Electrical Capacitance Tomography (ECT) and Gamma Radiation Meter for Comparison with and Validation and Tuning of CFD Modeling of Multiphase Flow

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***Abstract*—Electrical Capacitance Tomographic (ECT) approach is increasingly seen as attractive for measurement and control applications in the process industries. Recently, there is an increased interest in using the tomographic details from ECT for comparing with and validating and tuning CFD models of multiphase flow. Collaboration with researchers working in the field of CFD modeling of multiphase flows give valuable information for both groups of researchers in the field of ECT and CFD. By studying the ECT tomograms of multiphase flows under carefully monitored inflow conditions of the different media and by obtaining the capacitance values, C(*i,j,t*) with *i*=1 …N, *j*= 1,2, …N and $i \neq j$ obtained from ECT modules with N electrodes, it is shown in this paper how the interface heights in a pipe with stratified flow of oil and air can be fruitfully compared to the values of these obtained from ECT and gamma radiation meter (GRM) for improving CFD modeling. Monitored inflow conditions in the present study are flow rates of air, water and oil into a pipe which can be positioned at varying inclinations to the horizontal, thus emulating the pipelines laid in subsea installations. It is found that ECT based tomograms show most of the features seen in the GRM based visualizations with nearly one-to-one correspondence to interface heights obtained from these two methods, albeit some anomalies at the pipe wall. However, there are some interesting features the ECT manages to capture, features which the GRM or the CFD modeling apparently do not show possibly due to parameters not defined in the inputs to the CFD model or much slower response of the GRM. Results presented in this paper, indicate that a combination of ECT and GRM and preferably other sensor modalities with enhanced data fusion and analysis combined with CFD modeling can help to improve the modeling, measurement and control of multiphase flow in the oil and gas industries and in the process industries in general.**

Keywords- ECT, Multiphase flow, GRM, CFD, model validation and tuning, data fusion Introduction

I. Motivation

Electrical Capacitance Tomography (ECT) is gaining ground in industrial multiphase flow metering. Some key industrial actors in the oil and gas industries have ECT systems in their test facilities. In conjunction with multiphase flow metering, the identification of the regions of different phases with their associated pixels is one of the crucial stages in the ECT based measurements. Possibilities of ECT in interface estimation applications are explained in [1], [2] and [3]. Combined ECT and acoustic measurements in identifications in three phase flows are explained in [4]. This paper focuses on the interface behavior in multiphase flow as the necessary preamble for flow velocity and volume fraction calculations, which are typical parameters of interest in multiphase flow metering. The interface heights are measured and compared and then used to validate CFD models, which can be tuned to reflect the features detected by these two sensor modalities.

II. Measurement Systems

A. Electrical Capacitance Tomography

In a typical ECT application, the first set of results are the raw capacitance values, as well known comprising ½ N(N-1) values for an ECT system with N-electrodes. These values are usually processed by solving an inverse problem based on permittivities of the media flowing in the pipe leading to tomograms in the context of process tomography [5]. A typical ECT sensor system is shown in Fig. 1.

B. Single beam GRM

In GRM measurements the time average value of the density covered by each gamma beam is calculated. Hence liquid volume fraction of the volume covered by each gamma beam can be calculated. The beam can be adjusted to scan the pipe cross-section at any angle. Specially designed mechanical system can move the system with gamma beam to scan the whole cross section horizontally, vertically or at any desired angle with respect to the horizontal. Results presented in this paper are mainly based on vertical beam GRM measurements

C. Test Facility

The multiphase flow rig used in the present study is shown in Fig. 2. The experiments were conducted with two-phase flow of oil and air. The test section is 15m long with the ECT and GRM measurement systems have been installed as shown in

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Fig 2. Inclination of the test section can be changed from -10º to +10º. Mass flow rates of oil and air into the test section can be controlled.

III. Results

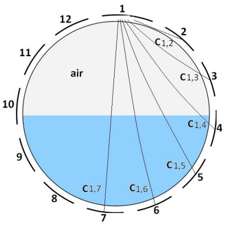


Figure 1. Capacitance sensors on the periphery of the pipe transporting oil and air delivering capacitance values $C(i,j,t)$ with i= 1, 2, ..12, j=1, 2, …12 in this case at time t

For different inclinations of pipe, the interface levels were observed using ECT images and measurements based on GRM densitometry. Here ECT measurements were performed for 60s with the capturing frequency of 100Hz. Then, all these images were fused using statistical techniques based on filtering and averaging. The interface was selected by defining a threshold pixel value which is 0.6 in a grey scale. Interface estimation results based on ECT and GRM are presented in Figs. 3 to 6 and 8 to 9, and comparisons of the techniques are further explained in Figs 7 and 10. The results show the same trend although some discrepancies are observed at the pipe wall. More discussions with reference to these and CFD based results will be included.

