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Multimodality Measurement Data Fusion in Image Reconstruction for Multiphase Flow Measurements

1. Introduction

This paper presents results of theoretical research and experiments performed within DENIDIA MC ToK and SPUB project in the Computer Engineering Department of the Technical University of Lodz and Department of Physics and Technology of the University of Bergen. The paper presents some theoretical investigations concerning capacitance measurements of a mixture of two components characterised with different electrical properties: non-conductive oil and conductive (approx. 5 S/m) sea water from North Sea. This situation is similar to North Sea oil platform environment, where crude oil is transported from wells in a sea bottom. Measurements of a different phase shares in a flow is crucial to the installation safety and economy of the process.

2. Capacitance measurements

Maxwell, Bruggeman and many others have developed formulae for the permittivity and conductivity of homogeneous mixtures of two different materials, which are commonly known from many manuals on an electricity and general academic publications. On the basis of a model developed by van Beek [2], Ramu and Narayana [7] have derived formulae, which are also valid, if one of the components in the mixture has a high conductivity. Let us assume, that $\sigma_1 << \sigma_2$ and $\varepsilon_1 << \varepsilon_2$, where σ in general describes conductivity and ε is used for permittivity. Then Ramu and Narayana equations for the expression of the mixture permittivity and conductivity can be written as:

$$\varepsilon_m = \varepsilon_1 \frac{1+2\beta}{1-\beta} \tag{1}$$

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$$\sigma_m = \sigma_1 \frac{1+2\beta}{1-\beta} \tag{2}$$

which is valid for component 1 as the continuous phase and

$$\varepsilon'_m = \varepsilon_2 \frac{2\beta}{3-\beta} \tag{3}$$

$$\sigma'_m = \sigma_2 \frac{2\beta}{3-\beta} \tag{4}$$

for component 2 as the continuous phase in the mixture.

The symbols in the above equations have the following meaning:

- ε_m – relative permittivity of the mixture when component 1 makes the continuous phase
- ε'_m – relative permittivity of the mixture when component 2 makes the continuous phase
- σ_m – conductivity of the mixture when component 1 makes the continuous phase
- σ'_m – conductivity of the mixture when component 2 makes the continuous phase
- ε_1 – relative permittivity of component 1
- ε_2 – relative permittivity of component 2
- σ_1 – conductivity of component 1
- σ_2 – conductivity of component 2
- β – volume fraction of the component 2

Let us assume that the conductivity of component 1 is zero and it makes the continuous phase when $\beta < 0.5$, component 2 is conductive ($\sigma_2 > 0$) and it is the continuous phase when $\beta > 0.5$. The relative mixture permittivity will then be as shown in Figure 1.

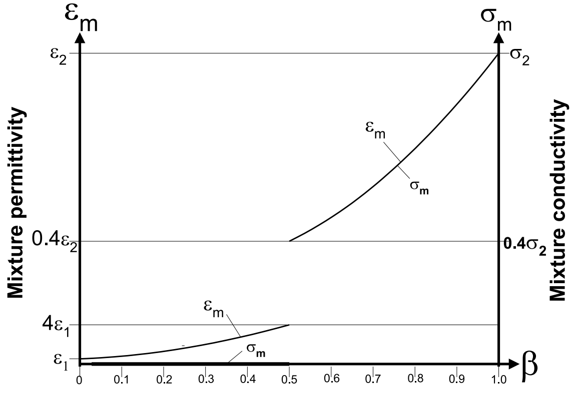

Fig. 1. Mixture permittivity and conductivity versus the volume fraction of component 2 of a homogeneous mixture of component 1 and 2. Only component 2 is conductive

As it can be seen from the chart, the water content in oil can only be determined accurately, when the distribution of the water is exactly known. In practice this means that usually only homogeneous mixtures of oil and water can reliably be determined. The continuous component in a process oil/water mixture changes from oil to water at around 20 to 40% water concentration. The transition point in a mixture of crude oil and water will occur somewhere between 60% and 80% water fraction, depending on the type of crude, temperature and content of emulsion breaker etc. In North Sea the conductivity of the water component in the crude oil will approximately be 5 S/m and the relative permittivity approximately 70. The water content of North Sea crude can therefore not be measured with capacitance sensors if the mixture is water continuous ($\beta > \beta_C$). It limits application of capacitance measurements, therefore another modalities – resistance and gamma radiation were also introduced.

