VOID FRACTION MEASUREMENT USING ELECTRICAL IMPEDANCE TECHNIQUES

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ABSTRACT
An electrical impedance method for measuring void fraction in multi-phase flow is presented. Two and four concave electrodes configuration are used in the study. The electrodes are mounted on the outer circumference of a pipe and excited by the applied voltage. The existing open literature indicated that most research work on void fraction measurement using capacitance sensor techniques focuses mainly on two phase flow. Little or no attention had been given to three phase flow. Hence the objective of this study is to investigate the effect of sand particles on the overall performance of the capacitance sensor for measuring void fraction in air-water-sand phase flow. The considered flow patterns are the stratified flow and the annular flow. ANSYS multi-physics, a finite element based software was used to implements the problem. Results showed that the addition of about 20% sand particles in the flow path leads to over 40.90% reduction in capacitance value. Hence, the model is capable of detecting the addition of sand particles to the two phase flow.

KEYWORDS: *Void fraction, capacitance sensor, air-water-sand phase flow, dielectric permittivity*

I. INTRODUCTION

Flow measurement is of paramount important in the field of engineering and beyond. Flows can be measured in a variety of ways using different variety of devices. Devices such as venture meter, orifice plat, Pitot tube and oval gear meter are used for fluids measurement. However, each one of these devices has the capability of measuring the flow rate of one phase flow only. In recent time, gas-liquid two phase flow has become an important aspect in many industries such as oil industry and the nuclear power plants. Thus, the development of better measuring devices to measure such a flow patterns is an on growing demand.

Two-phase flows are identified by their simultaneous flow of two phases like solid-liquid, liquid-gas, gas-gas, and liquid-liquid along a pipes wall and the phases are separated from each other. These kind of phase flow are usually found of fundamental and scientific interest as well as of great interest for their application in industries such as chemical industries, oil and gas industries and many more. The flow pattern of multi-phase flow is known when we combine different flow rates of different phases [1]. Complex multiphase flow are encountered in large percent of petroleum and petrochemical industries. The presence of solid particles in the production line affect the rate of production as it creates pressure drop along the pipe lines [2].

For efficient simulation of two- phase flow, a reliable measurements of the flow-pattern identification and void fraction is significant [3]. Void fraction is used for estimation parameters such as the two phase viscosity and density. Therefore, in characterizing two phase flow, the consideration for void fraction cannot be ignored as it is one of the main parameter to be considered. Void fraction is the ratio of area occupied by the vapor to the total area of the tube (pipe). Measuring void fraction of the phases had been a difficult task due to the highly non-symmetric nature of Liquid- gas two phase flow. However, Void fraction can be obtained through the use of variety of techniques such as optical (electrical) contact probes, X-Ray Absorption, capacitance (impedance) technique, Gamma Ray Absorption, quick closing valves and radiation attenuation [4].

The technique for measuring void fraction depends on the desire application. Due to its high cost and difficulty in its implementation, the radiation-attenuation method is usually not used. In using the intrusive probes, the flow field is disturbed making it disadvantageous. Hence, one of the most practical and inexpensive method of measuring void-fraction is the impedance-measurement methodology [3]. The technique is easy to design, not intrusive and quiet easy to implement [5]. Electrical impedance sensors have been developed by many researchers for measuring and monitoring void fraction in liquid-gas flow in a pipe. The reported capacitance value ranges from 0.1-10 pf. In order to achieve high sensitivity and better signal-to-noise ratio (S/N) measurement, the influence of stray capacitance has to be mitigated to the minimal level [6].

Stott et al [7] developed a theory that analysed the characteristic of concave plate electrodes fixed to a pipe internally or externally. The flow components are water-air phase flow. An experiment was conducted to validate the theory. It was proved that the capacitance and the conductance of the external electrode are both functions of permittivity and conductivity of the fluid. The result shows that it is better to used internal electrodes when measuring the permittivity of the fluid and it is better to used external electrode when there is low admittance of the fluid.

Gerraets and Borst [8] developed a capacitance sensor for measuring void fractions of phase flow involving water-air flow. Helical type of electrode configuration was utilized in the work. Results revealed that one of the important design parameter is the influence of dielectric tube wall thickness. It was concluded that the time-varying output signal is essential for the identification of flow pattern identification.

Elkow and Rezkallah [9, 10] developed two capacitive sensors for measuring the void fraction in vertical flow consisting air-water two-phase flow in a small diameter tube. Both concave plate and helical wound electrodes configuration were employed. The problem of nonlinearity in the flow was addressed in helical sensor and the concave plate sensor was improved based on the addressed nonlinearity in helical sensor. Results of the two sensors were compared with gamma densitometer and quick-closing valves. Results shows that there is good agreement between the average void fraction values and the annular flow, bubble, and the transitional flow regimes.

