Volume Fraction Determination of an Oil-Continuous Three Phase System using Electrical Capacitance Volume Tomography

Joshua Sines[1], Benjamin Straiton[1], Christopher Zuccarelli[1], Qussai Marashdeh[1]

[1]*Tech4Imaging, 1910 Crown Park Ct, Columbus, Ohio, 43235, USA*

ABSTRACT: Electrical Capacitance Volume Tomography (ECVT) is a real-time 3D imaging and measurement technique for the on-line study of multiphase flow behavior. Here, it is applied for the study of a static three phase oil-water-gas system. A cylindrical test column was constructed and an experiment conducted where the air and water volume fractions were varied in an oil continuous background. An ECVT system was used to capture real-time data about the system and this data was analyzed to determine the volume fraction of the three phases and analyze the systems accuracy in determining these volume fractions.

Keywords: Three-Phase, Three-Phase Flow, Gas-Liquid-Liquid, Oil-Water-Gas, Volume Fraction, Void Fraction, Electrical Capacitance Tomography, Electrical Capacitance Volume Tomography

I. Introduction

Three-phase gas-liquid-liquid flows serve an important role in numerous industrial processes. In these processes it is often beneficial to know the volume fractions of the three separate phases to ensure that the process is running at maximum efficiency.

Many fluid dynamic simulations and equations have been used to try to predict the behavior of various three-phase flows. However, actual three-phase flow dynamics are very complex and not easily modeled and simulated. Numerous measurement tools have been used for experimental analysis of three-phase flows but these often use invasive techniques such as venturi flow meters or radioactive methods such as gamma spectroscopy. A more practical method of flow validation is desired for the on-line monitoring of these reactions. Electrical Capacitance Volume Tomography (ECVT) is a noninvasive, real-time imaging and measurement method that can be used for the study of three phase gas-liquid-liquid flows.

II. Theory

ECVT is a natural extension of Electrical Capacitance Tomography that collects noninvasive capacitance measurements on a 3D space. An ECVT system consists of three major components: a passive sensor comprised of plate electrodes which surround a region to be studied, a data acquisition system that sends and receives electric fields from the sensor, and software to interface with the acquisition system and interpret its data in real time. Figure 1 shows a diagram of these three components.

With this ECVT system, distributions of electric field are measured with the multitude of electrodes on the sensor. The measured fields are related to the dielectric constant distribution within the sensing region via proprietary algorithms within the Tech4Imaging software [1].

Figure 1: The three major components of an ECVT system (from left to right): a sensor surrounding the flow, a data acquisition system, and data analysis software.

ECVT as a capacitance tomography technology has only one dimension of measurement (the capacitance between plates) and therefore can only measure two phase flow. New dimensions have been introduced by using the Maxwell-Wagner-Sillars (MWS) effect for three or more phases [2] and Displacement Current Phase Tomography (DCPT) for water based flows [3].

As this experiment measured a non-water continuous three phase system, an ECVT-MWS approach was used for volume fraction measurements. The MWS effect is a consequence of surface polarization at the interface between conducting and non-conducting phases (such as a mixture of air-water-oil). A mixture containing conducting and non-conducting phases will exhibit pronounced changes in frequency response due to the MWS effect. This effect is much stronger when the conductive phase(s) is dispersed in a non-conducting phase. The frequency response also depends on the phase volume fractions, the distribution of the conducting phase(s), and the conductivity values of the conducting phase(s).

The MWS effect can then be utilized to develop a relation between each phase's volume fraction and data collected from the ECVT system. To take advantage of the changes in frequency response due to the MWS effect, ECVT data is collected at two different frequencies on either side of the roll-off frequency. The capacitance signal due to the conducting, frequency dependent phase is derived by subtracting the high frequency data from the low frequency data.

$$c^{md} = c^{ml} - c^{mh} \quad (1)$$

This conducting phase signal can then be used to extract the volume fraction of the conducting phase(s).

The capacitance signal due to the non-conducting phases is derived by subtracting the conducting phase signal from either the low or high frequency signal.

$$c^{mn} = c^{ml} - \gamma_1 c^{md} = c^{mh} - \gamma_2 c^{md} \quad (2)$$

γ_1 and γ_2 are chosen constants where $\gamma_1 - \gamma_2 = 1$. The optimum values of these constants are derived through experimental analysis. This non-conducting phase signal is then used to extract the volume fraction from the non-conducting phase(s). The MWS effect and it's relation with ECVT are discussed further in [2].

This ECVT-MWS effect is applied experimentally on an oil-continuous system with air and water voids in the following sections.