3. Gamma radiation measurements

The complete multimodality system is built on 90 mm diameter PVC pipe and consist of 8 stainless steel pin shaped resistance electrodes and 8 copper capacitance electrodes with dimensions 100×25 mm placed outside the pipe. The system uses ECT measurements from copper electrodes when the mixture is oil or gas continuous and not conducting and ERT mode when the mixture is water continuous and conductive. ECT/ERT sensor is connected to the 16-channel electronic measurement unit, DENIDIA ECT designed and manufactured in the Technical University of Lodz. Additionally in the mid plane of ECT electrodes, two Americium (AMC.P1, QSA Global) gamma sources are inserted. The sources emit two collimated vertical and horizontal gamma beams, which are detected by two CTZ – sensors (eValuator 1000) including all necessary electronics for giving out a TTS shaped signal equal to number of counts. Output of the sensor is connected to counter inputs of National Instruments 6259 multifunction card. Additionally two Agilent counter/timer units are used for verification of data, software and continuous display of number of counts.

A sketch of the multimodality sensor is given in Figure 2. Sensor is built as 50 cm pipe segment with flanges for ease of replacement within the flow rig. The radioactive sources are inserted into protective lead holders. The construction is surrounded by radiation protecting 1.5 mm steel housing.

Prior to main flow measurements in the multiphase flow rig the measurements of gamma radiation inside the sensor were performed. Results of measurements are presented in the Table 1.

The ECT sensor is built of 8 copper outside electrodes. They are also shielded with the copper foil placed at a distance of 10 mm from the electrodes, so complete ECT sensor gamma radiation damping depends on two layers of PVC pipe and 4 layers of copper foil.

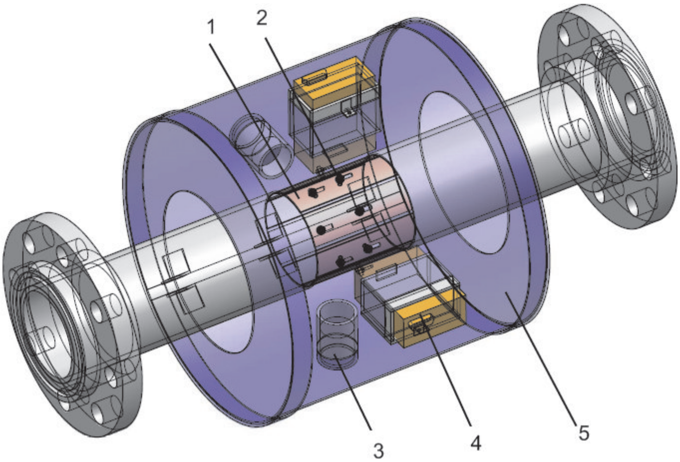

Fig. 2. Schematic view of the sensor: 1 – ECT copper electrodes, 2 – ERT pin electrodes, 3 – gamma source holder, 4 – eValuator 1000 gamma ray detector, 5 – steel gamma ray protective housing

Table 1
Count rates (pulse/sec) for different sensor setup. Scatter was measured by horizontal sensor with only vertical Am source inserted

System description	Average Counts	Scatter
Empty sensor housing (5)	6336	Not measured
Empty sensor housing (5) with 1 Cu layer	6016	20.18
Empty complete sensor (full air)	4909	2.93
Complete sensor (full oil)	1584	19.52
Complete sensor (full water)	956	12.84

4. Multi modality measurements and calculations

According to the information presented in the preceding point, different modalities: ECT. ERT, gamma ray are suitable for measurements of flow with different component fractions. ECT instrument works properly for non-conductive flow, so when overall sea water cut is below the threshold value from Figure 1. When the water fraction increases, capacitance circuit goes into saturation and measurement gives oversaturated or negative signals. These signals although are measured by the system cannot be treated as reliable and in such a case it is necessary to decrease measuring circuit sensitivity. Such "system tuning" – setting proper values for amplifier sensitivity was done before performing main measurements in the installation. In such a case valid measurement mode is ERT. When flow contains water-continuous medium – a conductive flow measurements from resistance circuit give valid information about resistance between electrodes, what enables to determine fraction of conductive component of the flow.

Gamma ray measurements are depending on attenuation coefficient of a flow and therefore give summarised information about liquid components within a flow. It is not possible to calculate oil and water fraction within a liquid only from gamma ray measurements. Acquiring the information from other modalities – ECT or ERT – depending on the type of mixture (non-conductive or conductive) it is possible to calculate fractions of all three components: water, oil and gas.

