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Liquid Holdup Measurement in Crude Oil Transportation Using Capacitance Sensors and Electrical Capacitance Tomography: Concept Review

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Abstract. Liquid holdup is one of the most significant parameters in multiphase flow. Accurate measurement of liquid holdup is required to calculate pressure drops in oil and gas wells which is essential in analyzing the well production, performance, well designing and optimization. This study reviewed different methods used in measuring liquid holdup and highlighted the most effective methods currently used in multiphase combinations. More importantly, liquid holdup measurements using capacitance sensors in slug flow, bubble flow, churn flow, annular flow and coaxial flow are discussed. The features considered during the review include, electrode material, angle of rotation, curvature and guard electrodes. The operational issues observed when using capacitance based sensors were highlighted. In single capacitance sensors like the helical arrangement which has high sensitivity, error in symmetry and inability to measure fluids with lower dielectric constants were however observed. Concave sensors are more accurate for phase shift detection but lower sensitivity compared to the helical type. From the knowledge and technical gaps identified from literature, this study proposed Electrical Capacitance Tomography tool with dual capacitance sensor for effective liquid holdup measurement in oil and gas transportation pipelines because of its ability to determine the dielectric permittivity distribution inside the pipeline from external capacitance measurements with real-time imaging of the multiphase flow.

Keywords: Concave and helical capacitance; Sensors; Liquid holdup; Hydrocarbon pipeline; Transportation.

1. Introduction

Accurate prediction of the pressure gradient is crucial for production, design and optimization of oil and gas wells. The most important parameter in calculating multiphase pressure drops in wells is Liquid Holdup [1]. A value for Liquid Holdup cannot be calculated analytically. It must be determined from empirical correlations and is a function of variables such as gas and liquid properties, flow pattern, pipe diameter and pipe inclination. Liquid holdup (H_L) measurement required to develop empirical correlations can be obtained experimentally by several methods [2]. Liquid holdup H_L , is defined as the fraction of an element of pipe which is occupied by liquid at a given time. The remainder of the pipe segment is occupied by gas. Gas holdup, $H_g = 1 - H_L$.



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Calculation of holdup is complicated by the phenomenon of gas/liquid slip. Gas, being less dense than liquid flows with a greater vertical velocity than liquid [3]. The difference in velocity between the gas and liquid is termed the slip velocity. The effect of slip is to increase the mixture density and hence the gravity pressure gradient. It is essential to be able to determine liquid holdup to calculate such things as mixture density, actual gas and liquid viscosities, effective viscosity and heat transfer. The value of liquid holdup varies from zero for single-phase gas flow to one for single-phase liquid flow [4].

Many different methods have been introduced to measure liquid holdup, some of which include Laser-Doppler Methods (Light), Ultrasonic (Sound), Gamma Ray or Neutron Absorption (Nuclear), and Capacitance or Conductance Probes (Electricity). Capacitance sensors are widely used in multiphase flows. It can be used to estimate the hold-up in a given section of the pipe, taking advantage of the different permittivity values of the two liquids or the multiphase flow.

1.1 Flow regimes in vertical and horizontal multiphase flow

The most important characteristics of multiphase flow are the flow pattern, $\epsilon(L)$ (including holdup fluctuations), gas holdup (that is, void fraction) and pressure drop [5]. The determination and identification of multiphase flow patterns is of great importance because $\epsilon(L)$ and pressure drop are highly dependent on the flow pattern [6]. Hence, the flow pattern is a defining feature of multiphase flow. A clear understanding of the flow patterns and the ability to accurately predict the type of flow is extremely important in designing pipelines and in calculating pressure drop and holdup, because each flow pattern has a different effect on these calculations. The prediction and calculation of two-phase flow are highly complex because they involve multiple variables including transfer of momentum, heat and mass, as well as the slippage between the two phases and the presence of interfaces [7]. Furthermore, the conductor cross section and configuration, flowrate, direction and inclination significantly affect the flow patterns, pressure drop and $\epsilon(L)$. Adding to the complexity of multiphase flow, the difference in densities between the components causes slip of the less dense fluids in the pipe. Another influential factor is the inclination angle of the pipe and the direction of flow where both significantly affect the flow patterns and $\epsilon(L)$ [25].