III. Experimental Setup

The column used was an acrylic tube with an outer diameter of 2.5 inches (6.35 cm), an inner diameter of 2.25 inches (5.72 cm), and a length of 1 foot (30.48 cm). Acrylic tubes with outer diameters of 1.125 inches (2.85 cm), 1 inch (2.54 cm), 0.75 inches (1.91 cm), and 0.625 inches (1.59 cm) were used as the inserts.

The ECVT sensor had an inner diameter of 2.5 inches (6.35 cm), and a height of 9.0 inches (22.86 cm). The ECVT sensor consisted of 24 plate-shaped electrodes, in four axial layers of 6 plates each. This sensor was attached to the exterior of the acrylic tube, with the sensor's bottom end 1 inch (2.54 cm) above the rubber stopper at the end of acrylic tube.

The experimental setup of the ECVT system and bubble column can be seen as a diagram in Figure 2 and a picture in Figure 3.

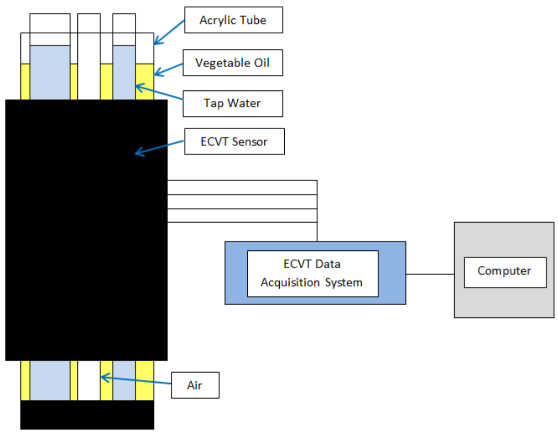

Figure 2: Experimental Setup

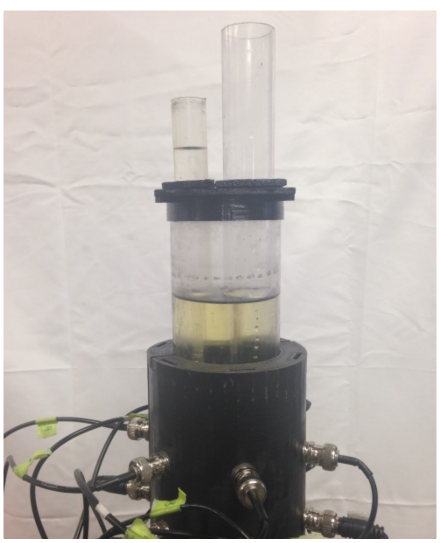

Figure 3: ECVT sensor on oil column with air and water filled inserts

The sensor was connected with coaxial cables to Tech4Imaging's patented Electrical Capacitance Volume Tomography system. This system was used to collect real-time data about the three phase system. The system sequentially excites the sensor plates with an AC voltage and receives readings from the other plates. The plates were excited with a 2-Megahertz wave and a 250-kilohertz wave, both at a 5 V peak amplitude. The system collected an average of 100 measurements a second. The excitation frequency, voltage, and data acquisition speed were all selected based on the flow being studied. The Tech4Imaging ECVT system operating conditions are adjustable to fit into a wide variety of measurement scenarios.

The ECVT system was connected to a PC with a USB 2.0 connection, and the system was controlled with Tech4Imaging's 4Sight software. This software was used to interface and operate the ECVT system, as well as analyze the system data in real-time and in post-processing.

The acrylic tube was filled with vegetable oil to a height of 11 inches (27.94 cm), with the oil level rising 1 inch (2.54 cm) above the top of the ECVT sensor. Vegetable oil was used as it has a similar dielectric to other oils (~3) and is easy to work with. The smaller acrylic tubes were inserted into the sensor vessel in varying combinations of tubes. The fluid inside of the insert tubes was also varied between air and water to achieve a variety of water-air-oil volume fractions within the sensing region.

The following volume fraction ranges were tested: Air 4%-48%, Water 4%-48%, Oil 48%-87%. All the insert tubes went completely through the sensing region so the actual volume fractions were equal to the ratio of air and water tube cross sectional area versus the cross sectional area of the whole sensing column. The region of the three phase triangle is highlighted in Figure 4.