Keska and Williams [11] developed, identified, and implemented four methods for measuring flow pattern detection in a vertical experimental setup. The flow pattern were generated and all the selected parameters were measured through the use of Computer-aided experimental system. The experiments were conducted on vertical adiabatic air-water phase flow. In terms of sensitivity and individual ability, the efficiency of each method was investigated. The result were discussed and documented.

Caniere et al. [12] developed a capacitance sensor for identifying flow pattern in air-water phase flowing in a small diameter horizontal tubes. Concave electrode configuration of 120, 140 or 160 arc-length were used in the work. Simulation through finite element was conducted to investigate the influence of electrode angle, vapour distribution and wall thickness. Experiments were conducted and the results are presented in frequency, time and amplitude and domain. The possibility of flow regime characterization with the capacitance measurements is reported.

Kathleen et al. [13] calibrated a capacitance sensor based on capacitive signal for void fraction measurement of small diameter tubes. Unlike available method for calibrating capacitance sensor, they used a technique based on the three statistical parameters of the capacitance signal. The sensor was used to measure about 270 points in 8mm inner diameter tube. The conditions upon which the measurement were made are the mass flux of 200kg/m2 – 500kg/m2 and 2.5% - 97.5% vapour quality. The used refrigerant are R134a and R410A. His results shows that very good agreement with the Steiner version of the Rouhani-Axelsson drift flux void fraction model with mean percentage error of 1.3% and 4% standard deviation. Poor agreement was observed in the case of slug flow when compare with the other flow pattern.

For measurement of local void fraction in air–water adiabatic flow through rectangular channels, a non-intrusive electrical impedance-based sensor was developed by Pierre et al. [14]. Two opposite aliened capacitors fixed on the wall of micro channel was used to investigate the flow regimes. A three dimensional multi-phase numerical simulation was performed. Relationship between the electrical impedance and the void fraction was established from the experimental data and the simulation results. Based on the stratified gas-liquid flow assumption, a model was developed which is capable of sensing not only one kind of fluid, but different working fluids.

Zubair and Tong [15] designed a non-intrusive system based on a capacitance to phase angle conversion method to measure ultra-low water content in crude oil. Two semi-cylindrical electrodes fixed on the outer wall of a glass tube was used to as the capacitor sensor. To guarantee non variation of temperature, background noise, phase jitter and amplitude, different measuring techniques was utilized. Hardware experiment was conducted using crude oil samples and validated with the model results. A resolution of ±50 ppm of water content in crude oil was obtained by the proposed design.
From the foregoing literature review, it can be concluded that no study has investigated the void fraction measurement using capacitance sensor method for air-water-sand phase flow. The disadvantages associated with commonly assume scenario (pure two phase flow) is: in practice, two phase flow is usually accompanies by some solid particles (impurities). The present of these solid particles perhaps have certain effect on the void fraction measurement. So, to the best of author's knowledge, void fraction measurement in Air-Water-Sand phase flow in a pipe using a capacitance sensor method has not appeared in the open literature. Therefore, the nucleus of present research is to evaluate the feasibility of employing the Electrical impedance sensors in measuring void fraction of air-water phase flow and study the role of sand concentration in water-air phase flow.

II. PROBLEM DESCRIPTION

A 2- dimensional pipe of 9mm internal diameter having a thickness of 0.05mm is considered. The pipe is made of acrylic material having permittivity (di-electric constant) of 3. Two opposite concave electrodes made of copper were mounted to the outer circumference of the pipe. Four copper electrodes with opposite and adjacent arrangements was as well considered. An earthed screen (shield) made of acrylic was used for housing and grounding (earthen) the copper electrodes. The electrodes was excited by voltages of 15volts and -15volts. Air-water as well as air-water-solids respectively were the considered multi-phase flow in the pipe. The inscribed electrode angle is set at $\beta = 20^{\circ}$ as depicted in Figure.2. The schematic diagram of problem statement is as illustrated in Figures. 1 and 2.

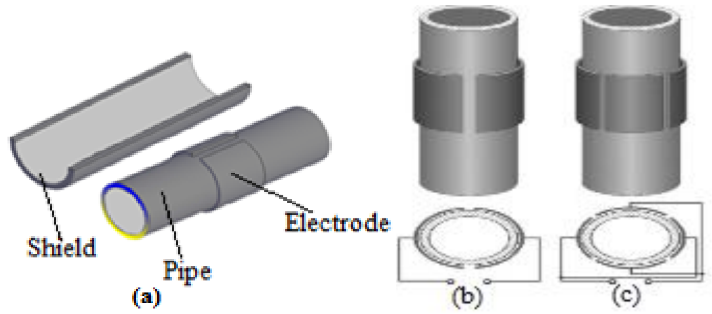


Figure. 1: Schematic diagram of electrode configurations: (a) two and (b and c) four Concave electrode [16].