The calculations of component fraction are presented in paper "Application of multimodality tomography for multi phase flow measurements" [8] submitted for the 6th World Congress on Process Tomography in Beijing. The final equations for calculating flow composition are the following:

$$\alpha_{gas} = \frac{\ln \frac{I_{mix}}{I_{oil}} - \alpha_w \ln \frac{I_w}{I_{oil}}}{\ln \frac{I_{gas}}{I_{oil}}} \tag{5}$$

$$\alpha_{oil} = \frac{\ln \frac{I_{mix}}{I_w} - \alpha_{gas} \ln \frac{I_{gas}}{I_w}}{\ln \frac{I_{oil}}{I_w}} \tag{6}$$

Where I_{gas}, I_{oil}, I_w are number of counts elapsed for sensor filled with gas, oil and water respectively, I_0 is the initial count elapsed with empty gamma sensor.

The different flow regimes that frequently occur in three-component flow are shown in Figure 3 placed on the next page. The left column shows the different idealized regimes. The next column gives the image of reconstructed data from the EIT-system. The third column shows the image from the GRT-system and the last column shows the three-component image.

Depending on type of a flow – conductive or non-conductive – different measurement data obtained from tomography modalities are reliable and can be used for calculation of three phase flow composition.

5. TomoKIS Studio and experimental results

Within the DENIDIA Project the program called TomoKIS Studio was developed. This program works as an user interface for multimodal tomograph and allows to register, save to file, process off-line and visualize measurement data obtained from both capacitance and resistance tomographic sensor. The left hand side of the program screen contains configuration panel (see Fig. 5), where the user can set up measurement environment, including 2D or 3D mode selection of data acquisition and post processing. For proper reconstruction user has to set up sensor configuration selecting number of electrode planes and electrodes in plane. In the case of used sensor its configuration was set to one plane and 8 electrodes.

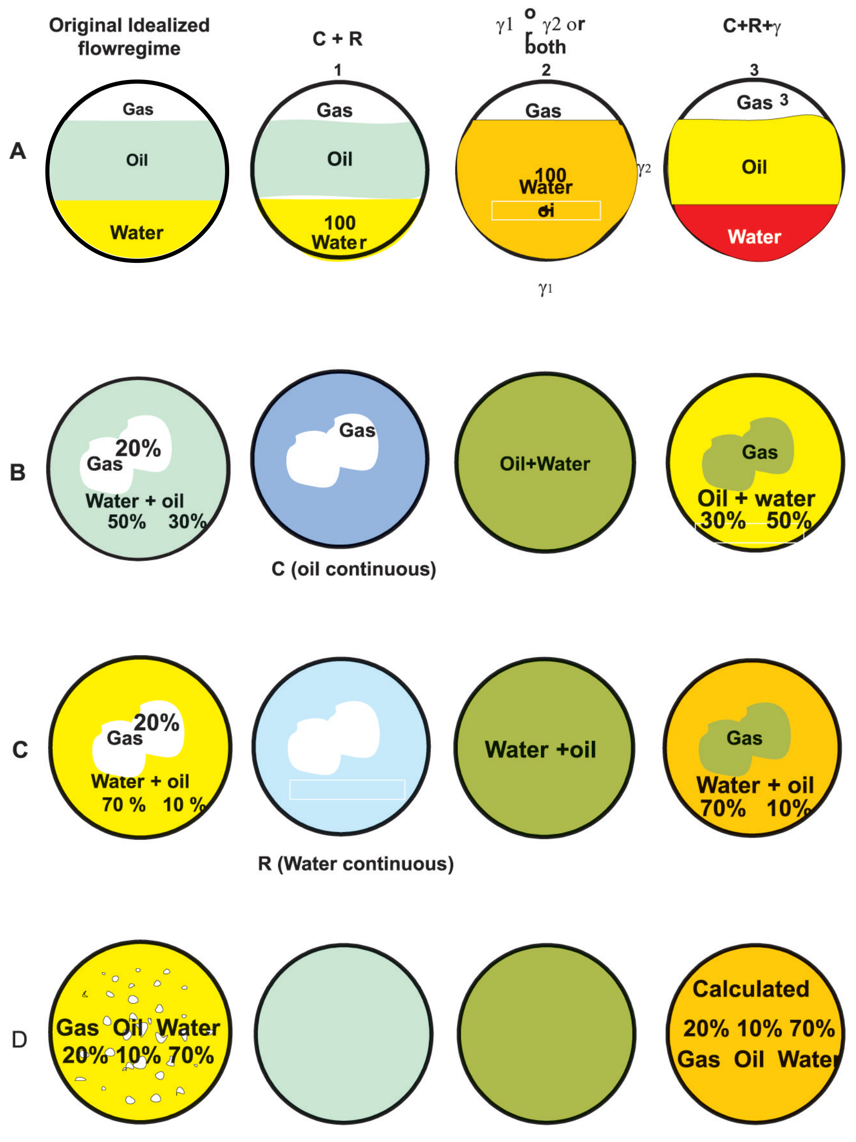

Fig. 3. Various idealized flow regimes and possible ways of calculation flow component fractions

