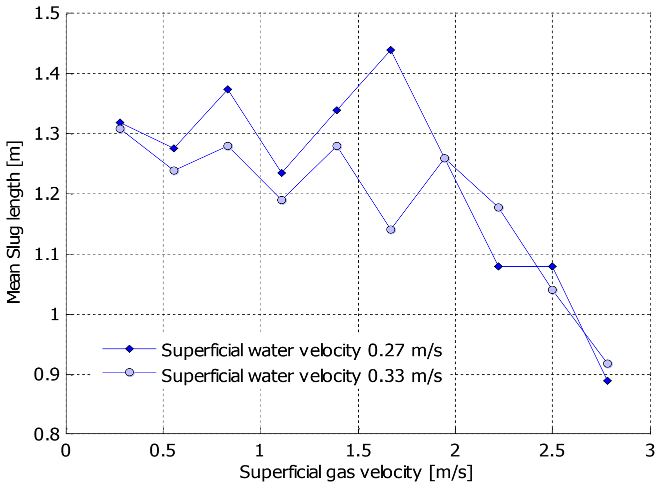


Figure 9. Slug Length for varying superficial gas velocities at superficial water velocity 0.27 m/s and 0.33 m/s

4.1 Variations in Velocities in cross-sectional area

Correlations between corresponding inter-electrode measurements of ERT signals were performed to see the possibilities of observing the velocity variations in the pipe cross-section. Figure 10 shows some selected combinations of electrodes to see the effects of flow regime on capacitance values. As given in Figure 11 correlations based on the electrode combinations $E_1E_2 - E_3E_4$, $E_1E_2 - E_{10}E_{11}$, $E_1E_2 - E_1E_{16}$, $E_2E_3 - E_5E_6$, $E_2E_3 - E_1E_{16}$, $E_4E_5 - E_{14}E_{15}$ and $E_5E_6 - E_{14}E_{15}$ give the slug velocity as 7 m/s. Since some of the combinations of electrodes given above, cover a larger sensing area of the pipe section, these particular combinations may lead to better estimates of the velocity and its variations. Not all combinations are sensitive to velocity variations, although they all give the average velocity as 3.5m/s.

The combinations $E_2E_3 - E_6E_7$, $E_3E_4 - E_7E_8$ and $E_4E_5 - E_7E_8$ covering the pipe bottom give an estimate of 2.3 m/s velocity.

Figure 11 shows only 3 different velocities from all different combinations. These 3 velocities are the same velocities discussed Figure 8.

