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DRAFT

VISUALISATION OF TWO-PHASE GAS-LIQUID PIPE FLOWS USING ELECTRICAL CAPACITANCE TOMOGRAPHY

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ABSTRACT

Electrical Capacitance Tomography (ECT) can be used to measure concentration and velocity distributions in two-phase flows. ECT is non-intrusive, and the reconstruction of the concentration and velocity distribution can be undertaken in real time and over an arbitrary number of zones in the flow cross-section. The concept of a 'virtual instrument' is introduced where zones of the image can be structured for comparison with other measurements. Numerical agreement with gamma-ray density measurements is shown to be excellent in slug and stratified flows.

For complex oil/gas slug flows we present a variety of 2-D cross-sectional images, time series velocity and concentration graphs and 3-D contour plots. The good temporal and spatial resolution of ECT throws an extensive new light on these otherwise difficult to measure dynamic flow structures. In particular with bubbly-slug structures known as 'ghosts' ECT shows clearly that they are in fact bubbly waves which have extended 'wings' up and around the pipe.

INTRODUCTION

Electrical capacitance tomography is one of the imaging techniques most likely to provide quantitative flow visualization and flowrate information in industrial flows. It has particular advantages in two-phase oil/gas flows typical of those in the petroleum industry [1], [2] and is also widely applicable in gas/solids flows [3], [4], [5].

This paper presents results taken during 2003 using ECT in the multiphase flow loop at SINTEF in Norway (Figure 1).

ELECTRICAL CAPACITANCE TOMOGRAPHY

ECT measurements are made by placing rings of electrodes around the circumference of the pipe or vessel of interest, measuring the electrical capacitance between each independent pairing of electrodes and using image reconstruction techniques to show the permittivity distribution within the sensor. Figure 2 shows a typical 8-electrode array, while Figure 3 shows a typical cross-sectional image where red is high permittivity material (in this case oil) and blue is low-permittivity (in this case air). In our experiments we used a Tomoflow R100 ECT Flow Analysis System with a twin-plane 8 segment guarded array of electrodes, where the electrode axial length was 30mm. The planes are separated by 100mm axially and the acquisition rate was 200 frames per second on both planes – the fastest rate currently available on a commercial ECT system [6].

The use of capacitance measurement for volume fraction estimation in non-conducting two-phase flows is well known, but the measurements are strongly dependent on sensor geometry and flow regime [7]. ECT offers an important improvement in that it measures the full concentration distribution in any regime or geometry.

ECT generates large quantities of information: concentration in two planes (over 800 pixels in each) several hundred times per second, and we calculate velocities over several zones (up to 10 or more) at each time step. Interpreting, analyzing and presenting this data can be done in many ways, and we are at the early stages of learning how best to do this for different applications.

EXPERIMENTAL FACILITY

The flow facility is a 217m long horizontal loop around which a variety of fluids may be pumped and which is very flexible in operation. Most of the rig is steel 0.069m inner diameter but some transparent PVC sections are inserted for observations. The mixture of fluids may contain water, oil and either air or sulphur hexa fluoride gas (SF_6). A 25m section dedicated to sand transport can also be inserted. The maximum operating pressure is 10bar, and the superficial velocity for the liquids range from 0.003m/s to 2m/s with 0.5m/s to 15m/s for the gas. (note: superficial velocity is the volumetric flowrate of the individual phase divided by pipe cross-sectional area)

For this particularly project the fluids used were Exssol d80 and air at atmospheric pressure, the physical parameters of the fluids are given in Table 1.

Measurements were performed in a 25m long section of transparent tubing within a shelter about 40m from the end of the loop where the fluids are separated. The first 150m are considered as inlet section to allow the flow to develop.

REFERENCE INSTRUMENTATION

The superficial velocities of the experimental fluids were measured in single phase lines before the mixing point at the start of the loop. Liquid flow rate is measured by coriolis meter (uncertainty 0.1% of full-scale), gas flow rate is measured by vortex meter (uncertainty 1% of full-scale). A single-beam gamma-ray densitometer was placed adjacent to the ECT sensor. Such single-beam gamma meters are well studied in two-phase gas-liquid flows, and known to give reliable measurements of equivalent liquid height in stratified flows [8], [9]. In addition video recording of the flow patterns through the transparent pipe wall was undertaken and absolute pressure and pressure gradient were measured in the test section.