Multiphase flow is the concurrent flow of two or more phases; liquid, solid or gas, where the motion influences the interface between the phases. The flow regime or flow pattern is a qualitative description of the phase distribution in the pipe [8]. Flow pattern in pipes is governed by the diameter of the pipe, the physical properties of the fluids and their flow rates. Pipeline transportation of natural gas in the presence of a liquid phase or mixture of crude oil and water are examples of two-phase flow. Three phase flow can either be gas-liquid-solid, gas-liquid-liquid, solid-liquid-liquid flows. For the purpose of this review, gas-liquid two and three phase flow was considered.

Flow regimes in horizontal flow can be classified into stratified, wavy, bubbly, annular, slug or intermittent and plug or elongated bubble flow. Bubble flow in which gas bubbles tend to float at the top in the liquid; stratified flow in which the liquid flows along the bottom of the pipe and the gas flows on top [9]. Intermittent or slug flow is flow in which large frothy slugs of liquid alternate with large gas pockets, and annular flow in which a liquid ring is attached to the pipe wall with gas blowing through [10],[11]. Usually, the layer at the bottom is very much thicker than the one at the top. Spedding and Spence [12] studied flow regimes in two-phase multiphase flow and highlighted that the existing models for prediction of flow patterns are deficient in handling changes in physical properties and geometry. They proposed that a more satisfactory method or approach be developed for predicting phase transition in gas-liquid flow. Wu et al. [13] examined the critical factors of pipe geometry, fluid properties and flow conditions that affect the transition from one flow regime to another. They believe that the important information concerning the flow regimes is often ignored, and these includes: the void fraction, or gas holdup. Udara et al. [14] used pressure differential and time series analysis of the

liquid holdup to characterize flow regimes and established criteria for the transition between flow regimes using parameters such as pressure and density.

In the oil and gas industry, it is recognized that the implementation of control strategies and the design of multiphase flows can bring significant benefits in terms of well testing, reservoir management, production distribution, production monitoring, capital costs and operating expenses. It is recognized. The most striking aspect of multiphase flow is the change in the physical distribution of phases in the flow tube. This property is known as a flow regime or flow pattern. Existing flow patterns depend on the relative magnitude of the forces acting on the fluid. All these forces, such as buoyancy, turbulence, inertia, and surface tension, are highly dependent on rate of flow, pipe diameter, deviation angle and phase fluid properties.

Thus, predicting the flow patterns within a pipe is essential as it is a critical parameter that determines the pressure gradient and liquid holdup in the conduit. Ganat and Hrairi[15] investigated the effect of flow patterns on two-phase flow rate in vertical pipes using oil well and reservoir properties. Ganat and Hrairi[15] observed the effect of flow regimes present in vertical pipes using the OLGA simulation model to simulate the performance of actual well flows under the uncertainty of many input data from well measurements. The multiphase simulation model was used to simulate the state of a multiphase flow in a vertical pipeline and also used to verify the predicted oil flow rate in the well. The well models were developed in accordance with the operating production conditions of each well.

2. Materials and Methods

Although many of the properties of multiphase flows can be measured one by one, there is currently no technique available that can measure all of them. If a flow consists of several phases, it is desirable to be able to measure the mass fractions and mass fraction velocities for all the phases. An accurate measurement of the fraction of the gas-liquid phase is necessary for the optimal modelling of the pressure drop, heat transfer coefficient, mass transfer rate and interface surface area in a two-phase flow. Liu and Bai [16] examined the problem of optical distortion as an approach in liquid holdup and proposed an analytical model for estimating and correcting liquid holdup in an annular gas-liquid flow through a round pipe using the high-speed camera method. Errors in measurements of liquid holdup caused by different refractive indices between a transparent round tube, a liquid film, and an air core were first theoretically analyzed based on geometric optics. Their results showed that the liquid holdup prediction worked well with the experimental data, and the measured liquid holdup was higher than the real one. Maley and Jepson [17] in their study on liquid holdup for large diameter horizontal pipelines observed that for multiphase flow, the liquid holdup begins at the liquid holdup of the liquid film before the slug, and then increases until the end of the mixing zone is achieved. Thus, if the mixing zone of the slug is exceeded, the average liquid holdup becomes constant. Abdul-Majeed [18] simplified and improved on Taitel and Dukler [19] several mechanistic model equations for estimating two-phase liquid holdup in horizontal flow to a single explicit equation. The validation of the single explicit equation showed excellent results and clearly outperformed the original model.

