MULTI PHASE FLOW MEASUREMENTS WITH THE APPLICATION OF ECT/ERT DECART MULTIMODALITY TOMOGRAPH

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Abstract. The multi-phase flow measurements are very important tasks in many areas of industrial processes applications. One of them is undersea exploration of oil in the petroleum industry. The submitted paper presents application of DECART tomograph designed and built in Lodz University of Technology - together with combined measurements of signals acquired from gamma ray measurement system. Use of all measuring modalities allowed for performing measurements of a flow composed of sea water, oil and gas. The paper presents theoretical principles applied to design multimodality tomograph and results of experiments performed in the University of Bergen. Measurement confirmed that multi-modality approach allows giving fast and reliable on-line results of measurements of composition of multi-phase flow. Applied algorithms allowed to speed up on-line measurements and presenting results in a form required in industrial applications. The derived conclusions can be used as guidelines for preparation of industrial applicable construction of tomograph.

Keywords: tomography, electrical capacitance tomography, gamma rays

POMIARY PRZEPŁYWÓW WIELOFAZOWYCH Z WYKORZYSTANIEM TOMOGRAFU MULTIMODALNEGO DECART

Streszczenie. Pomiary przepływów wielofazowych są szeroko wykorzystywane w wielu procesach przemysłowych. Jednym z nich jest przemysł petrochemiczny, w szczególności dziedzina eksploatacji podwodnych złóż ropy naftowej. W artykule zostało przedstawione zastosowanie tomografu DECART - zaprojektowanego i zbudowanego w Instytucie Informatyki Stosowanej Politechniki Łódzkiej. Pomiary z tomografu zostały powiązane z sygnałami uzyskanymi z systemu pomiaru promieniowania gamma. Wykorzystanie danych uzyskanych z różnych rodzajów czujników umożliwiło pomiar przepływu mieszaniny składającej się z wody morskiej, ropy naftowej i gazu. W pracy przedstawiono podstawy teoretyczne, które stanowiły punkt wyjścia do wykorzystania tomografu multimodalnego jak i wyniki eksperymentów przeprowadzonych na Uniwersytecie w Bergen. Pomiary potwierdziły, że podejście multimodalne umożliwia szybki i niezawodny pomiar udziału faz w przepływie wielofazowym. Zastosowane algorytmy pozwalają na przyspieszenie pomiarów on-line i przedstawienie wyników w formie wymaganej w zastosowaniach przemysłowych. Wnioski z badań mogą być wykorzystane jako wskazówki dla konstrukcji tomografu do praktycznych zastosowań przemysłowych.

Słowa kluczowe: tomografia, elektryczna tomografia pojemnościowa, promieniowanie gamma

Introduction

The multi-phase flow measurements are very important tasks in many areas of industrial processes applications. One of them is undersea exploration of oil in the petroleum industry.

Atkinson I., Theuveny B., et. al. [1] present review of current and possible future technologies in multiphase flow measurements. There were around 1300 such installations in 2004. Currently there are in use mixed flow measurement systems based on separation and independent measurements of component flow. An example of construction of separator is presented on Fig. 1.
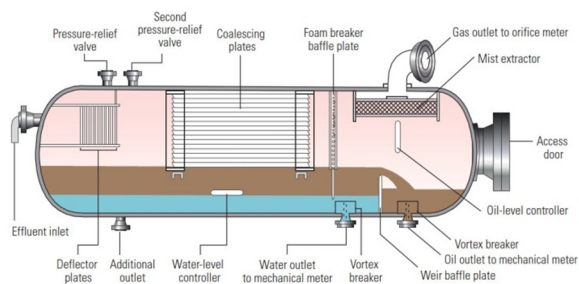

Fig. 1. Schematic design of water/oil/gas separator [1]

After separation of the components, fluid flow is measured by mechanical meters, gas flow is measured by an orifice meter. Cost of single separator installation comes to about 500 000 US$. Therefore there is a great demand for installation of low cost multiphase meters to avoid use of costly separators. Another type of three phase meter uses Venturi equipped with absolute and differential pressure sensor and dual energy gamma ray detectors. This device measures total mass flow and fractions of gas, oil and water. Different aspects of application of gamma radiation in process tomography is presented by Holstad [5, 6], Tjugum et. al [9, 10].

