

Water cut determination in co-current liquid-liquid flow using electrical capacitance metering

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Abstract

Despite intensive research dedicated to multiphase flow measurement in the past decades, accuracy remains one of the key challenges in the oil and gas industry. The Multiphase flow of gas-liquid mixtures has been extensively addressed in the literature. However liquid-liquid flows, are intrinsically more complex and their hydrodynamics are not yet completely understood.

The present study investigates the capabilities of in-line tomography technologies for water cut determination in co-current immiscible liquid-liquid flows. The proposed experimental metering system operates by interrogating the imaging region contained by the pipe walls with a high-frequency alternating electric field. The experiments are conducted on the horizontal section of a flow rig of 100mm in diameter using synthetic oil and saline water as test fluids. Measurements of stratified flows from electric capacitance tomography are contrasted to measurements from an electrical capacitance meter. Measurements enable the computation of water cut in horizontal pipes for diverse flowrates. The results show for the first time the potential of using high frequency non-intrusive electric capacitance meters for oil-water flow measurement.

1 Introduction

Multiphase flows are present in a vast number of industrial processes, including the chemical, aeronautical, food, and petroleum industries. The oil and gas industry, in particular, has led the advances in multiphase flow measurements since its early implementation in oilfields in the late 1990s [1]. Accurate multiphase flow measurement in pipelines is of paramount importance throughout the oil and gas value chain. Multiphase liquid flows are present in a variety of process, particularly in the transport of currents downstream the separation vessels all the way through the storage and dehydration facilities. Fluids flowing through pipelines present a variety of flow structures which are inherently dependant on the rheological characteristics of the phases and the process conditions. Measurement of multiphase flow in pipes is largely affected by this spatial distribution of the flow structures [2]. The hydrodynamics of liquid-liquid flows are highly complex due to the low density and viscosity ratios, and the effect of the interfacial tension. This makes the pattern characterisation and hence accurate measurement of liquid-liquid flow challenging [3].

The present study focusses on the use of in-line measurement of segregated horizontal oil-water flows. Here, a combination of electrical capacitance techniques is presented. The metering systems infer the phase concentrations based on measurements of the dielectric properties of the fluid flow [4]. This work investigates the capabilities of the Electric Capacitance Tomography (ECT) for co-current immiscible liquid-liquid measurement. The measurements of the ECT are contrasted against single-pair electrode capacitance measurements.

Following the analysis of the experimental data, the influence of the volumetric fractions on the measurements is assessed. The correlation between the measurement and the phase distribution is presented here.

The remainder of the paper is organised as follows: section (2) describes the methodology of the study and describes the experimental facilities used for measurement of the single-phase flows as well as eleven multiphase oil-water mixtures. The results of

the experimental campaign are discussed in section (3). Section (4) derives the numerical expression for water cut computation from experimental electric capacitance measurements. Finally, a brief summary of the most relevant findings is presented in section (5).

2 Material and Methods

The experimental campaign accounted for metering of the flow dielectric properties by means of two meters. Details of the experimental facilities and metering devices is presented following.

2.1 Multiphase flow rig

Experiments were conducted at the iPhase multiphase flow loop in Basingstoke, UK, illustrated in Figure 1. The experimental loop comprises a recirculation rig that uses gravimetric separation of the fluids in continuous operation. The liquid flows are recirculated around the test facility using centrifugal pumps. The injection flows are controlled by an automated circuit led by turbine flow meters located at the separation vessel outlet. The three-phase gravity separator, with a capacity to segregate the water and oil phases, also serves as a liquid storage tank.

The horizontal experimental segment of 100mm diameter and 3m long (30D) contains a clear acrylic section that allows visualization of the flow prior metering. Experiments were conducted at controlled laboratory conditions at a temperature of 20°C. The working liquids used on the loop were Ultramax10 oil and saline water. The experimental matrix and flow conditions are summarised in Table 1.

