VOL. 11, NO. 24, DECEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

SENSITIVITY ANALYSIS OF CONCAVE CAPACITANCE SENSORS FOR HOLDUP MEASUREMENT IN TWO-PHASE FLOW

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ABSTRACT

Due to the complex flow structures of two-phase flow, the holdup measurement is a very challenging problem. In this paper, we use the finite element method to analyse a three-dimensional model of concave capacitance sensor. Both two-plate and four-plate sensors are investigated and compared in terms of the average sensitivity and sensitivity variation parameters. The average sensitivity of sensors is greatly increased during the shift from two-plate design to four-plate design. However, this causes the sensitivity variation parameter to be increased despite the usage of more plates. The geometry of the concave capacitance sensor is determined be 40° electrode angle for four-plate design has a better result as compared to 80° electrode angle of two-plate design.

Keywords: two-phase flow, holdup, concave capacitance sensor, and sensitivity analysis.

INTRODUCTION

Two-phase flows are widely encountered in many technical, energy conversion and chemical engineering processes. One of the most important parameters characterizing such a flow is phase volume fraction or holdup measurement. For this purpose, capacitance method is widely used due to simple operation and structure, non-invasive and real-time measurement [1-3].

Many previous studies have been carried out where concave capacitance sensor was found to have the higher sensitivity compared to double rings and helical electrodes [4-6]. Also, the sensitivity distribution of concave capacitance sensor had been heavily studied by Xie *et al.* [7] who proposed the huge influence of pipe wall thickness on the sensitivity result. In a research done by Caniere *et al.* [8,9], different flow patterns had been identified by using a concave capacitance sensor. Meanwhile, a calibration method for concave capacitance sensor has been suggested by De Kerpel *et al.* [10] in measuring the phase volume fraction in two-phase flow.

In addition, the negative effect of conductive water on the response of capacitance sensor had been investigated and arguably solved by Strazza *et al.* [11]. As mentioned by Trallero *et al.* [12], the response of concave capacitance sensor towards two-phase flow with different flow patterns such as stratified flow and dispersed flow had also been investigated with limited related researches.

In this paper, for all angles of electrodes, two-plate concave capacitance sensor is divided equally to four-plate geometry with different placing position. The electrode angle is manipulated and the sensitivity analysis is performed. It is found out that 40° electrode angle for 2-plate sensor produced a better result than 80° for four-plate model in terms of sensitivity.

CAPACITANCE SENSOR DESIGN

The design configuration of two-plate and four-plate capacitance sensor has been illustrated in Figure-1 and Figure-2, respectively. As shown in Figure-1, the conventional concave capacitance sensor consists of only two plates, namely measuring electrode and exciting electrode. The parameters, θ is the opening angle of electrode, R_1 is the inner radius of pipe, R_2 is the outer radius of pipe and L refers to the length of each electrode. Meanwhile, Figure-2 shows the four-plate concave capacitance sensor which consists of two measuring electrodes and two exciting electrode. It should be noted that the concave plates are always placed alternately with measuring and exciting electrodes. The electric field is formed between exciting and measuring electrode where an AC voltage is applied. Typically, 0 V is applied on measuring electrode while 1 V is applied on exciting electrode.

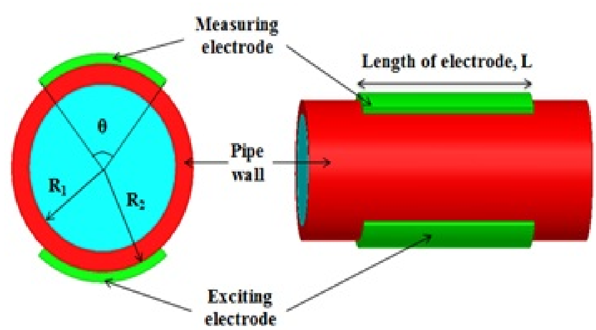

Figure-1. Electrode configuration of two-plate sensor.

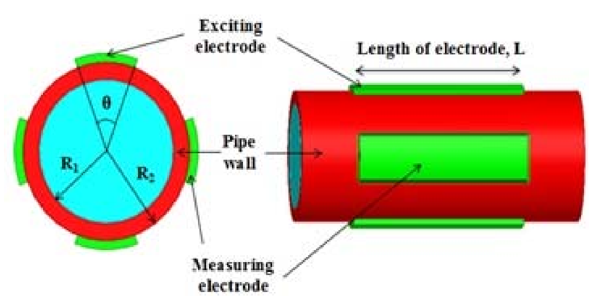

Figure-2. Electrode configuration of four-plate sensor.