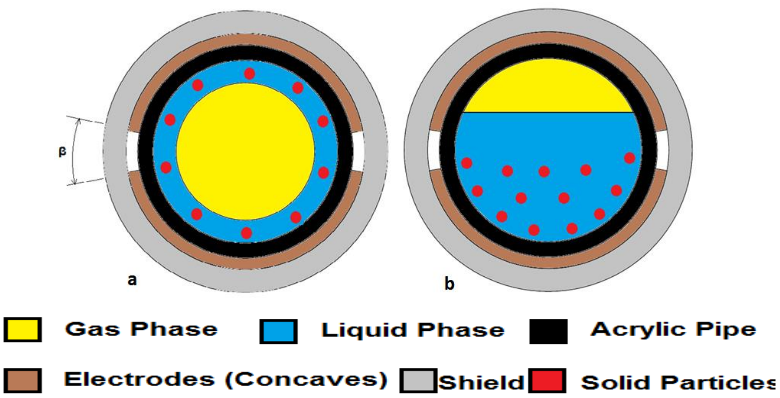


Figure. 2: problem statement: (a) 2 electrodes for Annular flow, (b) 2 electrodes for Stratified flow

III. MODELLING

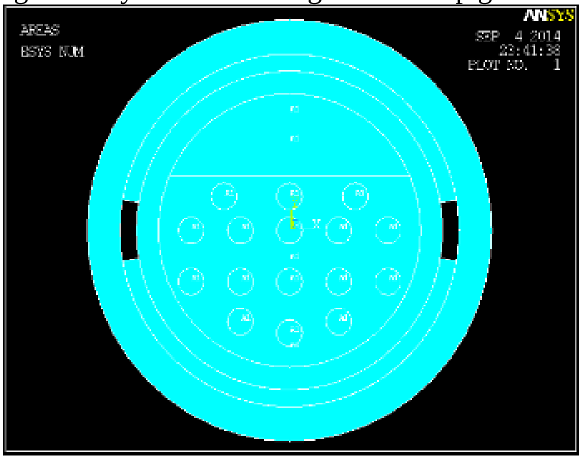
By means three dimensional capacitance model that is based on Poisson's equation, capacitance sensor has been investigated in depth [17]. The model was solve through Finite Element Method (FEM). FEM replicates the electrical field, and potential distribution, and the capacitance sensor for different, sensor geometries, flow pattern and design parameters like distance between the electrodes,, type of guard electrode, permittivity and thickness of the insulating layer, sensor length etc. ANSYS program which is based on FEM is employed in this work for determining the field distribution, capacitance between the electrodes and the electrical potential. The electrical potential of the system may be obtained by solving Poisson's equation given in Eq.1. The field distribution can be calculated from Eqs. 2, while Eq. 3 is used for estimating the capacitance between the electrodes [12].

$$-\nabla.\left(\varepsilon(\vec{x})\nabla u(\vec{x})\right) = \rho(\vec{x}) \quad (1)$$

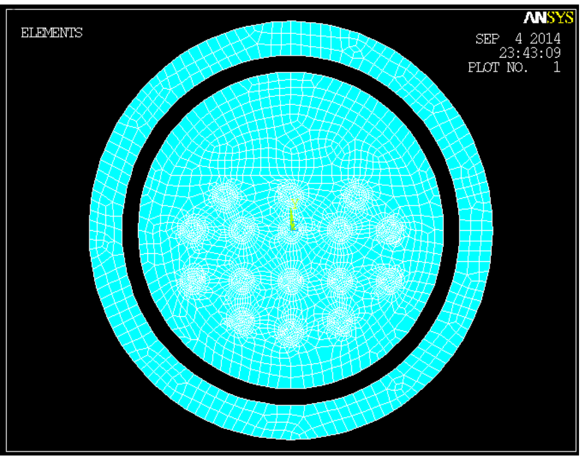
$$\vec{E}\,(\vec{x}) = -\nabla u(\vec{x}) \quad (2)$$

$$C\,\frac{1}{U}\int_{S} \varepsilon_o\,\varepsilon_r(\vec{E}.\vec{n})ds \quad (3)$$

Where, $\rho(\vec{x})$ is the charge density function, $\varepsilon(\vec{x})$ is the potential function, and $(\vec{x})$ is the space vector. ε_o= 8.542 x 10^{-12} (Fm^{-1}) for free space insulator. The dielectric constants used in the modelling are ε_r = 77.5, 1, 3, and 3.9 for water, air, acrylic and sand particles respectively. The voltage between the detector electrode and source electrode (U) is set at 15 V and -15V. $\vec{n}$ Is the unit normal vector to S and $\vec{E}$ is the electric field vector. The problem geometry of the problem is as depicted in Figure. 3(a). It is composed of a pipe, air, water, sand, electrodes and shield. Figure. 3(b) displayed a meshed geometry. The domain considered is meshed with Quadrilateral elements of aspect ratio 0.98. A mesh of high density was used at regions of steep gradients in order to obtain more accurate results.