Several empirical correlations and mechanistic models have been developed to predict liquid holdup and to prevent costly production disruptions due to slugging problems [20]. Wen et al. [2] observed that the accuracy of each liquid holdup predictive model is subject to specific conditions. In order to accurately measure liquid holdup, a representative sample of gas is trapped in a section of pipe, and physically measured to determine the volume fraction occupied by the liquid phase. This is commonly done by use of two Quick Closing valves that can be operated simultaneously. However, it often becomes necessary to obtain and average many measurements to ensure accuracy and repeatability [21]. This is obviously a time-consuming process.

In Addition, the use of quick closing valves in the field is not feasible. As a result, to measure liquid holdup continuously, other methods have been tried. The most popular methods are electrical impedance and gamma ray attenuation to determine the phase fractions, followed by microwave and infrared absorption [22]. The void fraction in the region of interest is one of the key

parameters in gas-liquid phase flow systems, as it is used for determining several other important parameters and for predicting heat transfer and pressure drops. These are measured using a number of techniques including radiation attenuation, optical or ultrasound techniques, impedance techniques and quick-closing valves for direct measurement of the volumetric void fraction [23]. Some of the broad categories of sensors used in multiphase flows to estimate the holdup are:

2.1 Nuclear absorption (sensors)

It involves the absorption of γ -, β - or X-rays. They have high time resolution and provide local measurements, that is, length of the measuring volume is quite small. They are also expensive and require safety conditions difficult to guarantee. Usually, the location of these sensors is fixed along the test facility and, once chosen, it is difficult to change. With complex and expensive nuclear sensors, it is possible to obtain the spatial distribution of the fluids inside the pipe (nuclear tomography).

2.2 Electrical probes (either conductive or capacitive)

They are most widely used to measure the hold-up. Conductance measurements are widely used in different applications and allow relatively easy hold-up measurements. They work only when one of the two fluids are conductive and the hold-up is obtained by measuring the resistance of the mixture inside the test section and comparing it with the value of single fluids. Many configurations and shapes of the electrodes can be found in literature [24]. Such probes are relatively simple to manufacture and, since electrodes are flush mounted on the inner pipe wall, they are almost non-intrusive. On the other hand, they have low sensitivity and the calibration may prove tricky.

If both fluids are electrically non-conductive (such as air and oil), the hold-up is measured by capacitance probes [24]. The relation between the pure fluid dielectric constant and the measured effective dielectric constant is used to obtain the hold-up. The electrodes are placed on the external part of the pipe wall, which needs to be non-conductive. When non-conductive pipes are used, multiple measurement sections can be easily placed along the pipe. The possibility to upgrade (in a relatively simple way) a two-electrode capacitance system to Electrical Capacitance Tomography (ECT) is also very attractive [25].

The capacitance sensor measurement technique is a practical and cost-effective method. The technique is non-intrusive and relatively simple to design and implement, one just needs to attach the electrodes on the outer surface of the non-conductive section of the pipe. The estimation is obtained by capacitance measurements between two electrodes, flush mounted on the external surface of the experimental pipe. Usually, capacitance sensors are used to investigate flows with non-conductive fluids, but they have the possibility to work also with conductive fluid [24].

2.3 Capacitance sensors for liquid holdup measurements

When using capacitance measurement technique there are two main aspects to consider:

- i. The configuration of the electrodes; and
- ii. Transducer circuit.

Studies have shown that there is a relationship between configuration of electrodes and type of fluids in two phase flow (conductive and non-conductive) [26]. For liquid/liquid two phase flow, with a conductive liquid, the concave type was recommended. In the case of liquid/gas, with conductive liquid, like air/water system concave type was found to be more sensitive [27]. One of the first investigations was carried out by Abouelwafa and Kendall [28] on the different shapes of the electrodes. Six different configurations were proposed for oil-gas, water-gas, and water-oil flows with the double helical solution recommended as the best for all flow regimes; for certain flow patterns, such as core-annular flow, the concave electrodes are more sensitive [24]. Jaworek and Krupa [29] examined five electrode configurations for air/water system such as double ring, using concave and helical; and found that concave was more sensitive. Also, Dos Reis and Da Silva [30] used a static bench to compare concave, helical and ring electrodes for air/water system, and their

results showed that the concave sensor had the highest sensitivity and the double ring had the lowest sensitivity. Though, their study was conducted only on stratified flow regime.