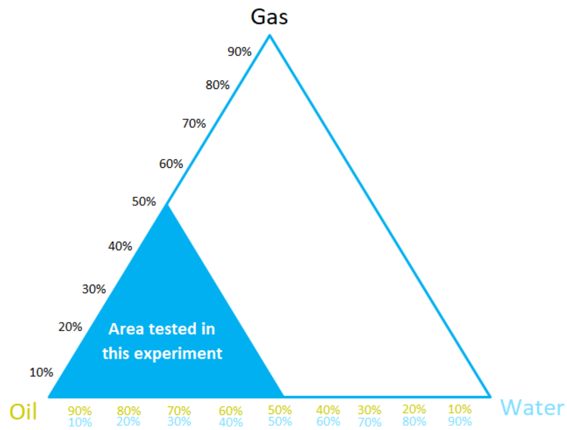

Figure 4: Area of the Three Phase Triangle Tested in this Experiment

In the three phase triangle the corners represent a single phase flow, the edges represent a two phase flow between the respective corners, and the middle represents a three phase flow of varying volume fractions.

The experiments were conducted at standard temperature and pressure.

IV. Experimental Results

The real time water, air, and oil volume fractions were calculated by relating the differential frequency readings from the ECVT Data Acquisition System to each phase volume fraction per the ECVT-MWS analysis methodology [2]. Table 1 shows the actual volume fraction vs the volume fraction extracted using ECVT-MWS for each test.

Table 1: Actual vs Calculated Volume Fractions

Volume Fraction (%)					
Air		**Water**		**Oil**	
Actual	Calculated	Actual	Calculated	Actual	Calculated
16	11.94	6.25	5.97	77.75	80.56
6.25	7.85	16	9.22	77.75	80.46
4	8.26	16	9.26	80	80.15
16	13.90	4	4.08	80	80.78
6.25	10.94	9	7.73	84.75	79.72
9	13.21	6.25	6.05	84.75	79.81
4	10.74	9	7.24	87	80.32
9	12.97	4	5.59	87	79.94
16	9.39	6.25	7.97	77.75	79.69
6.25	1.05	16	16.2	77.75	78.10
4	1.03	16	16.34	80	77.96
16	10.23	4	7.36	80	79.97
6.25	8.10	9	9.79	84.75	78.93
9	9.09	6.25	9.02	84.75	79.24
4	6.08	9	11.53	87	78.97
9	9.77	4	7.87	87	79.79
4	15.26	16	17.07	80	71.26
16	28.96	4	5.055	80	72.62
25	28.48	4	5.45	71	72.40
9	17.13	20	15.07	71	70.99
4	8.83	25	22.19	71	70.68
16	13.00	13	18.68	71	71.42
13	19.96	16	12.42	71	71.48
20	22.59	9	9.73	64.7	72.61
4	6.22	31.3	38.64	64.75	56.21
10.25	8.26	25	22.74	64.75	70.64
19.25	20.06	16	12.85	56	70.94
37.77	24.97	6.25	8.40	56	71.68
28	18.78	16	13.65	48	71.64
48	28.89	4	2.42	48	74.64
4	5.19	48	45.07	77.75	51.01
16	11.69	6.25	6.76	77.75	79.81
6.25	3.31	16	13.96	80	79.01
4	3.35	16	13.95	80	78.99
16	14.44	4	4.10	84.75	80.43
6.25	7.24	9	12.10	84.75	77.85
9	12.86	6.25	6.04	87	79.80
4	7.24	9	12.12	87	77.81
9	14.10	4	4.49	75.33	80.24

The ECVT absolute error was plotted against the volume fractions of water, air, and oil as can be seen in Figure 5.

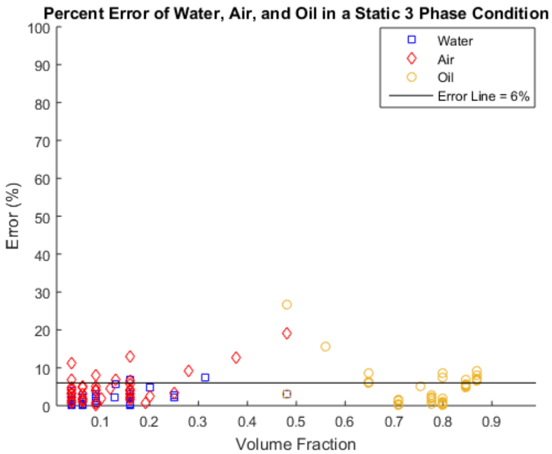

Figure 5: Percent Error for ECVT Calculated Volume Fractions

Using this method the average absolute error is 3.95% with 85% of the values below a 6% absolute error.

V. Conclusions

Three-phase gas-liquid-liquid flows tend to be complex and difficult to measure with non-invasive or non-radioactive techniques. Electrical Capacitance Volume Tomography can be used in conjunction with the Maxwell-Wagner-Sillars effect to accurately and non-invasively measure the volume fraction of each phase in a gas-liquid-liquid system. This makes ECVT the ideal technique for the volume fraction measurement of three phase systems.

VI. References

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