FLOW CONDITIONS

Oil and air flows were used with superficial gas velocities of between 0.2 and 12m/s and superficial oil velocities of 0.05 to 1.0m/s. Gas concentrations (void fraction) ranged from 6% to 55%. Flow conditions varied from stratified flow where the two phases flow smoothly in separate parts of the pipe, through slug flow with long coherent fluid slugs to highly turbulent periodic passage of frothy flow structures (known colloquially as 'ghosts').

In a typical horizontal gas-liquid flow at these velocities flow the dominant structure is the slug, whose passing frequency and turbulence intensity increases as the flow velocity increases. Figure 4 shows a video frame of the arrival of an oil slug (yellow), Figure 5 a slug tail, and Figure 6 the stratified flow between slugs. The image in Figure 3 corresponds approximately to the cross-section at the centre of Figure 4.

FLOW ANALYSIS FROM IMAGES

Twin-plane sensors were used in conjunction with guard electrodes to create two image 'planes' axially separated along the flow. Each 'plane' (as shown in Figure 3) is in fact a cylinder of 30mm length made up of 812 pixels on a 32x32 square. To investigate details of flow conditions it is often more helpful to divide each image plane into a number of zones arranged appropriately for the flow conditions. For flow measurement purposes it is often useful to divide the flow into equal-sized zones, but here, to facilitate comparisons with the reference gamma-ray we define a 'virtual instrument' from the image to mimic the spatial sensitivity of the gamma-ray meter. The zone is a simple double line of pixels arranged vertically across the flow. The concentration value within each zone can now be expressed against time as the arithmetic average of all the pixel values within the zone.

Figure 7 shows a typical output screen for the system. The data display window shows the concentration (left hand axis) against time for the chosen zone. The green line represents the concentration in plane 1 and the red line for plane 2. The right hand axis can be used to display a variety of other information on the same time scale. The statistics display shows the correlogram derived from the cross-correlation of the concentration in the two planes. The image display shows from left to right: the zones used with the current zone highlighted white, the average values of various parameters in those zones, the image at plane 2 and the image at plane 1 – both images referring to the time at the cursor in the data display window.

COMPARISON OF ECT WITH GAMMA-RAY DENSITY

Figure 8 shows data from a slug flow. The data is plotted for the vertical line zone. Concentration varies periodically with time as each slug passes. The right hand axis in the data window shows the gamma-ray density 'liquid-height' to the same scale. Comparison of this virtual sensor with the gamma-ray measurements show good agreement in the stratified and slug flow periods. In principle the gamma-ray calibration is only valid for flows which are horizontally stratified, but in the flows shown here this is not a serious limitation. In vertical and deviated pipes the limitation is much more severe and future papers will investigate these errors. The gamma-ray has a longer averaging time (0.02s cf. 0.005s for ECT) and other experiments show that the differences between the measurements appear to be in the favour of ECT in fast highly structured flows.

FLOW VELOCITIES

The velocity at each point in time within each zone is calculated by correlating the instantaneous concentration of one plane with the same zone in the other plane. The result is plotted in the statistics display. Although mathematically the correlation is described for the averaging time T approaching infinity, in practice the velocity will fluctuate over some much shorter time scale and the user will need to set the window T at some suitable value appropriate to the particular length and velocity scales in the flow and the sensor geometry.

The correlogram has a clearly discernible peak if the flow structures are coherent over the sensor length and contains information about the time domain statistics of the flow – primarily convection and dispersion. The simplest assumption is that the time delay at the peak of the correlogram corresponds to the transit time of flow structures between the two planes. This does not assume that the flow structures do not evolve, it is simply an estimate of the axial velocity component. For other applications the dispersion may be modeled [10] or other velocity components may be measured [11]. The correlogram peak may be found by the greatest single value, centre of area or polynomial fitting. For many flows polynomial fitting gives the most consistent results though all the other techniques are available in our software. The time window used for the correlation process needs to be shaped in some way to minimize artefacts caused by sharp-edged windows. This shaping is known as apodization – the results presented here use the common Hanning window, which is a smooth bell shape.

Figure 9 shows the same slug flow data as Figure 8, but this time the right hand axis shows the correlation velocity. As obvious from visual observations, the slug velocity does not vary greatly from slug to slug. In this case the velocity is between 3 and 4 m/s.