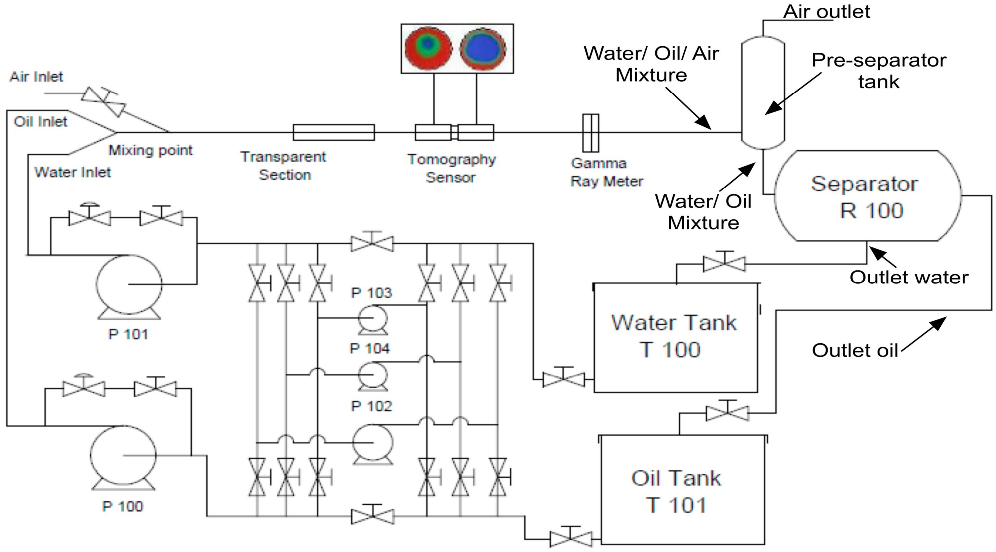


Figure 2. Multiphase flow rig with twin plane ECT system, GRM and other meters for monitoring inlet conditions of fluid flow into the test pipe section. Pipe section with ECT/GRM adjustable to desired angle with respect to the horizontal. GRM scans pipe cross section. Transparent section for LDA and external mechanical measurements

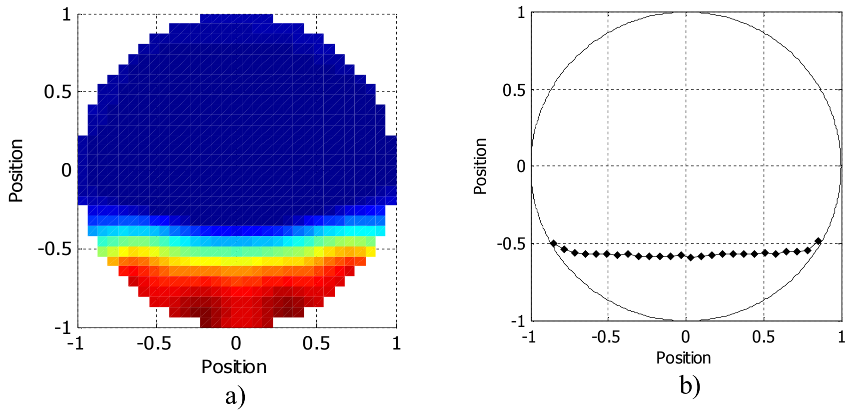
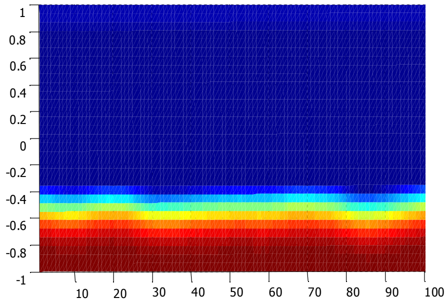


Figure 3. ECT and GRM measurements of horizontal flow with mixture velocity of 5m/s and oil fraction of 0.01. The interface levels are clearly seen to be around position -0.5.



a)

b)

Figure 4. a) ECT measurements for horizontal flow with mixture velocity 5m/s and oil fraction 0.01. b) Still camera image of the flow

IV. GRM Densitometry and ECT Measurements

Gas liquid flows in horizontal and with pipe inclination of 1 º downward to the horizontal were measured using GRM and ECT. Fig 3 shows the measurement results from vertical beam GRM and ECT at the mixture velocity of 5 m/s and liquid fraction of 0.01. Under given inlet conditions layered flow can be seen and both ECT and GRM results show the oil air interface level to be around position 0.5. Camera images captured through the transparent section are used for further validations (Fig 4), confirming the results.