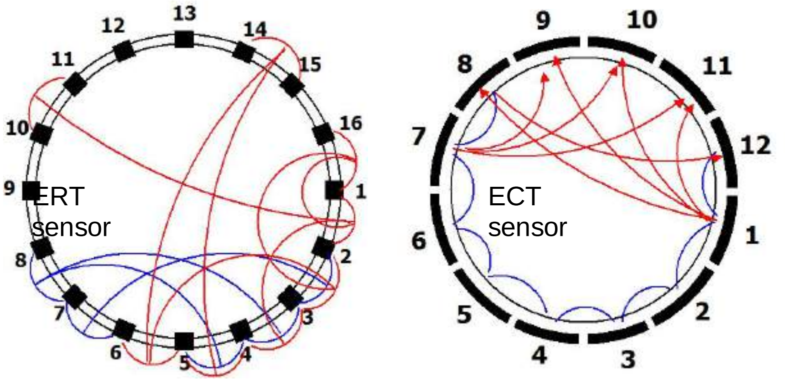


Figure 10. Electrode arrangements of ERT and ECT sensors

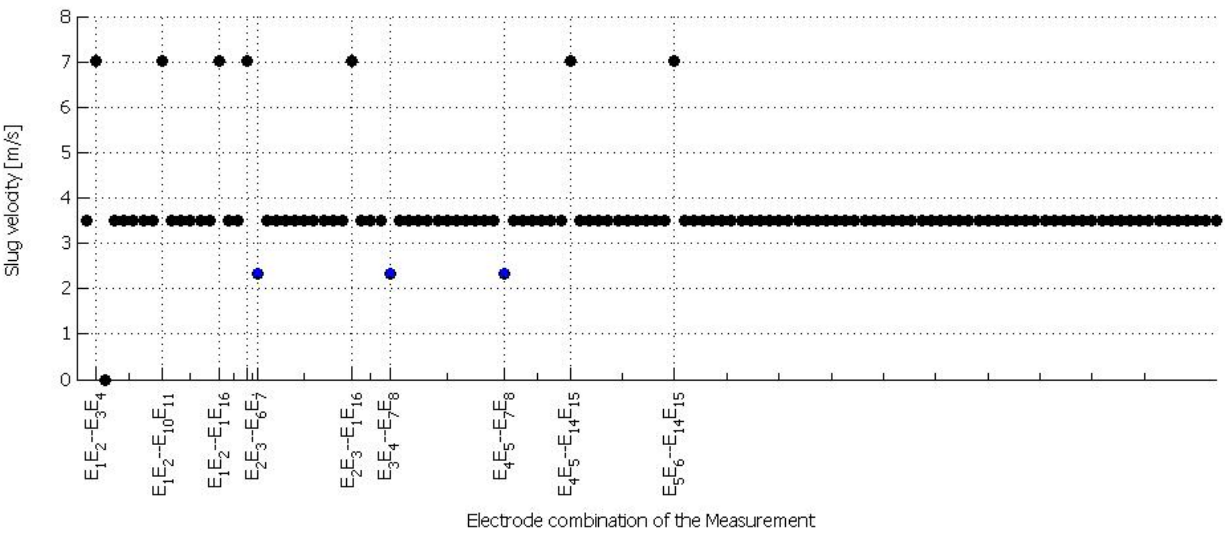


Figure 11. Slug velocities with cross-correlation of individual ERT measurements at superficial gas and water velocities 2.78 m/s and 0.2 m/s

Figure 12 shows the slug velocities obtained with ECT measurements. Correlation measurement of signals of the capacitance values $C_{1,8}$, $C_{1,9}$, $C_{1,10}$, $C_{1,11}$, $C_{7,9}$, $C_{7,10}$, $C_{7,11}$ and $C_{8,12}$ *at both planes,* give the estimated velocity as 4.7m/s. These combinations are from the top half of the sensor and cover a larger area of the medium air, i.e. the top part as shown in Figure 4. Signals of adjacent electrode combinations $C_{1,2}$, $C_{1,12}$, $C_{2,3}$, $C_{3,4}$, $C_{4,5}$, $C_{5,6}$, $C_{6,7}$ and $C_{7,8}$ show lower slug velocities (most of them are around 3.1 m/s). Most of these combinations are from the bottom half of the pipe. The ECT results give better estimates of the slug velocities compared to those estimated using the ERT data.