Geraets and Borst [31] developed a helical capacitance sensor for gas–liquid flows. Helical configuration is not easy to manufacture and the axial length, L of the probe increases the size of the averaging volume. On the other hand, the measured values are independent on the fluid distribution and depend only on fluid quantities. Literature had recorded that a simple capacitance-meter directly connected to such a probe (working frequency 1 MHz) is enough to get good results. The results obtained with such a modified probe compared reasonably well with independent measurements [24]. Tollefsen and Hammer [32] used Finite-Element Method (FEM) simulations to support the design and manufacturing of a capacitance probe for gas–oil and water–oil flows. The Authors compared their simulations with experimental data using deionized water and concluded that to reduce errors in the hold-up, the helical configuration is preferred because it is insensitive to the spatial position of the phases. Jaworek and Krupa [29] proposed a capacitance sensor overcoming the conductive effects of water using an 80 MHz oscillator: hold-up variations give rise to frequency variations; that is, compared to a reference value, can be related to the hold-up value.

Canière et al. [33] developed a capacitance sensor with concave electrodes for gas–water flows. They made an analysis of the sensor signals to obtain an objective discrimination of the flow regimes. They used conductive water and de-ionized water and the core-annular flow obtained with conductive water showed an unexpected behaviour. It was observed that the core-annular signal obtained from de-ionized water was larger than that of water only, that is, they measured a capacitance increase when a fluid with a lower dielectric constant was inserted [34]. The authors claimed that this non-physical behaviour is due to polarization of the water–air interface. Dos Reis and Da Silva [30] proposed a 2D numerical simulations with a capacitance probe to determine the water–film thickness in oil–water core-annular flow, and showed the effects of the core eccentricity on the effective capacitance. For this particular flow regime, simulations show that the opening angle of the concave electrodes has to be lower than the usual one used in capacitance probes [24]. The use of the different techniques depends on the applications and whether a volume averaged or a local void fraction measurement is required. All the techniques in literature are based on the use of a sensor that is sensitive to the variation of the physical properties of the phase mixture, and therefore able to detect the presence of one of the phases. The summary of previous studies from literature proposing Capacitance sensor design were highlighted in the study of [29].

2.4 Simple geometric design models of Capacitance sensors

The capacitance level measurement process involves knowing the capacitance of the sensorial part of the built system. Hu and Yang [35], investigated the sensing mechanism, design challenges, performance evaluation and applications of capacitive sensors. Their findings showed that the sensors of the transmission mode or single-electrode mode were suitable for determining the characteristics of the flow. The distribution of the sensitivity of the sensor largely depends on the shape of the electrode. Xue et al. [36] studied the relation between the geometric parameters design of the sensor and the sensor performance, and concluded that complex structure sensor can improve the measurement linearity, signal strength and measurement sensitivity. Two most widely used capacitance sensors in oil and gas industry are helical and concave capacitance sensors. Others include Ring, Double Ring, Double Helical, and Coaxial Capacitance Sensors. Limitations arise when using capacitance sensors, but they are considered to be less constraining than those presented by some other techniques for oil film thickness and liquid holdup measurement. Some of these popular capacitance sensors in hydrocarbon liquid holdup measurements are discussed below.

2.4.1 Helical Capacitance Sensor: Helical capacitance sensors are often proposed to measure the void fraction of gas-liquid two-phase flow in transportation pipelines of different diameters. Its structure is analyzed using the orthogonal array testing strategy and finite element method. Tollefsen and Hammer [32] demonstrated that 180° and 360° twisted helical sensors exhibited similar trends of response between the capacitance value and holdup, but at different measurement ranges. In this case, a larger