(a)



(b)

Figure. 3. (a) The geometry and (b) the meshed geometry as built in ANSYS.

After meshing the geometries, static electric loads (voltage) is then applied to the electrodes and the shields. Solution to the problem is then obtained through solve current LS. The plot of the electric potential is achieved through post processing, plot results, contour plot, Nodal solution and DOF solution while the plot to the electric field is achieved through post processing, plot results, vector plot, predefined, and flux and gradient. Furthermore, the capacitance between the electrodes is calculated by applying potential difference to the electrostatic energy expressed as $w_e = \frac{1}{2}C\,(V1 - Vo)^2$, where C is the capacitance and w_e is the electrostatic energy

3.1 mesh independent test

In order to obtain mesh size optimization, mesh independent test was conducted. This is also to ensure that the solution to the problem does not depend on meshed grids. Figure 4 shows the results of various element number and its corresponding capacitance values for two electrodes stratified flow for α = 0.5. It is obvious that the optimum value is located at 1174 number of element. At this point, the solution to the problem does not longer depend on the mesh size, as further increment in number of mesh grids gives approximately the same capacitance values

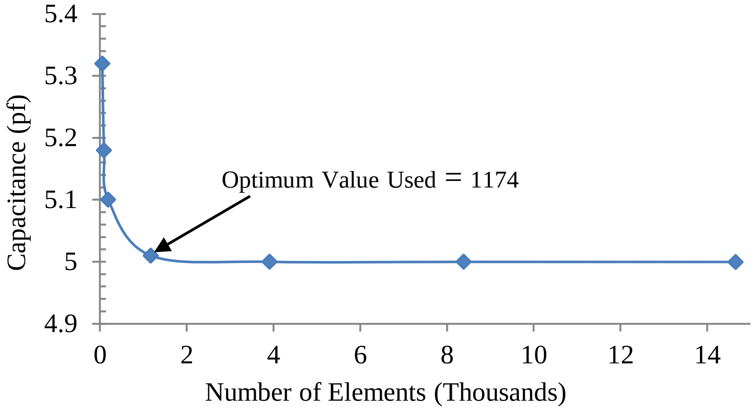


Figure. 4. Independent test result

3.2 Electrode Sensitivity

Since the study involve two and four number of concave electrodes configurations, comparing the sensitivity of these electrodes for both opposite and adjacent arrangements is of paramount important. Hence, the sensitivity of the sensor may be estimated from the expression given as [3]:

$$\text{Sensitivity} = \frac{\text{capacitance (all liquid)} - \text{capacitance (all gas)}}{\text{capacitance (all liquid)}} x\ 100\% \quad (4)$$

The above expression can be re written as:

$$\text{Sensitivity} = \frac{\text{capacitance } (\propto = 0) - \text{capacitance } (\propto = 1)}{\text{capacitance } (\propto = 0)} \text{x } 100\% \quad (5)$$

IV. RESULTS AND DISCUSSIONS

Different void fractions for stratified flow pattern was obtained by simply changing the level of liquid in the flow pipe whereas for annular flow pattern, the void fraction was achieved by decreasing or increasing the liquid film in the pipeline. The introduction of sand concentration to two phase flow was obtained by subtracting the required sand percent from the area of the liquid and then divided this percent of solid into smaller areas. It must be pointed out that effect of solid concentration (percent) was simulated at a fixed void fraction of 0.25 in all the cases considered.