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By manipulating the θ, the surface area of two-plate sensor and four-phase sensor can be made equivalent easily for comparison purpose in this paper. The opening angle for four-plate sensor is always half of that of equal-area two-plate sensor. For example, two-plate sensor with θ = 40˚ has the same area of contact on the pipe wall as four-plate sensor with θ = 20˚.

For a given dielectric distribution, electrodes configuration and boundary conditions, the potential inside the screen can be calculated by solving Poisson's equation as shown below:

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon} \tag{1}$$

In the three-dimensional electric field:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = -\frac{\rho(x,y,z)}{\varepsilon(x,y,z)} \quad \varphi = \varphi(x,y,z) \tag{2}$$

where φ is the space potential distribution function, ρ is the space charge density and ε represents the space permittivity distribution function. For the case where there is no free charge in the measurement field, i.e. $\rho = 0$, Equation. (1) can be expressed as follows:

$$\nabla^2 \varphi = 0 \tag{3}$$

With that, based on the Gauss law, finite element method can be applied to calculate the capacitance value.

METHODOLOGY

The distribution of element sensitivity field forms a sensitivity field for the whole measurement region. The measurement field of the sensor is meshed into several small elements by using the finite element method (FEM), in which the sensitivity of element i can be expressed as

$$S(i) = \frac{C(i) - C(\varepsilon_l)}{C(\varepsilon_h) - C(\varepsilon_l)} x \frac{V}{V_i} \tag{4}$$

where $S(i)$ is the sensitivity of the ith element, $C(\varepsilon_l)$ is the capacitance between exciting and measurement electrode while the permittivity or dielectric constant of all the elements in measurement region is ε_l. $C(\varepsilon_h)$ is the capacitance between the two electrodes while the permittivity of all the elements in the measurement region is ε_h. $C(i)$ is the capacitance between the two electrodes while the permittivity of the ith element is ε_h and the dielectric constant of other elements is ε_l. Also, V represents the total volume of detection region while V_i represents the volume of the ith element. In this paper, the two-phase flow is set to be oil-water flow where $\varepsilon_l = 2$ for oil and $\varepsilon_h = 81$ for distilled water. The measurement region of the fluid is divided into a total of 246 elements.

In order to describe the sensitivity field homogeneity and obtain the capacitance variation with respect to the change of permittivity distribution, the sensitivity variation parameter based on the element sensitivity is defined as

$$SVP = \frac{S_{dev}}{S_{avg}} x\ 100\% \tag{5}$$

where S_{avg} is the average value of all the element sensitivities which can be expressed as

$$S_{avg} = \frac{1}{M} \sum_{i=1}^{M} S(i) \tag{6}$$

and S_{dev} is the standard deviation of element sensitivities in the measurement region which can be expressed as:

$$S_{dev} = \left[\frac{1}{M} \sum_{i=1}^{M} \left(S(i) - S_{avg}\right)^2\right]^{1/2} \tag{7}$$

where M represents the total number of elements in the measurement region, which is 246 in this paper.

ANSYS Maxwell software is utilised for simulation of the two-phase flow in order to obtain the capacitance values for all locations of element in the measurement region. With that, based on the formulas stated above, for two-plate concave capacitance sensors, both S_{avg} and SVP values are calculated for different angles of electrodes ranging from θ = 60˚ to θ = 160˚ with an incremental of 10˚ each time. Similarly for four-plate concave capacitance sensors, S_{avg} and SVP values are calculated for different angles of electrodes ranging from θ = 30˚ to θ = 80˚ with an incremental of 5˚ each time. With angles of electrodes, θ as the only manipulating variable, the simulation of all models is performed based on the design parameters such as of pipe and capacitance sensors or electrodes which have been made constant as listed down in Table-1 below.

Table-1. Design parameters in simulation.