capacitance value obtained from 360° helical configuration is preferable in order to increase the sensitivity of the sensor. In addition, the pitch of helix is better correlated with the 360° helical configurations. Thus, the 360° twisted electrode is selected. Zhai et al. [37] investigated the double helix capacitance sensor for measuring liquid holdup in horizontal oil-water two-phase flow. They applied the finite element method to determine the sensitivity of the sensor in a 20 mm inner diameter pipe. A horizontal oil-water two-phase flow experiment adopted to measure the response of the double helix capacitance sensor, in which a novel method was proposed to calibrate the liquid holdup based on three pairs of parallel-wire capacitance probes. Ye et al. [38] optimized a small diameter helical capacitance sensor for void fraction measurement for gas-liquid multiphase flow. Lim et al. [39] developed a 360° twisted helical capacitance sensor for liquid holdup detection in horizontal two-phase stratified flow pattern. The further examined the sinusoidal relationship between the capacitance value and the holdup was observed and investigated, and good agreement was reached between the finite element model and the approximate model. In addition, all design parameters were analyzed and studied to determine their intersection and their effect on symmetry on the sinusoidal function introduced. Static experiments with stratified air-water and oil-water flows justified the proposed sinusoidal function. Ye et al. [38] highlighted that the helical sensor is significantly less dependent on the angle of orientation of the electrodes in stratified flow than the classical surface plate capacitance sensors with straight electrodes. Their study concluded that helical capacitance sensor demonstrates a good linearity between the capacitance value and the void fraction to be measured. In addition, the helical capacitance sensor has a good adaptability to different flow patterns.

2.4.2 Concave Capacitance Sensor (CCS): The concave capacitance sensor consists of an exciting electrode, a measuring electrode, and shield electrodes. All the electrodes are flush mounted on the outside of the pipe wall. The main geometric parameters of the CCS are the electrode length, the electrode angle θ , the pipe wall thickness δ , and the pipe inner radius R [40]. Strazza et al. [24] proposed a concave electrode sensor system for oil/ conductive water flows. The novelty was on the proposed modelization to the problem of capacitive sensing in presence of conductive fluids. The new approach gave a new design method for the working frequency and the electrode measurement head.

The void fraction is an important parameter measured in a gas-liquid flow for estimating liquid holdup. Because two-phase flow in pipelines is very common in the oil and gas industry, it makes the holdup measurement a very challenging problem. Various designs of two-electrode capacitive sensors for measuring void fractions were analyzed and optimized by Lim and Tang [41]. From literature a conventional two-electrode concave capacitive sensor showed high sensitivity, but it is most affected by the air-water distribution. Most studies have only investigated the concave construction of the two electrodes. But, Lim and Tang [41] advanced the concave structure study by dividing the electrodes into 2, 4 and 6 using the finite element method. The sensitivity of the sensor, the effect of the air-water distribution, and the linearity of the response was analyzed and compared. Numerical results showed that the four-electrode concave sensor is more suitable for measuring the fraction of voids in a gas-liquid flow than a conventional two-electrode sensor [41].

Pal and Vasuki [42] compared low cost and non-invasive design of the concave capacitive sensor through analytical evaluation and experimental validation to estimate the void fraction of a non-metallic pipe. Their proposed symmetrical geometry design was based on the ability to reduce the fringing effect. The study concludes that the change in capacitance was continuous and the resolution of the system depends on the resolution of the capacitance measuring system. Beh et al. [43] applied finite element method to analyze a three-dimensional model of concave capacitance sensor used for holdup measurement in two-phase flow. During their sensitivity analysis, it was observed that the concave capacitance sensors average sensitivity increased during the shift from two-plate to four plate design. Xie et al [44] in their study on sensitivity distribution of concave capacitance sensor highlighted the huge influence of pipe wall thickness on the sensitivity results.

2.4.3 Coaxial Capacitance Sensor: The coaxial capacitance sensor consists of an inner electrode and an outer electrode. The inner electrode is located at the center-line of the pipe with Teflon coating, while the outer electrode surrounds the pipe and is in contacts with the fluid. If there is a change in the equivalent dielectric constant of the mixture passing the annular space between the two electrodes, the capacitance value will change accordingly, indicating the ability of the coaxial capacitance sensor in detecting the phase concentration of two-phase flows [45].