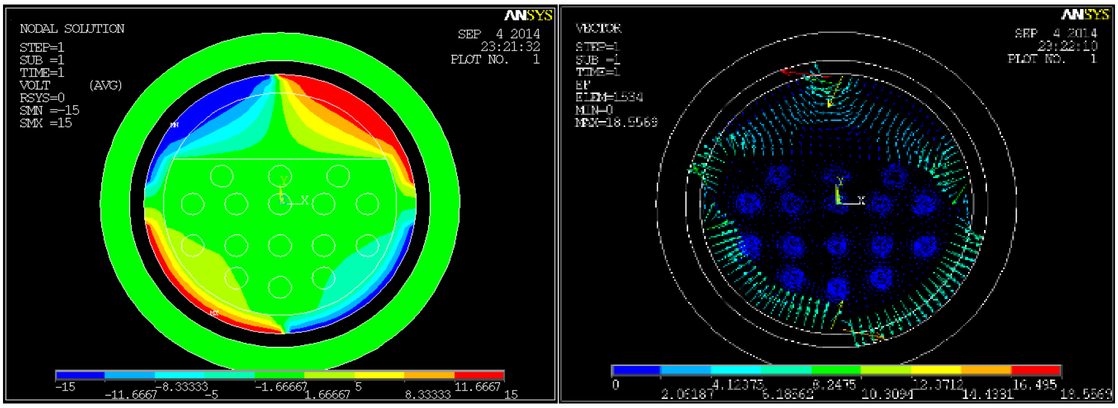


Figure. 5(a): Electric potential Figure. 5(b): Eelectric field

Figures. 5(a) and 5(b) are the electric potential and electric field respectively for four (4) opposite concave electrodes at void fraction (α) of 0.25 and 20% sand concentration for stratified flow. The figures shows the electric potential and field in a cross-sectional plane for a sensor filled with heterogeneous dielectric material. The magnitude of the electric field component in the cross-sectional plane is proportional to the length of the arrow. Careful observation revealed the presence of large gradients of electric field near the shield electrodes. However, the contribution of these field lines to the capacitance is however negligible.

4.1 Validation

Available for validation is the data obtained from the work of Caniere et al. [12]. As noticed from figures. 6 and 7, the simulation results and the data [12] were in good agreement. The recorded mean percentage error between the data and the simulation is 13.72%. It can also be noticed that most of the simulation results falls within the range of the data [12] with the maximum and minimum percentage error of 22.53% and 1.06% respectively.