3-D IMAGES

By plotting 3-dimensional pictures based on the images as time slices separated by the local transit time we can generate concentration contours that clearly show the internal structure of the flows. Other workers have plotted 3-D pictures through simple stacking of images based on the sampling time, for example [12], but our images space the planes based on measured transit velocity. Direct 3-D imaging may be possible in the future [13]. Images such as we present here show the structure as it passes a fixed point, possibly at varying velocity, and if the structures are not rapidly evolving in time this is almost equivalent to a 'snapshot' of the structure.

It is apparent from the images that many of the 'slug' structures have an air-core passing through the centre. One particular type of bubbly slug is known colloquially in Norwegian as a 'ghost' because it drifts past in the working section with a particular soft whispering sound. Figure 10 shows the 50% concentration contour for one of these structures. Note that in the figure the axis along the flow direction has been significantly compressed with respect to the radial axis. From the outside of the pipe these ghosts appear as frothy slugs with no particular structure visible. Seen from ECT measurements however it is apparent that they are bubbly waves which have thrown 'wings' up around the pipe circumference leaving an air core.

Even other slugs which appear as continuous liquid structures may also have gas cores. Figure 11 shows one such structure which has a nearly continuous gas core which breaks into bubbles through the central area.

These structural visualizations are limited by the fact that the 50% contour is not actually an interface, but they give an unusually good insight into the way the flows are built. It should also be remembered that the pictures are a way of presenting quantitative data, and not just qualitative indications. Within each pixel we have a numerical measurement of concentration at every point in time and within each zone a good estimate of axial velocity.

CONCLUSIONS

ECT is an established method of visualizing the cross-sectional permittivity distribution in non-conducting flows. We have extended the analysis of the images to allow the calculation of velocity distribution across user-defined zones representative of the flow scale. For complex oil/gas slug flows we have presented a variety of 2-D cross-sectional images, time series velocity and concentration graphs and 3-D contour plots.

Direct comparisons with gamma-ray density measurements have been made through the introduction of a 'virtual instrument' using the ECT images to mimic the spatial sensitivity of the gamma ray system. Quantitative agreement between the two techniques is excellent in stratified and coherent slug flow.

The good temporal and spatial resolution of ECT throws an extensive new light on the complex flows in horizontal gas-liquid systems. Such dynamic flow structures are otherwise difficult to measure quantitatively. In particular, a type of structure known as a 'ghost', which appears visually from outside the pipe to be a bubbly slug is shown by ECT to be a bubbly wave which has extended 'wings' up and around the pipe.

ECT gives a full 3D picture of the multiphase flow structures. Within each pixel there is a numerical measurement of concentration at every point in time and within each zone a good estimate of axial velocity.

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TABLES

	Density	Visvosity
Air	1.2 kg/m3	0.015 mPa.s
Exssol d80	795 kg/m3	2mPa.s

Table1: fluids properties

FIGURES

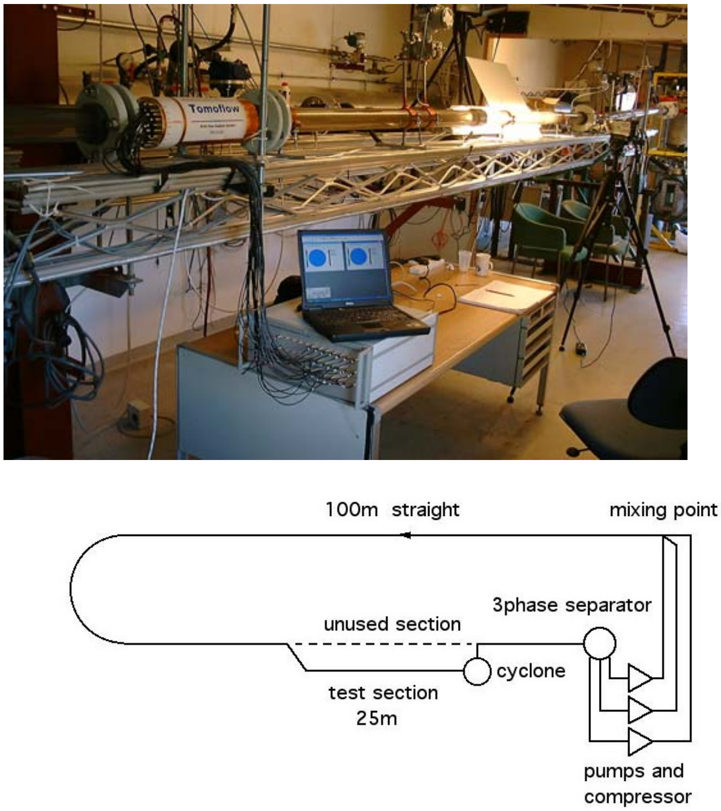


Figure 1. Upper: photograph of test section (flow moving away from camera), lower: flow loop layout