Parameters	Remarks
Material of electrode	Copper ($\varepsilon = 1$)
Thickness of electrode	0.5 mm
Length of electrode, L	3 mm
Material of pipe	Plexiglass ($\varepsilon = 3.4$)
Inner radius of pipe, R_1	8.01 mm
Outer radius of pipe, R_2	10 mm
Total volume of fluid, V	604.6947 mm³
Volume of element, V_i	2.3562 mm³

The ideal case in this paper is to achieve maximum S_{avg} that represents the detection ability for a certain amount of change in capacitance. At the same time, the SVP values should be minimised so that the measurement results are less affected by the flow pattern, i.e. higher homogeneity or linearity of results. In other words, the results will be more independent of the location of the equal-volume element i throughout the measurement region of the two-phase fluid.

VOL. 11, NO. 24, DECEMBER 2016 ISSN 1819-6608
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NUMERICAL RESULTS AND DISCUSSION

The sensitivity analysis on both two-plate and four-plate concave capacitance sensors has been performed with a total of 11 angles of electrodes, θ for both designs. The results are obtained and tabulated as shown in Table-2.

Based on Table-2, SVP and S_{avg} versus θ is plotted for both two-plate and four-plate sensors in Figure-3 and Figure-4, respectively. The electric field distribution diagram in terms of magnitude and direction for two-plate concave capacitance sensors with θ = 80˚ and four-plate concave capacitance sensors with θ = 40˚ are illustrated in Figure-5 and Figure-6, respectively.

Table-2. Results for two-plate and four-plate sensors.

Two-plate sensor			Four-plate sensor		
θ (˚)	S_{avg}	SVP (%)	θ (˚)	S_{avg}	SVP (%)
60	1.0999	7.36	30	3.3739	17.47
70	1.0577	6.45	35	2.4829	18.75
80	1.0860	7.82	40	3.9001	7.53
90	1.0350	5.30	45	2.2755	26.70
100	1.1091	6.03	50	3.8772	12.38
110	1.1892	7.35	55	2.9889	8.44
120	1.1996	7.93	60	2.9256	9.23
130	1.2869	9.91	65	2.3616	21.32
140	1.4266	12.10	70	4.2456	16.85
150	1.2743	16.14	75	5.2807	51.57
160	1.4557	13.54	80	2.9110	22.52

Based on Figure-3, for the sensitivity analysis on two-plate concave capacitance sensors, the S_{avg} values obtained are relatively low and close to each other, ranging from 1.0350 to 1.4557. It means that the sensor relative sensitivity is generally low for all angles of electrodes using two-plate capacitance sensors. With respect to this, two-plate sensor with θ = 160˚ performs the best with the highest S_{avg}. Meanwhile, the SVP values computed are relatively low, indicating a good homogeneity of sensitivity distribution of two-plate capacitance sensors in general. In terms of SVP, sensor with θ = 90˚ produces the best result with its SVP value of only 5.30%. In means that with θ = 90˚, the capacitance measurement results are proven to be least independent of the location of equal-volume elements.

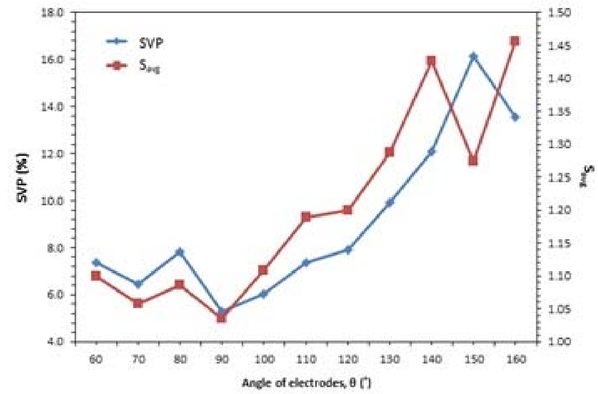

Figure-3. Effect of angles of electrodes on sensor sensitivity for two-plate sensors.

Based on Figure-4, for the sensitivity analysis on four-plate concave capacitance sensors, the S_{avg} values obtained are relatively high and of less consistency, ranging from 2.2755 to 5.2807. It means that the sensor relative sensitivity is generally high for all angles of electrodes using four-plate capacitance sensors. With respect to this, four-plate sensor with θ = 75˚ performs the best with the highest S_{avg} Meanwhile, the SVP values computed are relatively high , indicating a poor homogeneity of sensitivity distribution of four-plate capacitance sensors in general. In terms of SVP, sensor with θ = 40˚ produces the best result with its SVP value of only 7.53%. In means that with θ = 40˚, the capacitance measurement results are proven to be least independent of the location of equal-volume elements.