The geometry dimensions of the coaxial capacitance sensor considerably affect the distribution of the sensitivity field, and thus have effects on the performance of the sensor in the two-phase flow measurement. Jin et al. [46] in their study on structural design and performance of coaxial capacitive sensor adopted a backward difference calculation that will offset the effects of the parasitic capacitance. Majid and Mohammad [47] modelled coaxial cylindrical probe capacitive sensor using MATLAB/ Simulink to establish the relationship between different capacitance and the height of conductive liquid. Their result showed that there is a linearity function between the sensor capacitance and the height of liquid. Al-Mously and Ahmed [48] designed some capacitors using multi-coaxial cylinders to determine the volume and weight fractions of a two-phase pipe. Theoretical and experimental results showed that the solid-core sensors had a linear relationship exists between capacitance and volume fraction measured in both static and dynamic flows, while the hollow core sensors showed a non-linear relationship. The sensitivity, linearity and simplicity of the design made the proposed sensor design even more practical than previously used capacitive sensors.

Zhang et al. [40] conducted an experiment of horizontal oil-water two-phase flow is carried out in a 20 mm inner diameter pipe with a flow concentration device. The response signals of the coaxial capacitance sensor under different flow patterns are collected by a data acquisition device. The liquid holdup is measured using three pairs of parallel-wire capacitance probes and quick closing valve technology to uncover the complex slippage behaviors between phases [49]. Then, the effects of the flow slippage and non-uniform phase distribution on the sensor response characteristics are investigated based on the equivalent impedance circuit analysis and Adaptive Optimal Kernel Time-Frequency Representation. Generally, the results show that the coaxial capacitance sensor presents preferable response resolution for selected horizontal oil-water two-phase flow patterns, such as stratified flow (ST) and stratified flow with mixing at interface. However, as the flow pattern evolves to dispersed oil-in-water and water flow with high water-cut, the response resolution of the coaxial capacitance sensor is lower [45].

2.4.4 Electrical Capacitance Tomography (ECT): ECT sensors typically consists of three units, namely the ECT sensing system, Data Acquisition System and the Computing System. The performance of an ECT sensor depends on several parameters, such as the number of electrodes, their dimensions, type of electrostatic shielding, axial resolution and its sensitivity [50]. ECT is particularly valuable in characterizing multiphase flow for many reasons. First, the fluctuations of the dielectric properties of the gas or liquid within a pipe can be measured and the capacitance of components estimated when they pass through the sensor region. Second, it is non-intrusive to the flow, which means that flow patterns are not disrupted and there will be no erosion of electrodes [51]. ECT sensors usually comprise 8, 12 or 24 electrodes around the cross section of the pipe (mostly configured in circular array), separated from each other by small and equal gaps [25]. The measured values of capacitance will be affected by the geometry of the sensor, the number of electrodes, the configuration of the electrode guard insulators, the fluid temperature inside the pipe and any undesirable stray capacitance, such as that of the cable connecting the sensor to the multiplexer. The disadvantages of ECT include the need for a fast data acquisition system, the distortions often affecting reconstructed tomograms and the simultaneous iterative techniques that must be employed to reconstruct an image from permittivity signals [52].

ECT basic principle is to take multiple measurements at the periphery of the pipeline and combine these to provide information on the electrical properties of the process volume. The principle is based on the measurement of the capacitances between electrodes located on the exterior of the

section of interest (Figure 1). It is often applied to visualize multiphase unit processes to develop understanding, provide a basis of control and optimize performance [53]. Since the capacitance depends on the dielectric constant of the material located between the electrodes, this method can distinguish between substances with different dielectric properties. To obtain a spatially resolved image of the dielectric distribution in the pipe, several electrodes are placed on the pipe and all capacitances between the electrodes are measured. The application of the corresponding algorithm will give the distribution of dielectric in the pipe. Typical ECT systems are based on a linear relationship between capacitance and permittivity [52]. Although such systems are fast, but reconstruction quality is not satisfactory since the true relationship between capacitance and permittivity is highly non-linear and cannot be approximated by linear imaging for high-quality reconstruction [54].