For proper sensitivity matrix calculation the appropriate mesh model of the sensor has to be generated. The special tool – Mesh Generator can be easily accessed from Tools menu. This program allows to define and generate mesh modelling the sensor. The user defines geometrical parameters of the sensor and mesh by submitting sensor dimensions and mesh density parameters. Example of mesh generated for the used sensor in capacitance mode is presented on the Figure 4.

The TomoKIS Studio software is constantly under development. The current version allows to connect to the tomography devices owned by The Computer Engineering Department. Various types and modes of measurement can be selected from the appropriate pull down menu. System allows also for storing on disk measurement data both from ECR and ERT system (up to 1000 frames). Figure 5 presents reconstruction of the flow in the rig containing 50% of sea water and 25% of diesel oil. On reconstructed image left part of a picture corresponds to the sensor bottom.

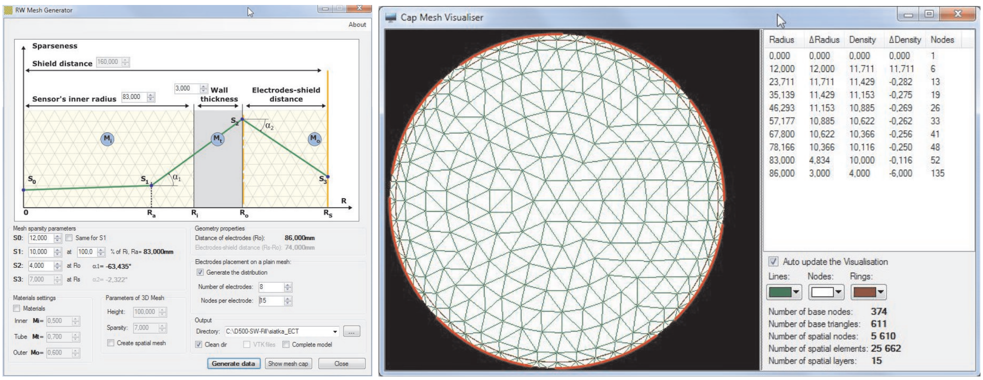

Fig. 4. Mesh generated for the used sensor with 8 capacitance outer electrodes

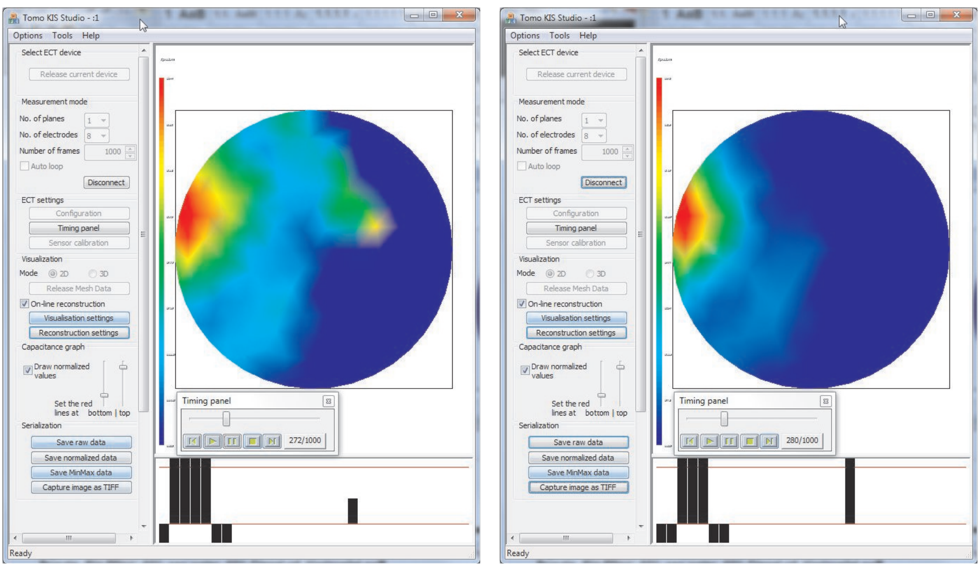

Fig. 5. TomoKIS Studio application. Example of reconstruction of a flow while pump start in a flow rig. Rig filling: 50% sea water, 25% Diesel oil

To calculate all three phase fractions in the flow, a new software for gamma ray measurements and processing was developed. The program allows to acquire, store to file and process off line data obtained from gamma sensors. System works with NI6259 multifunction card using counters' inputs connected to eV1000 gamma radiation sensors.