One of the aims of the research performed within DENIDIA MC ToK project in cooperation of the Institute of Applied Computer Science of the Lodz University of Technology and Department of Physics and Technology of the University of Bergen was to design and test three phase flow meter based on principle of combining three modalities: electrical capacitance tomography (ECT) , resistance tomography (ERT) and gamma ray radiation toography (GRT). Compact three phase flow meters have existed for more than 30 years but they are only working for well-mixed flows in vertical pipes. There is a demand for multiphase flow meters down holes, in the oil production industry, where the pipes are inclined or horizontally positioned.

1. Description of the system

The 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 100x25 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 Lodz University of Technology. In addition to this, a vertical and a horizontal directed narrow gamma beam from two pin sources (AMC.P1, QSA Global) are placed in the radial mid plane of the EIT system. These two beams are detected by two CTZ - sensors (eValuator 1000) including all necessary electronics for giving out a TTS shaped signal equal to number of counts. The presented measurement system was submitted to European Patent Office and a patent was granted by EPO in 2015.

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 closed in 1,5mm thick steel housing.

2. Calibration of the measurement system

Prior to performing measurements in an installation the system has to be calibrated. Calibration of EIT system is performed in few steps.
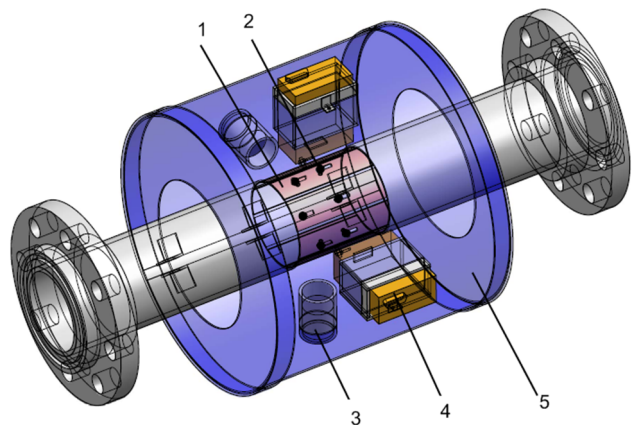
Fig. 2. Schematic view of the sensor: 1-ECT copper electrodes, 2- ERT pin electrodes, 3-gamma source holder, 4-eValuator 1000 gamma ray detector, 5-steel gamma ray protective housing
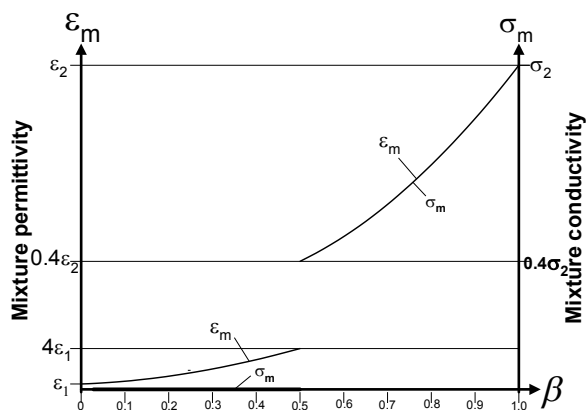

Fig. 3. Mixture permittivity and conductivity versus the volume fraction of component 2 of a homogeneous mixture of component 1 and 2. Only component 2 is conductive [3]

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 other modalities – resistance and gamma radiation were also introduced.

2.1. The ECT-system

The ECT- system must be calibrated at empty pipe and the pipe filled with oil, and the calibration data stored in the flow computer. It can also be calibrated at distilled water to control the validity of the calibration equations.

1) Pipe filled with gas:
$$C_i^{gas} = K_i^{gas} \varepsilon_0 \varepsilon_{gas} \qquad (1)$$

2) Pipe filled with oil:
$$C_i^{oil} = K_i^{oil} \varepsilon_0 \varepsilon_{oil} \qquad (2)$$

3) Pipe filled with distilled water:
$$C_i^{w_d} = K_i^{w_d} \varepsilon_0 \varepsilon_{w_d} \qquad (3)$$

where i = 1-2,1-3,…1-N, 2-3, 2-4…..2-N…… N=total numbers of electrodes, $\varepsilon_0 \varepsilon_{gas}$, $\varepsilon_0 \varepsilon_{gas}$, ε_{w_d} are dielectric constant and relative permittivity of gas, oil and distilled water respectively.

$$K_i^{gas} = \frac{C_i^{gas}}{\varepsilon_0 \varepsilon_{gas}} \qquad (4)$$

Thus all the K_i^{oil}, $K_i^{w_d}$, K_i^{gas} can be derived from equations corresponding to water and gas.