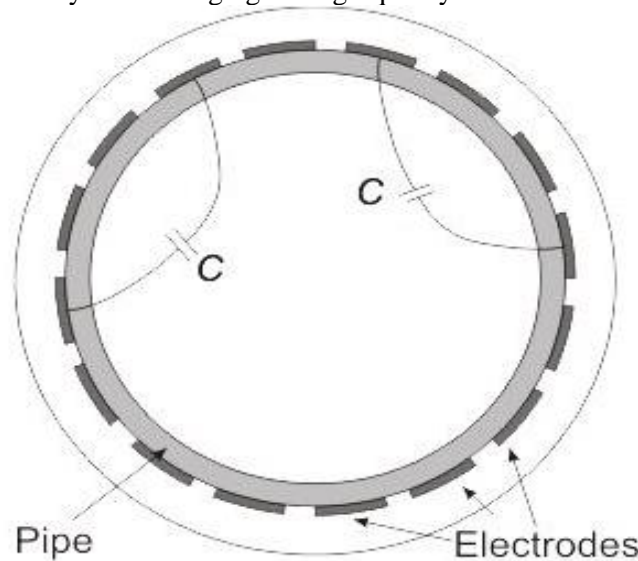


Figure 1. ECT Electrical Capacitances between some Electrodes (ECT measurement Principle)

Zhang et al. [55] in their review on the application of ECT noted that the twin-plane ECT sensor has the ability to estimate the flow velocity in any particular process. Equation (1) shows the proposed pixel-pixel correlation for particle velocity at corresponding pixel estimation with reference to the particle velocity profile in the cross-section.

$$c(x, y, d) = \frac{1}{T} \int_0^T \{ [\alpha(x, y, z_1, t) - \tilde{\alpha}(x, y, z_1)] [\alpha(x, y, z_2, t + d) - \tilde{\alpha}(x, y, z_2)] dt \} \quad (1)$$

Where, $\alpha(x, y, z, t)$ is the solids concentration fluctuations at two cross-sections, T is the average period, d is the delay time, and z_1 and z_2 are up and down stream planes.

Marashdeh et al. [53] also observed that the ECT detection problem corresponds to the reconstructing of the dielectric distribution of the image domain from a set of capacitance measurements taken at the domain boundary, that is, between a set of electrode plates placed around the domain. Also, the capacitance between a pair of electrode plates is defined as the ratio between the increase in the accumulated charge and the increase in the voltage difference between the pair of plates. The challenge then lies on determining the dielectric distribution in the image area (or, equivalently, the spatial distribution of various phases in the stream), taking into account the measured capacitance between all combinations of plate pairs. Plate pairs are considered independent if the sensitivity maps, they provide are distinct. Marashdeh et al. [53] also observed that the ECT image reconstruction algorithms can be divided into two main types: algebraic methods and optimization methods. Both types begin with a response characteristic of the sensor at low dielectric noise. This essentially provides an “impulse response” of the capacitive measurement “sensor output signal” to the “input signal” of the dielectric distribution with a linear approximation of the problem. The easiest way to solve the direct algebraic iteration problem is to project images from the last iteration into the sensitivity matrix. This method is very fast and convenient because it takes advantage of the same sensitivity matrix previously calculated, but is limited by linearization error. Solving the problem of

progress using more accurate methods, such as the finite element method, can improve the accuracy of the iterative reconstruction approach. Although, more researches that are aimed at improving reconstruction techniques for ECT are encouraged.

3. Application of Capacitance Based Sensor

Accurate measurement of liquid holdup is extremely important in two-phase flow of gases and liquids. Void fraction is another crucial primary design parameter. Capacitance sensors are very effective in the measurement of liquid holdup and void fraction. For the petroleum industry, the real-time phase fraction is important to ensure oil production safety and exploration economy. Because of the difference of viscosity and density of the oil and the water, the mixture fluid exhibits several flow patterns during the flow process in a horizontal pipe.

An Understanding of capacitance sensors and its working principles provides more knowledge on liquid holdup measurement and flow regimes that can be used to develop technologies and design tubing and pipe systems. Measurements based on capacitance generally provide better reproducibility than those based on conductance because the latter depend on ion concentration, and this can be difficult to control. Capacitance sensors are seldom affected by conductivity and also possess a high measurement sensitivity. This presents a unique advantage in measuring the water holdup in oil-water two-phase flow [56].