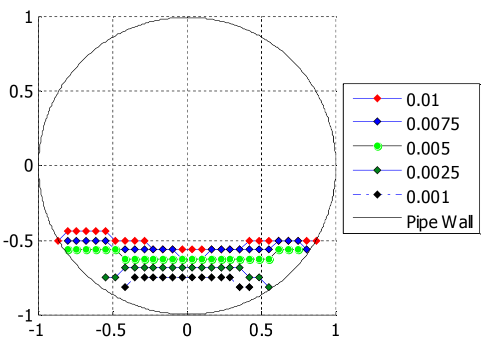
Uncertainties of the measurements close to the pipe wall are high in both ECT and GRM based measurements. As explained in [6] and [7], gamma beams closest to the pipe wall pass very small distance through the flowing mediums compared to the beams passing through the central part of the pipe. When the gamma beam passes near the pipe wall, some parts of the gamma beam hit the wall thus changing the traversing length of the beam through the attenuating medium, i.e. oil and water in our case. This increases the uncertainties in the GRM measurements, particularly close to the pipe wall. Distortions in electrical field due to different permittivities of the flow components will certainly affect the image reconstruction in ECT. This is called soft field effect and this causes the unclear interface boundaries seen in the images based on ECT. Low spatial resolution leads to increased uncertainty in interface level and volume fraction estimations.

Fig 3 b) shows the interface curvature as obtained with the results using vertical gamma beams. The measurements near the walls were measured using angular gamma beams through the pipe center. Results show that the interface is uniform except the near the pipe walls, showing the right form of meniscus for oil.

A. Effects of changes in liquid fraction for horizontal flow with mixture velocities 5.0 m/s and 10.0m/s

Flows with the pipe test-section held horizontally with different oil fractions were then investigated. Here the mixture velocities were maintained at two levels: 5m/s and 10 m/s. Figs 5 and 6 show the results with ECT and GRM measurements. Interface shown in ECT based approach had deviated hold up measurements near the wall. Unlike in the GRM measurements, the interface meniscus is seen to bend downwards for the low oil fractions, 0.001 and 0.0025. But ECT and GRM measurements show that increase in inlet oil fraction at mixture velocities 5 and 10m/s lead to an increase of the interface level height of horizontal flows, as expected.

In Fig. 7, the GRM measurements and ECT measurements are used to compare the interface levels. ECT image (pixel) based interface calculations are found to be slightly higher than the interface levels obtained using GRM based calculations. When interface level goes down the difference in the interface levels using these two techniques increases. Camera images and ECT based images, sample of which is given in Fig 4 confirm that the flow is stratified and wavy.



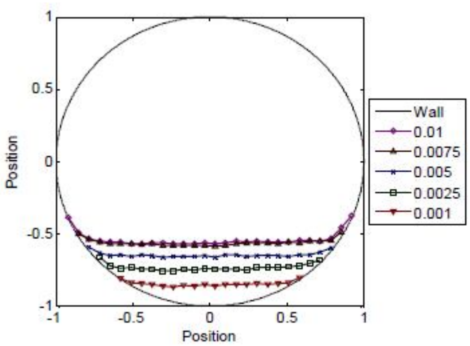


Figure 5. Interface level measurements with ECT (left) and vertical beam GRM (right) for air/oil flows with mixture velocity 5m/s and different liquid fractions when pipe inclination is 0º. Oil fractions used are given in the inset.