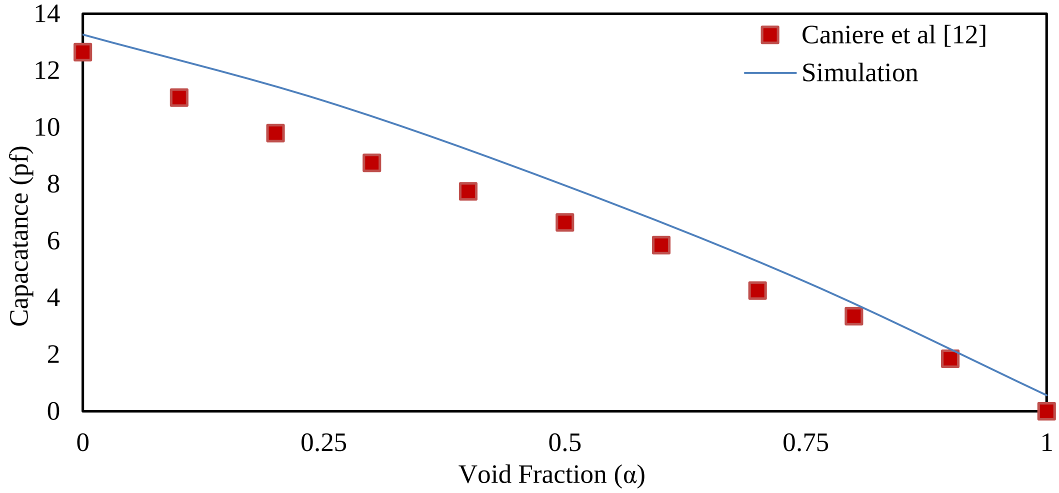


Figure. 6: Capacitance of annular flow patterns for air-water phase flow

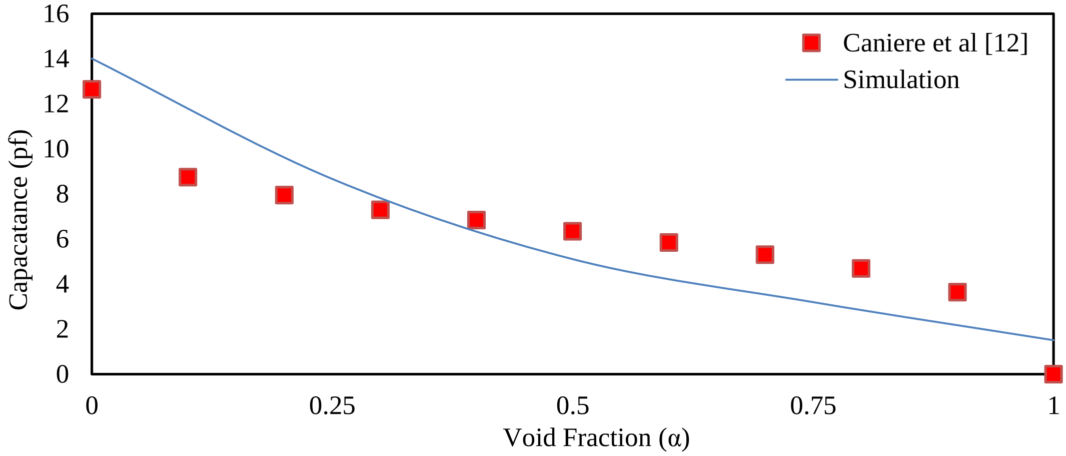


Figure. 7: Capacitance of stratified flow patterns for air-water phase flow

Figures. 8 and 9 presents the capacitance and its corresponding void fraction for 2 and 4 concave electrodes configuration. It can be observed that the illustrated figures exhibit nonlinear curve. This is attributed to the fact that near the edge of the electrodes, there is large contribution of area which makes the sensitivity distributions of the cross section inherently nonlinear

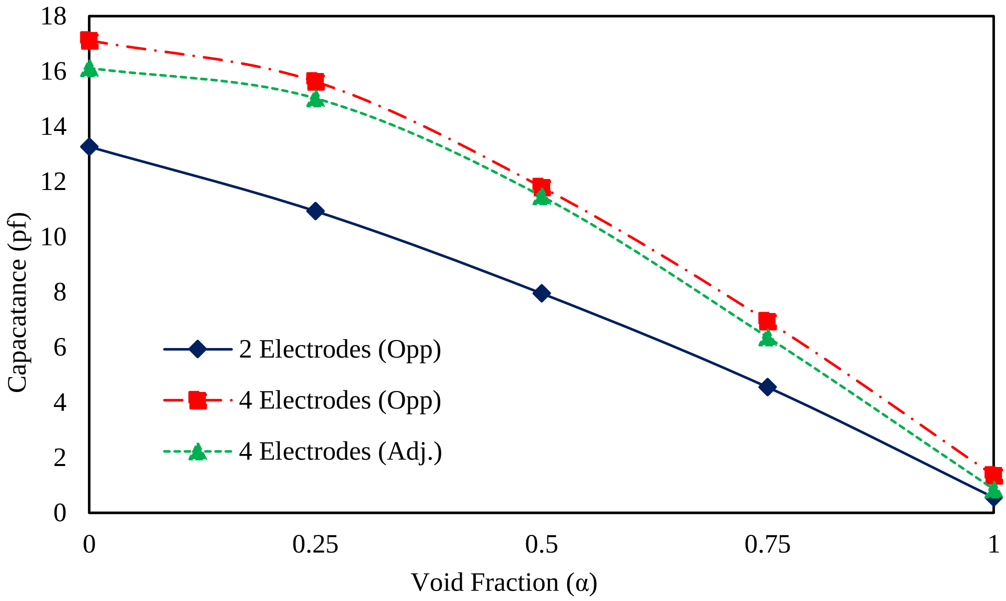


Figure. 8: capacitance of annular flow for air-water phase flow.

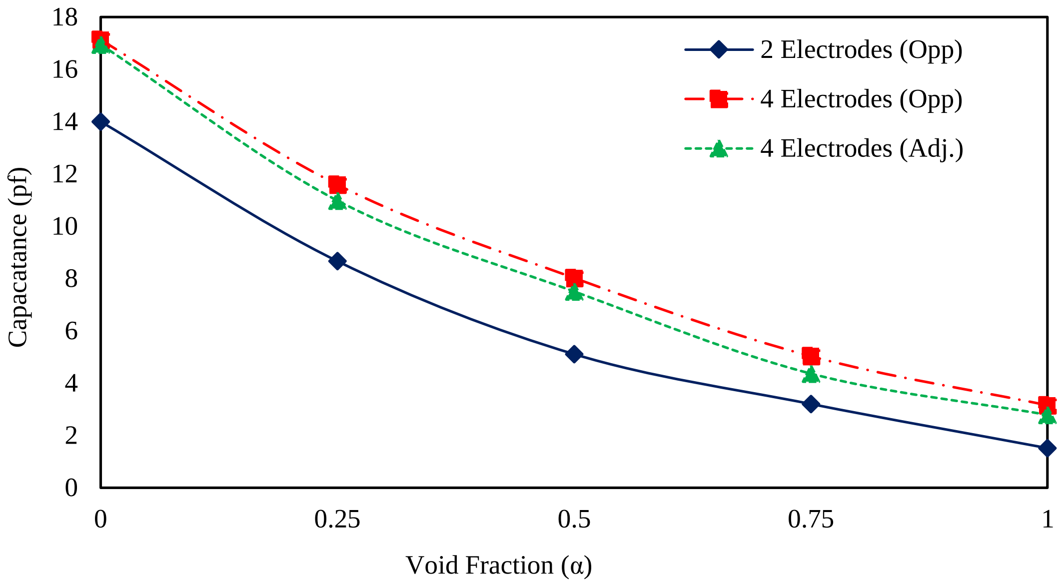


Figure. 9: capacitance of stratified flow for air-water phase flow.