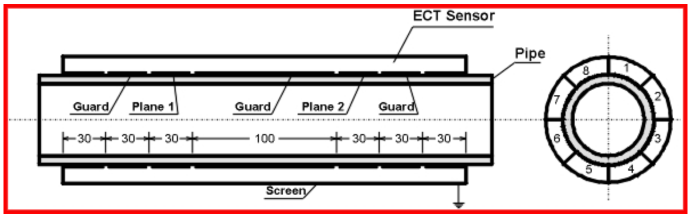
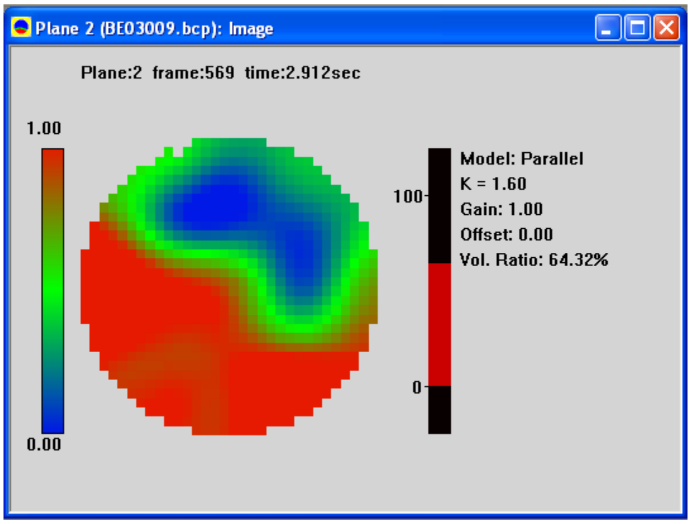


Figure 2. Sensor electrode arrangement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Plane:2 frame:569 time:2.912sec

Model: Parallel
K = 1.60
Gain: 1.00
Offset: 0.00
Vol. Ratio: 64.32%

Figure 3. ECT image of gas-liquid slug cross-section

Figure 4. Photograph of slug front (flow left to right)

Figure 5. Photograph of slug tail (flow left to right)

Figure 6. Stratified flow (flow left to right)

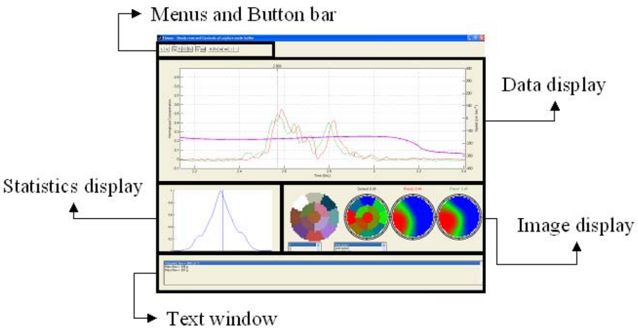
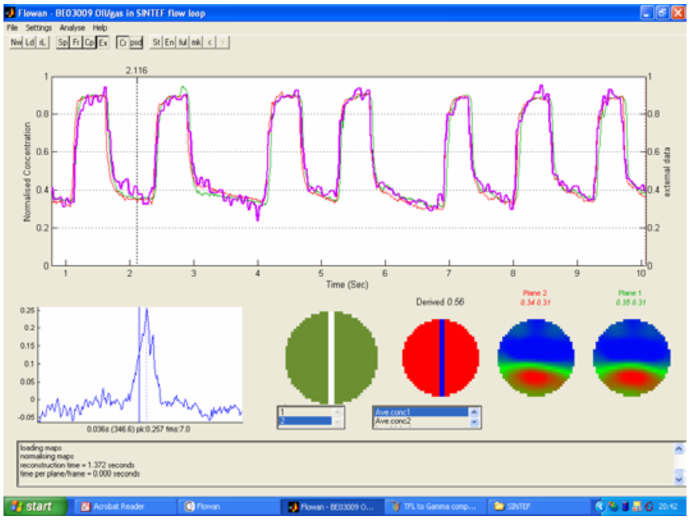