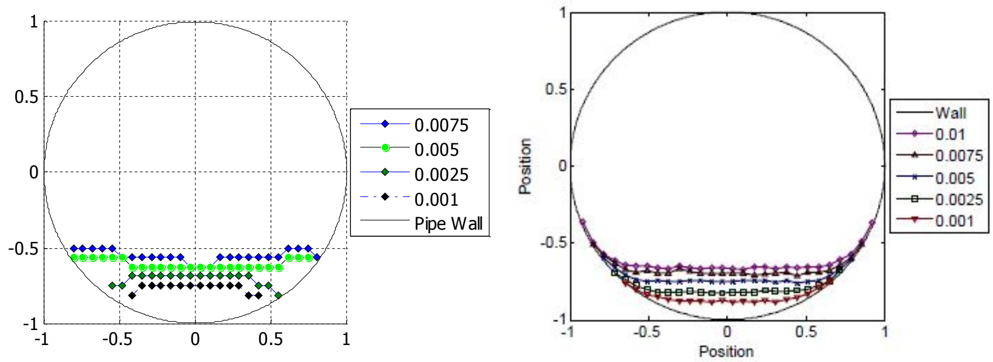


Figure 6. Interface level measurements with ECT (left) and vertical beam GRM (right) for air/oil flows with mixture velocity 10m/s and different liquid fractions when pipe inclination is 0°. Oil fractions used are given in the inset.

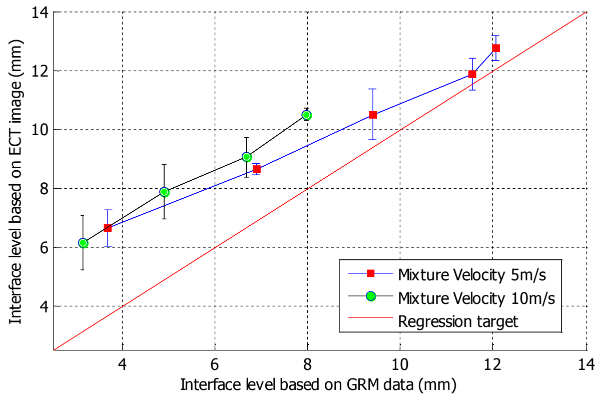


Figure 7. Interface levels based on ECT and GRM for horizontal flows with RMS uncertainties

B. Effects of changes in liquid fraction for flow with mixture velocities 5.0 m/s and 10.0m/s with -1 degree downward flows

Similarly, flows in the pipe section with an inclination of 1° downward with different oil fractions were investigated with mixture velocities of 5m/s and 10 m/s. Figs 8 and 9 show results with ECT and GRM measurements. For the oil fractions 0.001 and 0.0025 with ECT, interface meniscus slopes downwards as observed with horizontal flows. Increase in interface level with increased inlet oil fraction is observed with pipe-inclination at -1°.

Interfaces resulting from GRM measurements and ECT measurements are given in Fig 10. The similarities in interface levels from these two techniques are clearly seen and the trends discussed in the case of horizontal flows are seen here too.

However, the two measurement methods show a tendency to give a higher estimate of the interface levels when comparing them with the interface levels obtained from external measurements performed through the transparent pipe section. This may be attributed to wetting of the pipe walls by the oil in this set of experiments.

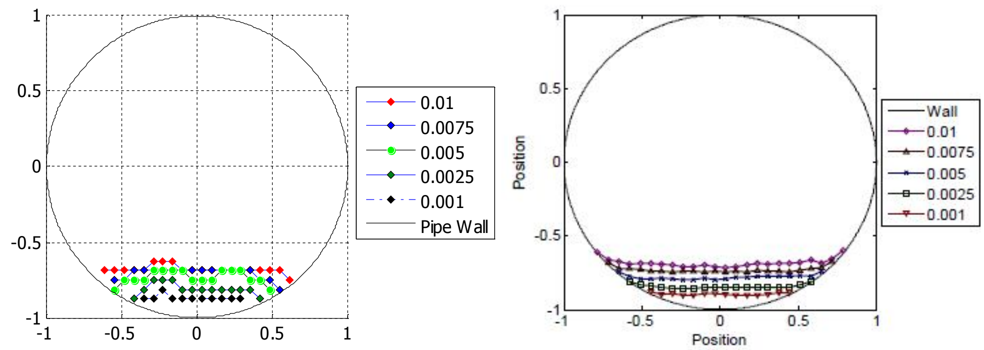


Figure 8. Interface level measurements with ECT (left) and vertical beam GRM (right) for air/oil flows with mixture velocity 5m/s and different liquid fractions when pipe inclination is -1°. Oil fractions used are given in the inset.