The nonlinearity of the model results may also due to the electrical-circuit analogy that leads to a series capacitance circuit, where the overall capacitance is a nonlinear function of the individual capacitances. An observation revealed that the capacitance between the electrodes decreases with increasing void fraction. This is attributed to the fact that the higher the relative permittivity, the lower the electrical energy discharge across the two opposite plate, thus the lower the capacitance values. Further observation showed that for different number of electrodes, the trends of the curves is concave downward and upward for annular and stratified flow pattern respectively. If these trends continue to take shape with further simulation at different conditions, then we concludes that this method can be used for not only measuring the void fraction, but also for flow pattern identification. It can also be seen that the capacitances for two electrodes in figures. 8 and 9 are lower than that of four electrodes arrangement, and the maximum capacitances are observed from four opposite's electrode arrangement. It can be concluded that capacitance between electrodes depends on the number of electrodes and the electrodes arrangement within the geometry (opposite and adjacent arrangements).

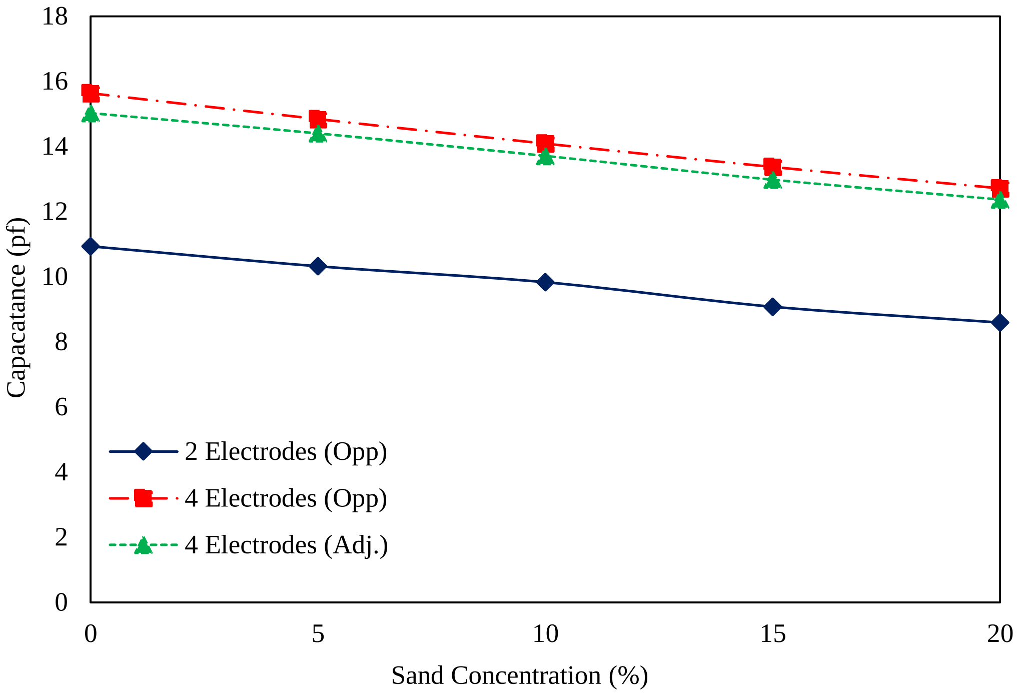


Figure. 10: Annular flow of void fraction of 0.25 at different percent of sand concentration