Figure 7. Data window structure



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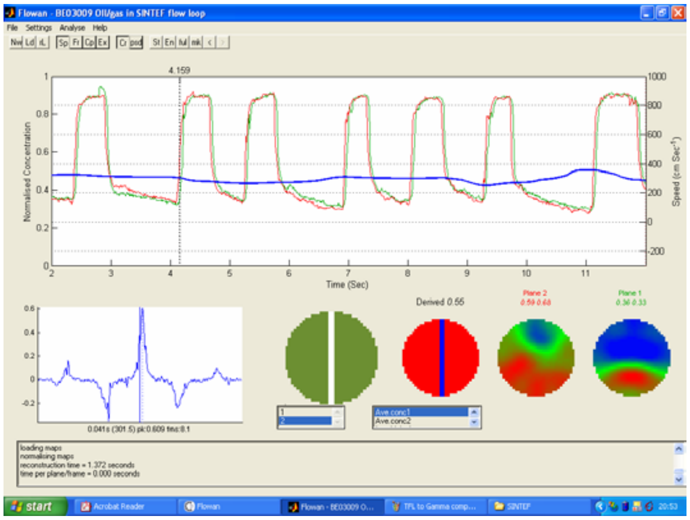
normalising maps
reconstruction time = 1.372 seconds
time per plane/frame = 0.000 seconds

Figure 8. Comparison with gamma-ray densitometer



loading maps
normalising maps
reconstruction time = 1.372 seconds
time per plane/frame = 0.000 seconds

Figure 9. Slug flow velocity

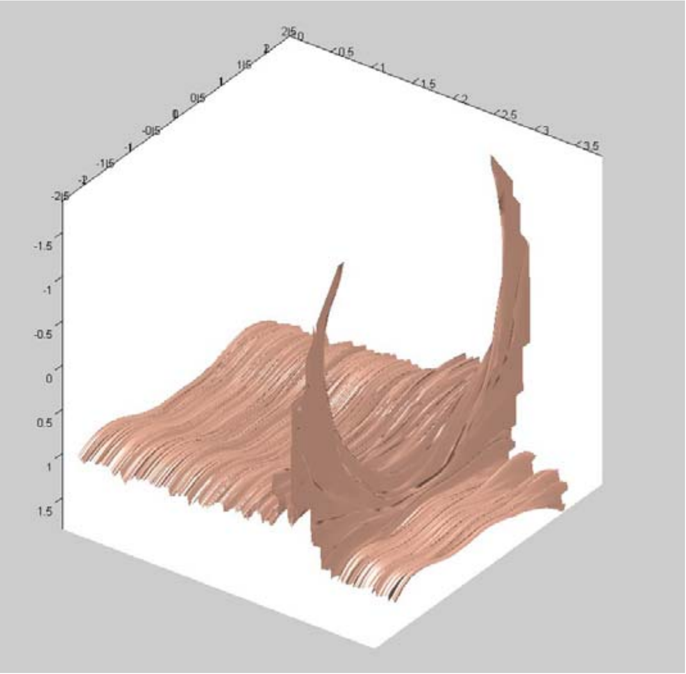


Figure 10. 3-D surface at 50% concentration – 'ghost'. Pipe not shown. Note that the horizontal scale is very much reduced compared to the radial scale.

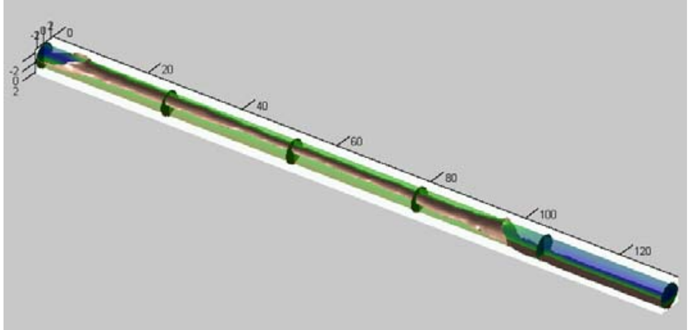


Figure 11. 3D surface at 50% concentration – 'slug'. Also shown are concentration cross-sections at intervals along the pipe.