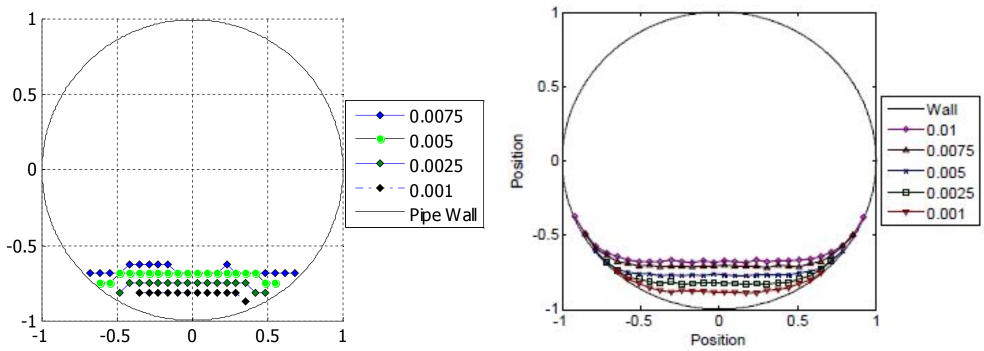


Figure 9. Interface level measurements with ECT (left) and vertical beam GRM (right) for air/oil flows with mixture velocity 10m/s and different liquid fractions when Pipe inclination is -1°. Oil fractions used are given in the inset.

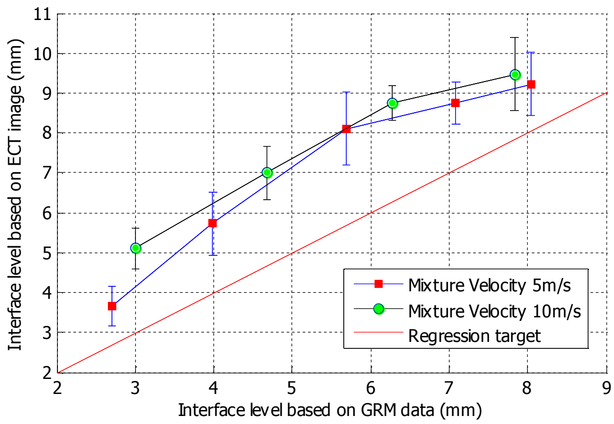


Figure 10. ECT vs GRM in interface calculation for pipe inclined 1° downward from the horizontal with RMS uncertainties

It may be relevant to note the following facts related to the usage of ECT and gamma ray based measurements in this particular application. The speed of operation is better with the ECT-system used in the experiments conducted, whereas the depth of penetration of gamma rays is much better than the electrical field penetration from the ECT system. The vertical resolution is found to be better for the gamma ray based measurements. These complementary advantages will give a set of data to verify the CFD based simulations of the distribution and flow of the different components in the multiphase flow. Table 1 summarizes these issues clearly.

TABLE I. COMPARISON OF SELECTED PERFORMANCES OF ECT AND GRM

Selected parameters of the ECT/GRM systems	GRM	ECT
Horizontal Resolution	3%	3%
Vertical Resolution	1%	3%
	1×32-1D array	32×32-2D pixel grid
Measurement speed	1600s	0.01s
Measurement mode	Time average measurements	Online

Exposure to high dosage of Gamma radiation may be hazardous to health. The ionizing radiation near the GRM in the current experiments is 50µSv in operation and 0.2µSv otherwise. The acceptable limit for a person according to the Norwegian regulations is 20mSv per year [8]. As such the exposure dosage in the current study is well below the regulatory limits. In industrial applications, the radiation source is covered with sufficient mass of lead to shield personnel operating GRM.

V. CONCLUSION

The series of two phase measurements using ECT and GRM give similar results in the case of predominantly stratified and wavy flow of oil and gas with varying oil fractions. The comparison of the interface levels from both these methods show a tendency of giving the interface levels somewhat higher than those levels recorded using mechanical means through the transparent section of the pipe section containing the ECT / GRM sensor suite. The results indicate that the wetting of the pipe wall has a significant influence on the interface level estimations based on ECT and GRM. In commonly used codes in CFD simulations, the wetting effects are rarely taken into account. The wetting effects can be taken into account by selecting material properties of the pipe and the fluid transported in the pipe. In conjunction with the image studies, the meniscus of the interface particularly in the vicinity of the pipe walls needs to be studied in more detail, as a fusion of the data from the various sensor suites may give an enhanced insight into the wetting phenomena particularly at various flow rates and volume fractions of the different phases in the pipe. These are some of the issues currently being studied in this multidisciplinary study involving CFD and ECT/GRM measurements.

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