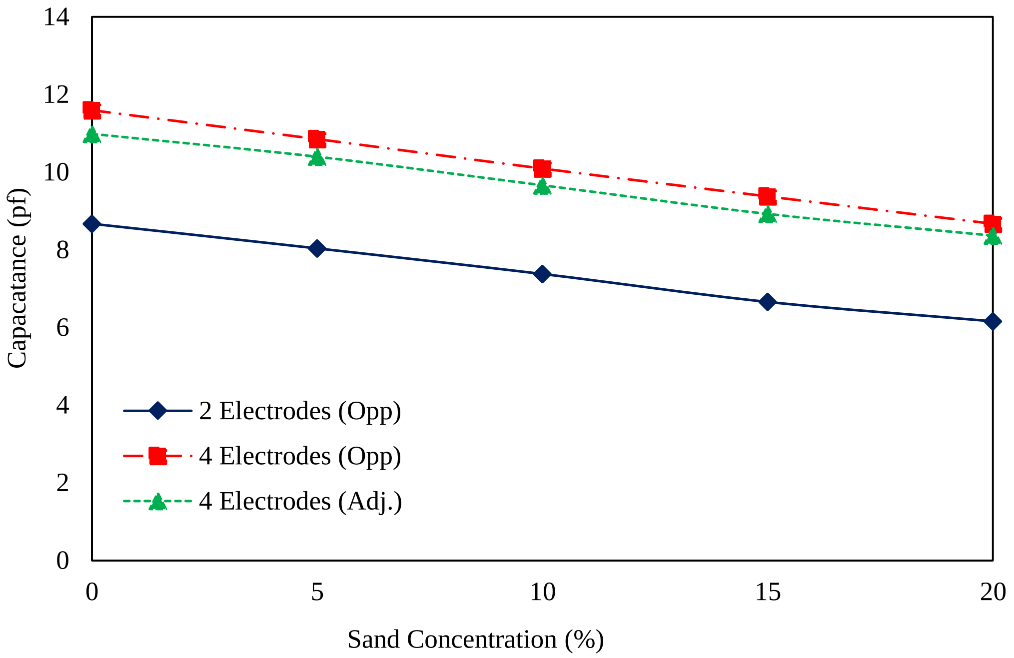


Figure. 11: Stratified flow of void fraction of 0.25 at different percent of sand concentration

Figures. 10 and 11 illustrate the capacitance for annular and stratified flows pattern for void fraction of 0.25 at different percent of sand phase. It can be observed that increasing the sand phase in the liquid phase leads to gradual and linear reduction in capacitance between electrodes. This signifies that solid particles in two phase flow if not accounted for will affect the void fraction measurement. Increasing the solid concentration in liquid from 0 to 20% for stratified flow pattern leads to about 40.91% reduction in capacitance between the two concave electrodes arrangement. So the high drops in capacitance value will definitely introduces errors in void fraction measurement if not taken into consideration.

The sensitivity of a sensor needs to be maximized and it depends on the gap between the electrodes, which also influence the spatial resolution of the sensor. Sensitivity of the sensor also depends on the shape of geometry. The sensor sensitivity can be calculated from Eq. (4 or 5). The sensitivity values of different number of the electrodes and electrodes arrangement are tabulated in table 1.

Table 1: Electrodes Sensitivity

Electrodes Number and arrangement	Sensitivity of the Electrode (%)	
	Stratified	Annular
2-Electrodes (Opposite arrangement)	89.20329	95.75434
4-Electrodes (Opposite arrangement)	81.58726	92.08596
4-Electrodes (Adjacent arrangement)	83.56858	94.69611

It can be noticed that the capacitance sensor with two concave electrodes has the highest sensitivity in comparison with those of four concave electrodes arrangements. From foregoing discussion, we can therefore conclude that for concave capacitance sensor, increasing the number of electrodes decreases the sensitivity of the sensor and increases the capacitance of the sensor.

V. CONCLUSIONS

A finite element method based software was used to simulate capacitance sensor for measuring void fraction in air-water and air-water-sand phase flow accordingly. The adopted electrode configuration was the concave type electrode and the considered flow pattern are the stratified and the annular flow. The influence of sand addition to air-water phase flow as well as electrode sensitivity were investigated. The comparison were made between the simulated results and the data of Caniere et al. [12]. Good agreement was achieved as the recorded mean percentage error was found to be within 13.72%. The recorded maximum and minimum percentage errors are 22.53% and 1.06% respectively. Further results shows that two concave electrode arrangement is more sensitive than four concave electrode arrangement, and the capacitance sensor measurement decrease nonlinearly with increasing void fraction for both annular and stratified flow regimes.. It was also found that at a fixed void fraction, the capacitance of the sensor decrease linearly with increasing sand concentration. The addition of about 20% sand particles in the flow path leads to over 40.90% drops in capacitance sensor value. Hence, the capacitance sensor model is capable of detecting the addition of sand particle air-water phase flow.

VI. RECOMMENDATIONS

For future work, the following points were recommended:

- In this study, effect of percentage sand concentration was investigated at a fixed void fraction, so more investigation should be conducted at different void fraction for different percentages of sand concentration.
- Since capacitance sensor measurement depend on number of electrodes, more than four electrodes number such as six, eight, etc., should be investigated.
- Helical and ring type of electrodes configuration should be investigated if possible.
- In this work, the considered flow regimes were the stratified and annular flow patterns. Possibility of more flow patterns such as slug and bubble flow should be considered.

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