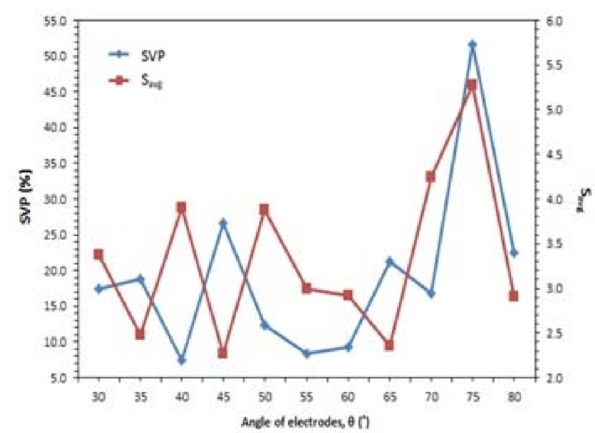

Figure-4. Effect of angles of electrodes on sensor sensitivity for four-plate sensors.

Figure-5 and 6 showed the electric field distribution in two-plate and four-plate arrangement. The electric fluxes vector indicated that four-plate design is likely to more sensitive, i.e. ability to detect water volume fraction, than two-plate design due to the wider coverage of electric fluxes in the cross section.

For the comparison of sensitivity analysis on both two-plate sensors and four-plate sensors, it is found out that the four-plate sensors have advantage of higher sensitivity or detection ability of capacitance changes as compared to the two-plate sensors. However, for almost all equivalent angles of electrodes, the shift from two-plate design to four-plate design produces an undesirable result. This is because there is an increase in the SVP values with the reduction in linearity of capacitance measurement results or the homogeneity of sensitivity distribution. Interestingly, only for four-plate sensor with θ = 40˚, as compared to the two-plate sensor with θ = 80˚, there is a drop in SVP values of about 7.82 - 7.53 = 0.29%. Also, increase in S_{avg} can be observed as well. This is due to the optimum spacing between the electrodes that results in better linearity of measurement results.

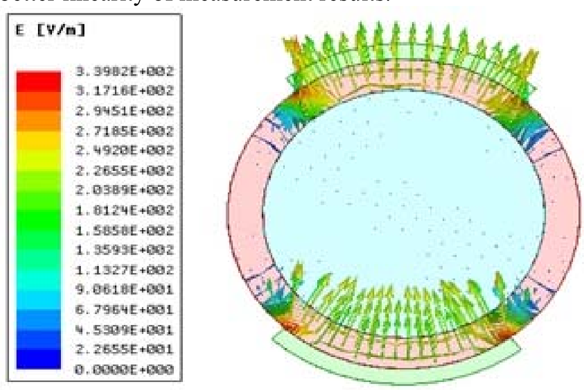

Figure-5. Electric field distribution of two-plate sensors.

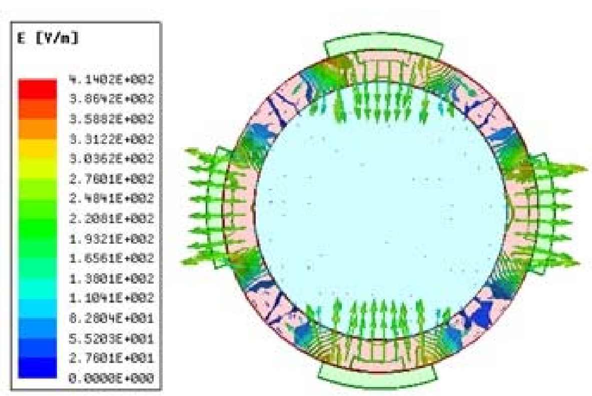

Figure-6. Electric field distribution of four-plate sensors.

CONCLUSIONS

Based on the comparison on the sensitivity analysis between two-plate and four-plate capacitance sensors, the four-plate sensor is found to be better in terms of sensor relative sensitivity for all angles of electrodes. For the sensitivity variation parameters, almost all angles of electrodes for four-plate sensors have lower linearity of capacitance measurement. However, there is an exception for four-plate model with θ = 40˚ which is found to be better than the two-plate model with θ = 80˚ in terms of SVP. This increase in homogeneity of sensitivity distribution for four-plate model can be investigated further in future by carrying out experimental works to verify the simulation results in this paper.

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