ECT is gaining popularity due to its non-invasive nature and its capacity to differentiate between different phases based on their permittivity distribution. The ECT electrodes are usually made of highly conductive materials such as copper. Literature had shown that the electrodes dimensions and geometry depend on the volume of the target medium, and in addition, the ECT space dimension. For example, Saied and Meribout[57] during electronic hardware design of ECT observed that for a regular 4-inch pipeline two-dimensional ECT system, eight electrodes of dimensions around 1 cm width and 10 cm length was optimal. Depending on the application, the electrodes are either put in direct contact with the process or protected by a thin non-conductive insulation layer. A large number of electrodes will give a higher resolution image but the measurement sensitivity will be low. Also, the sensitivity can be increased by using longer electrodes but this will lower the axial resolution. From literature, the accuracy of the image depends on the method used to construct the image from the inter-electrode capacitance measurements. At present, the only image construction algorithm which is fast enough to be used for on-line image display is the linear back projection method. This produces approximate images which are of acceptable quality for many applications. Other methods can be used to produce improved images off-line from captured capacitance measurements. These methods involve the use of iterative computational methods, or alternatively, the application of neural network techniques.

For pipeline velocity measurement, if two or more sets of sensor electrodes are fitted to the pipe and spaced a short distance apart, it is possible to measure the axial flow velocity of the material inside the pipe by correlating information from the two sets of images or capacitance measurements. ECT can be used to investigate the internal dynamic behavior of multiphase flow in the pipeline by presenting cross-sectional distribution of materials, that is, tomographic images, which is similar to CT scanners. Shafquet et al. (2013) used single-plane ECT sensor in studying the non-invasive nature of the sensor using waxy crude oil. Their result showed that ECT measurements are dependent on calibration method performed as well as the relative permittivity of the material being used for the sensor. Liu et al. [59] noted that the successful application of Electrical Capacitance Tomography (ECT) depends heavily on the image reconstruction speed and quality. Oil and Gas companies can invest in research to develop on existing capacitance sensor technology, for example, ECT, which has shown some promising features.

4. Knowledge and Technical Gaps Identified

- i. Capacitance probes encountered problems whenever conductive water, instead of de-ionized water, is used. Many explanations are given (polarization, overshooting), but to our knowledge the

only way this problem has been solved successfully is the increase of the working frequency at 80 MHz

- ii. Traditional concave electrode configuration has high sensitivity and it is easier to manufacture than helical arrangement however it is over dependent on angle orientation.
- iii. Another challenge is to design and manufacture a probe able to measure holdup up when the conductive fluid is the only one in contact with the pipe wall.
- iv. There is need for further studies on electrical probes (both conductive and capacitive) when conductive water (tap water or ionized water) is used. Current literature shows unsatisfactory results when conductive water is used.

5. Proposed Further Study

- i. Distribution characteristics of sensitivity field and geometry parameter optimization regarding coaxial capacitance sensors.
- ii. Further studies are required in Electrical Capacitance Tomography (ECT) to address issues such as slow data acquisition time, low resolution images, and the accuracy of the capacitance value.

6. Summary and Conclusion

In summary, Liquid Holdup occurs in multiphase flow when liquid or gas flows at different velocities. Calculation of holdup is complicated by the phenomenon of gas/liquid slip. The effect of slip is to increase the mixture density and hence the gravity pressure gradient. It is essential to be able to determine liquid holdup to calculate such things as mixture density, actual gas and liquid viscosities, effective viscosity and heat transfer and pressure drop.

Capacitance sensors are widely used in multiphase flows. This is due to their simplicity, non-invasiveness environmental compatibility and sensitivity. It can be used to estimate the hold-up and void fractions in a given section of the pipe, taking advantage of the different permittivity values of the two fluids. The estimation is obtained by capacitance measurements between two electrodes, flush mounted on the external surface of the experimental pipe. Capacitance sensors are used to investigate flows with non-conductive fluids, but they have the possibility to work with conductive fluids. It can also be used to determine the flow regimes present in a pipe segment. Some capacitance sensors used currently include ring, concave, helical, coaxial and ECT Sensors.

Electrical Capacitance Tomography (ECT) can be obtained by adding more electrodes to a capacitance sensor, usually between 8-24. ECT sensors generally consist of a purpose-built multiplexer, an impedance analyzer and a computer for image reconstruction, interpretation and display. They can be used in place of the capacitance sensor to measure liquid holdup, void fractions and flow regimes.

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