Program displays continuously counts elapsed by vertical (V), horizontal (H) counters and calculated fractions of three flow components: G – gas, O – oil, SW – sea water. Counting time is set to 100 ms, flow fractions are calculated every 1s using averaged values of last 10 elapsed counts. The graph on Figure 6 shows flow behaviour while starting pump in the rig filled with 50% of sea water and 25% of diesel oil.

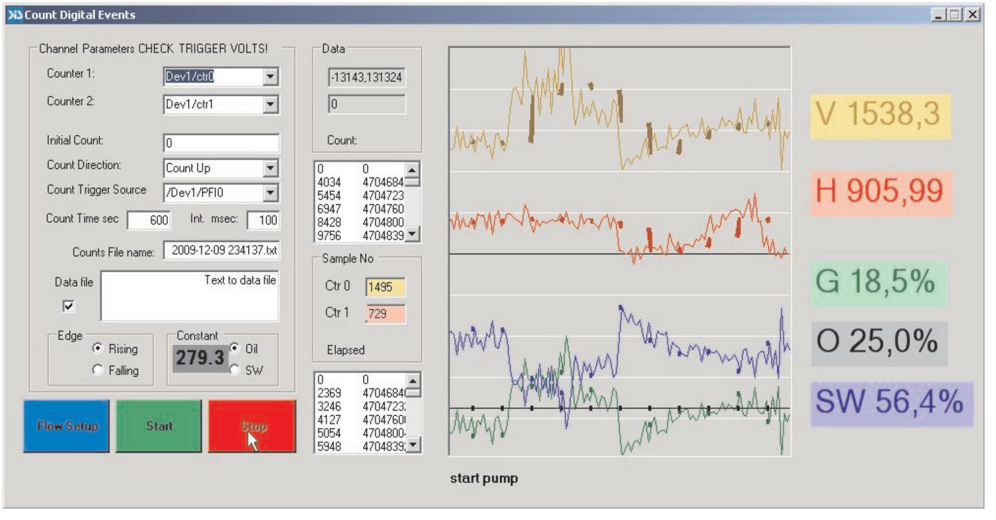

Fig. 6. Example of gamma radiation measurements while pump start in a flow rig. Rig filling: 50% sea water, 25% Diesel oil

The experiments on multi modality sensor were performed in University of Bergen using flow rig with capacity of 35.6 l. For experiments North Sea water and diesel petrol was used. After calibrating of the system (ECT, ERT, GRT) the flow measurements were performed for series of two phase and three phase flow compositions covering wide range of fractions of flow components. According to the technical aspects of rig filling/emptying diesel and sea water fractions were changing with the steps of 25%. The shown graphs present measurements performed for liquid mixture containing 50% of sea water and 25% of diesel oil. In a steady state the flow is stratified, so lower part of the sensor is filled with water. The graphs show flow composition oscillations caused by pomp start. The calculated average flow composition are displayed every 1 s, the count oscillations, which are normal for eV1000 signal show, that calculated real water fraction is around 6% higher.

6. Conclusions

The experiments with newly designed multi modality sensor performed on a multi phase flow rig in Bergen showed, that combined mode tomograph (ECT/ERT) with added gamma sensors (horizontal and vertical) allow to determine flow composition of a mixed flow. Different experiments showed, that accuracy of measurement of water or oil cut varies from 3% to 12%. According to linearity of gamma ray attenuation calculations of liquid fraction in flow took into account, that measurements are performed using circular pipe. Therefore volume fraction of a liquid, calculated from gamma attenuation was corrected according to pipe shape. Resulting error in measurement shows, that for non stratified flow taking into account reconstructed image obtained from different measurement modalities may increase accuracy of calculation attenuation of gamma ray in liquid and therefore may increase accuracy of calculations. The construction of the sensor enables robust measurements. Some efforts have to be made according to the electronic ECT/ERT measurement unit to protect the system against noise, mainly originating from pump power inverter.

Acknowledgment

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