Table 1. Conditions for experimental liquid-liquid flow measurement.

Water cut (%)	{0,25,30,35,40,45,50,55,60,65,70,75,100} ±2%
Pressure (psig)	3
Temperature (°C)	20
Oil superficial velocity (m/s)	0.11 – 0.32
Water superficial velocity (m/s)	0.11 – 0.32
Oil type	Exol Ultramax10
Oil density (kg/m³)	851
Oil relative permittivity	2.156 – 2.224
Water conductivity (S/m)	1.05



Figure 1 Flow rig diagram showing the metering system on the horizontal test section.

2.2 Electrical Capacitance metering

Electric Capacitance Tomography (ECT) is a non-intrusive tomography technique that has been largely used for imaging and velocity measurement of non-conducting two-phase flows [4] [5]. ECT applications concerning the Oil and Gas Industry, have proved highly accurate in oil-gas metering [6] [7]. However, its use for conductive phases has been restricted to mixtures with low water cuts [8].

The principle of operation of ECT is based on the sensitivity of the electrodes to changes in the dielectric properties of the fluid contained within the imaging region. The difference between the permittivity of the fluids give rise to variations in the inter-electrode capacitance measurement. Hence, the measurements from the sensing electrodes are directly proportional to the distribution of the dielectric properties within the pipe.

The sensor array was arranged around the outside of the horizontal test section of the rig. ECT measures the capacitances between combinations of pairs of electrodes placed around the perimeter of the pipe. The meter comprised 16 electrodes arranged in two measurement planes of 8 sensors each. All unique capacitance pairs were measured yielding a full set of measurements. The calibration of the ECT meter used oil and air as reference fluids. When water is present the value of average mixture permittivity may exceed the calibration range, in which case simple extrapolation is used. Secluded single-pair electrode data was also collected for every test point. This allows to correlate the measured capacitance, relative permittivity, and the water cut, which as shown below, is key for high water contents.

The excitation signal used consisted of 24 V peak to peak square wave at a frequency of 2.5 MHz. The experimental setup of the sensor array is illustrated in Figure 2.

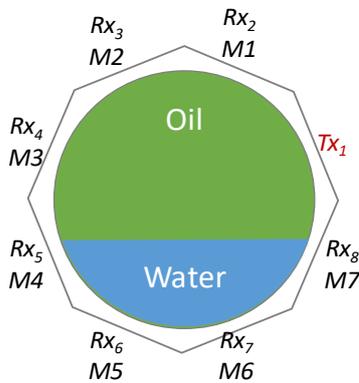


Figure 2 Illustration of the experimental setup showing a transversal view of the sensor array around the pipe perimeter. Example positions of the transmitter (Tx) and receiving sensors (Rx) are shown for a given excitation mode.

3 Results

The calibration of the ECT system is restricted to low permittivity values from air and oil. Water flow through the meter is expected to affect the overall metering accuracy. To address this issue, the ECT measurements are contrasted to single-pair electric capacitance measurements. The results of the study are presented following.

The mean relative permittivity of single-phase flows and low water contents is plotted in Figure 3. The results show two clearly different levels of relative permittivity for single-phase flows, namely air and oil. As the water content increases in the oil-water flow from 25% to 35%, the measured relative permittivity also increases. As expected, the multiphase flow shows relative permittivities larger than the single-phase flows, with an increasing difference as the water cut increases.