2.2. The ERT-system

The ERT-system can only be calibrated at salt water. Since this tomograph is mainly intended for use in the North Sea, sea water or water at same conductivity (5 S/m) should be used.

1) Pipe filled with saline water:
$$R_i^{w_s} = K_i^{w_s} \frac{1}{\sigma_{w_s}} \qquad (5)$$

where values for i are the same for all electrode pairs, as for ECT system. Thus

$$K_i^{w} = R_i^{w} \sigma_{w_s} \qquad (6)$$

2.3. The GRT-system

The used system consists of two perpendicular narrow beams. It is therefore not a full tomography system but never the less of necessity it helps in a three-component flow specially designed for horizontal pipes. Calibration procedure of the GRT-system is performed in a similar way, sensor is filled with all flow components: gas, oil and water.

1) Pipe filled with gas:
$$I_{gas} = I_0 e^{-\mu_{gas} D - 2\mu_d d} \qquad (7)$$

2) Pipe filled with oil:
$$I_{oil} = I_0 e^{-\mu_{oil} D - 2\mu_d d} \qquad (8)$$

3) Pipe filled with water:
$$I_w = I_0 e^{-\mu_w D - 2\mu_d d} \qquad (9)$$

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.

Using ECT it is often difficult to determine the border between gas and oil. It is usually easier to determine the interphase between water and oil where the difference in electrical permittivities are large (71/2.3). This inter-phase border can be applied to increase the accuracy of determining the border between oil and gas using the GRT. If the sensor is filled with a mixture of the components: gas, oil and process water, the linear absorption coefficient along the gamma ray beam in an oil/gas/water- mixture can be presented in the following form:

$$\mu_{mix} = \mu_{gas} \alpha_{gas} + \mu_{oil} \alpha_{oil} + \mu_w \alpha_w \qquad (10)$$

$$\alpha_{gas} + \alpha_{oil} + \alpha_w = 1, \; \alpha_{oil} = 1 - \alpha_{gas} - \alpha_w \qquad (11)$$

This gives:

$$\mu_{mix} = \alpha_{gas}(\mu_{gas} - \mu_{oil}) + \alpha_w(\mu_w - \mu_{oil}) + \mu_{oil} \qquad (12)$$

where α_{gas}, α_{oil} and α_w are the fraction of the components in the gamma beam and μ_{mix}, μ_{mix}, μ_{mix} are linear absorption coefficients of gas, oil and water respectively.

Elapsed number of counts for the multi-phase mixture can be described by the following formula.

$$I_{mix} = I_0 e^{-\mu_{mix}D - 2\mu_d d} =$$

$$= I_0 e^{-\alpha_{gas}(\mu_{gas}-\mu_{oil})D - \alpha_w(\mu_w-\mu_{oil})D - \mu_{oil}D - 2\mu_d d} \quad (13)$$

$$\frac{I_{mix}}{I_{gas}} = e^{-\alpha_{gas}(\mu_{gas}-\mu_{oil})D - \alpha_w(\mu_w-\mu_{oil})D - (\mu_{oil}-\mu_g)D}$$

Since α_w is known from the EIT image we can find α_{gas} from gamma measurements. After some calculations the fractions of different phases can be derived from the following formulae:

$$\alpha_{gas} = \frac{\ln\frac{I_{mix}}{I_{oil}} - \alpha_w \ln\frac{I_w}{I_{oil}}}{\ln\frac{I_{gas}}{I_{oil}}} \quad (14)$$

$$\alpha_{oil} = \frac{\ln\frac{I_{mix}}{I_w} - \alpha_{gas} \ln\frac{I_{gas}}{I_w}}{\ln\frac{I_{oil}}{I_w}} \quad (15)$$

Examples of GRT sensor calibration are shown in the following table.

Table 1. Gamma sensor calibration.

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

3. Experimental results

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. Experimental setup of the installation is presented in Figure 3. After calibrating of the system (ECT, ERT, GRT) the flow measurements were performed for series of two phase and three phase flow compositions.

The following graphs present measurements performed for liquid mixture containing 50% of sea water and 50% 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 measurements captured while start of the pump and volume fraction oscillations leading to water/oil emulsion. The graphs of ECT and ERT show relative values of capacitances and resistances. The negative values of capacitances are caused by salt water and noise component of the signal. GRT graph shows oscillations of counts acquired by vertical and horizontal gamma sensor. Horizontal axis corresponds to gamma counting periods.