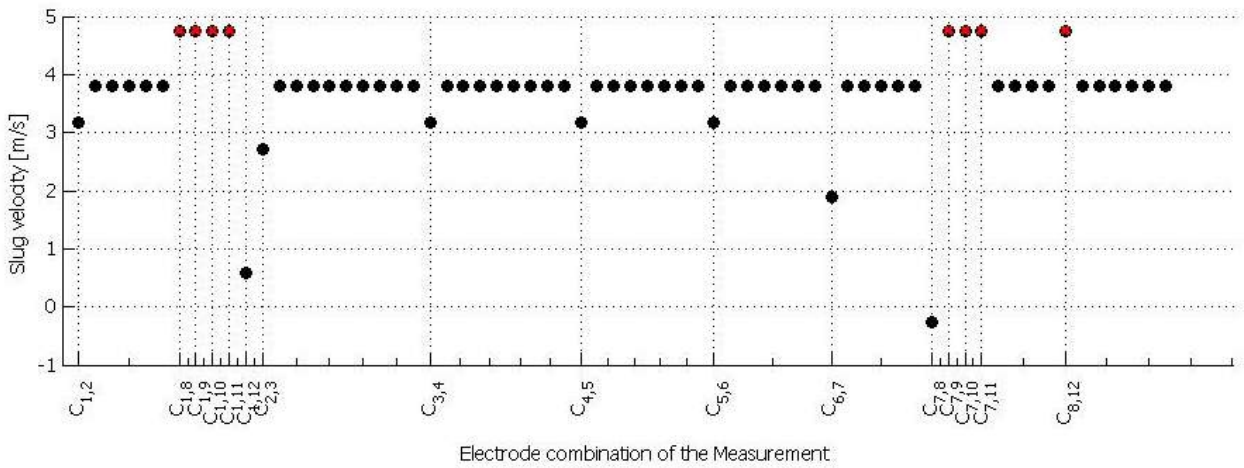


Figure 12. Slug velocities with cross-correlation of ECT measurements at superficial gas and water velocities 2.78 m/s and 0.2 m/s. The capacitance values indicated on the axis refer to the respective electrode combinations on plane 1 and plane 2.

5 CONCLUSION

The study presented here compares the estimates of the following parameters for a two phase air/water flow: slug frequency, slug length, slug velocity and some information on velocity distribution across the pipe section. For the estimation a data fusion methodology based on cross-correlation of inter-electrode resistance/capacitance values from ERT and ECT systems is used. From the estimates thus obtained, uncertainty of the slug velocity is also calculated. Some parameters are verified using high speed camera. These results show that the trend is the same for the slug parameters calculated as functions of superficial air velocities. Increasing frame rates of both ECT/ERT systems and simultaneous capturing of the raw resistance and capacitance values may improve the quality of all the estimates.

6 NOMENCLATURE

N_R	Number of electrodes in ERT sensor	t_s	Time window of the slug (s)
N_C	Number of electrodes in ECT sensor	T	Observation time period (s)
M	Number of measurements per frame	τ_{max}	Time delay at correlation peak
S	Signal	L	Distance between two sensors (m)
pl_i	Plane i	$\rho_{S_{pl_1}S_{pl_2}}$	Cross-correlation function of signals from 1st and 2nd planes
τ	Time delay (s)	$C_{i,j}$	Capacitance between i th and j th electrode
V_s	Slug velocity (m/s)	$E_iE_j - E_kE_l$	Voltage measurement between k and l Electrodes when i and j electrodes are used for injecting the current (ERT)
n_s	Number of slugs		
f_s	Slug frequency (Hz)	ERT	Electrical Resistance Tomography
L_s	Slug length (m)	ECT	Electrical Capacitance tomography

7 ACKNOWLEDGEMENT

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8 REFERENCES

ISMAIL I., GAMIO J. C., BUKHARI S. F. A., YANG W. Q. (2005) Tomography for multi-phase flow measurement in the oil industry, *Flow Measurement and Instrumentation*., 16(2011), 145-155.

AHMED W.H., (2011), Experimental investigation of Air-oil slug flow using capacitance probes, hot-film anemometer and image processing, *International Journal of Multiphase Flow*., 37(2011), 876-887

KANG C., JEPSON W.P., GOPAL M., (1999) 'Effect of Drag-Reducting Agent on slug characteristics in Multiphase flow in inclined pipes', Journal of Energy Resources Technology. Vol. 121.

Al-LABABIDI S., (2006), *Multiphase Flow Measurement in the Slug Regime Using Ultrasonic Measurements Techniques and Slug Closure Model*, Thesis submitted to the Cranfield University for the degree of philosophiae doctor, UK.

RANDALL E. W., WILKINSON A. J., LONG T. M., SUTHERLAND A. (2004), A high speed current pulse electrical resistance tomography system for dynamic process monitoring., Proceedings of 7th Biennial ASME Engineering Systems Design and Analysis., Manchester, UK.

DAILY, W., RAMIREZ A., NEWMARK R., GEORGE V., RANDALL J., (2000) 'Imaging UXO Using Electrical Impedance Tomography', in Proceedings for SAGEEP, Washington D.C., pp793, 2000

DATTA U., (2007) *Multimodal Measurements in Dilute Phase Pneumatic Conveying Systems*, Telemark University College, Thesis submitted to the NTNU for the Degree of philosophiae doctor, Norway.

CAI J.Y., WANG H.W., HONG T., JEPSON W.P., (1999) Slug frequency and length inclined large diameter multiphase pipeline. Multiphase flow and heat transfer proceeding of Fourth International Symposium. China.