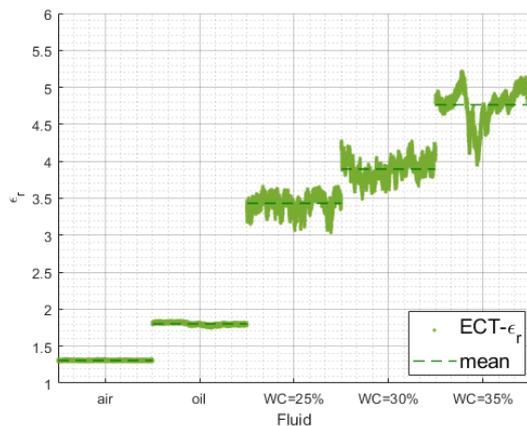


Figure 3 Measurement of mean relative permittivity in the ROI for two single phase flows (air and oil,) and multiphase flow with low water cuts (25% to 35%)

Figure 4 shows the mean relative permittivity of the oil-water multiphase flow within the imaging region and the induced capacitance between the electrode pair T_{x1} - R_{x4} (M3) from the full ECT system (see Figure 2). The results show consistent trends between both measurements for varying water cuts. The increase in water volume, which holds a higher relative permittivity than oil, results in a higher overall mixture permittivity and hence in a larger inter-electrode capacitance for water cuts between 25% and 45%. Conversely, for water contents above 45%, the trend shifts and a slight decrease is evident as the water content continues to increase. The shift in trends suggests an inversion in the coupling mechanism of the electrodes as the conductive phase becomes dominant in the liquid-liquid mixture and the water level reaches the sensor pair T_{x1} - R_{x4} .

Figure 5 shows the capacitance measurements from a selected single-pair electrode. The measurements were gathered at the top section of the pipe at 135 deg from the transmitting sensor (position M3). The two-channel electrical capacitance meter provides a consistent increase in capacitance with increasing water cut throughout all oil-water ratios. The capacitance measurements show improved signal to noise ratio with decreasing water content.

The full 8-sensor ECT provides a larger dynamic range for lower water cuts (25%-45%) but fails to accurately predict the relative permittivity when the conductive phase inundates the pipe cross-section in agreement with [8].

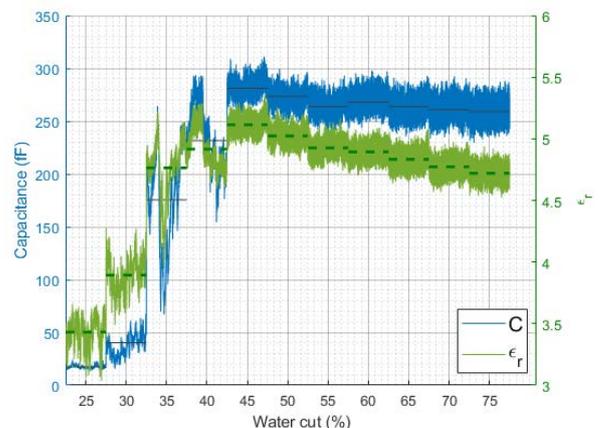


Figure 4 Measurement from the full ECT system of mean relative permittivity in the ROI (green) and capacitance from electrode pair T_{x1} - R_{x4} (blue) for various multiphase flows.

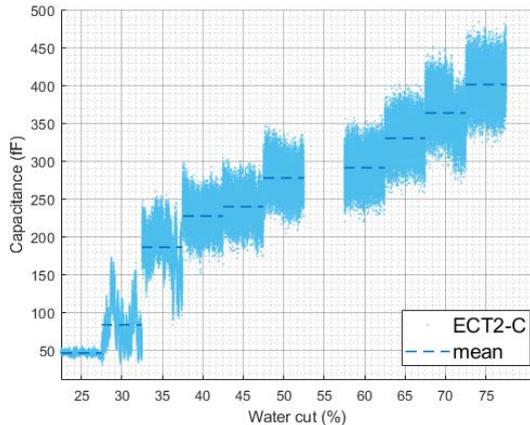


Figure 5 Measured capacitance from a single-pair electrode located at the top of the pipe.

The difference seen in the measurements at high water cuts from both meters plotted in Figure 4 and Figure 5 can be attributed to the inherent signal compensation that occurs during the solution of the inverse problem of the full ECT system.