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, 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.
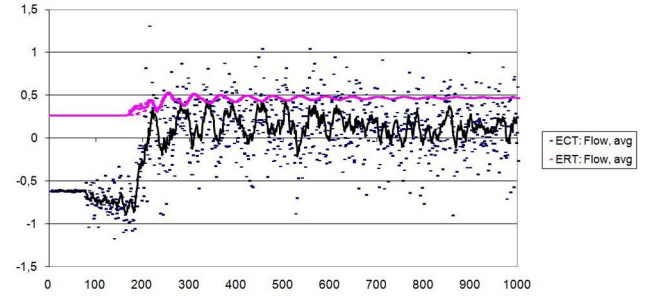

Fig. 4. Measurements of relative values of capacitances and resistances while pump start in a flow rig. Rig filling: 50% sea water, 50% Diesel oil. Horizontal axis: measurement frames

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 defining and generating mesh modelling the sensor. The user defines geometrical parameters of the sensor and mesh by submitting sensor dimensions and mesh density parameters.
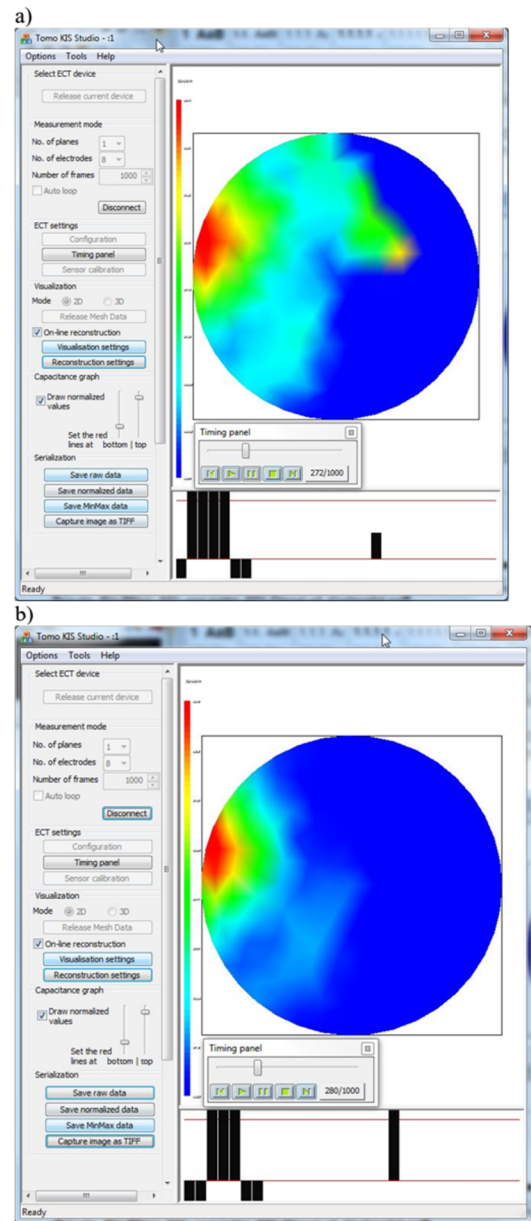

Fig. 5. Image reconstructed from ECT sensor a), and ERT sensor b)

The TomoKIS Studio software is constantly under development. The current version allows processing data acquired from different tomography devices owned by the Institute of Applied Computer Science. 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.

To calculate all three phase fractions in the flow, new software for gamma ray measurements and processing was developed. The program allows acquiring, 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 100ms, 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.
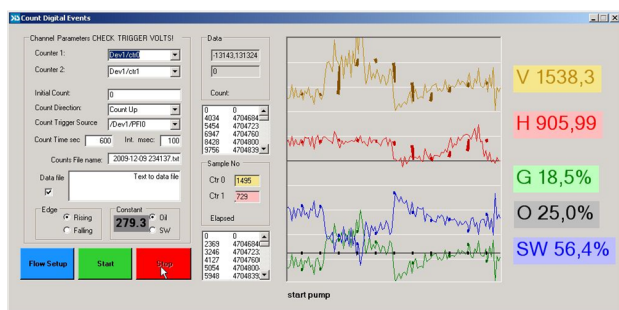

Fig. 6. Flow composition measurements for mixture 50% of sea water and 25% of diesel oil

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, gamma) 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 1s, the count oscillations, which are normal for eV1000 signal show, that calculated real water fraction is around 6% higher.

4. 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 strongly helps 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%. 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.

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