4 Water cut prediction

The quasilinear trend of the single pair electrode measurement seen in Figure 5 allows back-computation of the water cut in the pipe. Through multiple regression analyses, the influence of the volumetric fractions on the mean measured capacitance was assessed by fitting the measured data with quadratic curves. The capacitance was determined to vary against the water content in the stratified flow a ratio given by Equation (1). The developed correlation describes over 96% of the variability of the measurement.

$$C_{M3} = [2931(WC) - 73570]^{\frac{1}{2}} \quad (1)$$

where C_{M3} is the capacitance in pF measured from the electrode pair $T_{x1}-R_{x4}$ at the measurement position M3 (see Figure 2) and WC is the water volumetric fraction expressed in percentage.

The predicted water cut against the reference water flowrate is illustrated in Figure 6. Results show a significant linear relationship between predicted and reference values with an overall fitting inside the $\pm 10\%$ deviation range.

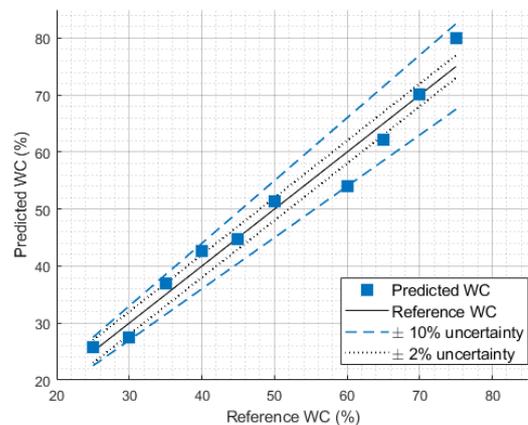


Figure 6 Predicted water fraction against reference measurements showing data dispersion around linear trend.

5 Conclusions

An 8-sensor ECT meter was used to measure oil-water flows in horizontal pipes. ECT was found to be able to recognise changes in liquid-liquid concentration for low water ratios.

The analysis of data from selected electrodes pairs indicated that electric capacitance meters are sensitive to changes in flow concentrations regardless of the conductive properties of one of the phases or its volumetric fraction. A correlation for water cut computation was developed from single-electrode pair measurements. The water cut predicted provides an uncertainty range below 10% over a spectrum of water cuts from 25% to 75%.

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References

- [1] G. Falcone and B. Harrison, "Forecast expects continued multiphase flowmeter growth," *Oil Gas J.*, vol. 109, no. 10, pp. 25–34, 2011.
- [2] R. Thorn, G. a Johansen, and B. T. Hjertaker, "Three-phase flow measurement in the petroleum industry," *Meas. Sci. Technol.*, vol. 24, pp. 1–17, 2012.
- [3] R. Ibarra, I. Zadrazil, C. N. Markides, and O. K. Matar, "TOWARDS A UNIVERSAL DIMENSIONLESS MAP OF FLOW

REGIME,” in *11th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, 2015.

- [4] M. Zhang, Y. Li, and M. Soleimani, “Experimental Study of Complex-valued ECT,” in *9th World Congress on Industrial Process Tomography*, 2018, pp. 19–24.
- [5] X. Zhu, P. Dong, and Z. Zhu, “Gas-solids Flow Measurement in Cyclone Dipleg by Dual-plane Electrical Capacitance Tomography Sensor,” pp. 203–209, 2018.
- [6] A. Hunt, L. A. Abdulkareem, and B. J. Azzopardi, “Measurement of Dynamic Properties of Vertical Gas-Liquid Flow,” *7th Int. Conf. Multiph. Flow*, pp. 1–10, 2010.
- [7] R. Yan and S. Mylvaganma, “Flow Regime Identification with Single Plane ECT Using Deep Learning,” in *9th World Congress on Industrial Process Tomography*, 2018, pp. 289–297.
- [8] A. Hunt, “Industrial Applications of High-speed Electrical Capacitance Tomography,” in *9th World Congress on Industrial Process Tomography*, 2018, pp. 857–864.