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Assessment of the Different Arrangement of the Electrodes in the Capacitive Sensor in Two-Phase Flow Using Numerical Simulation and the Introduction of a New Electrode

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Abstract: Multi-phase fluid flows widely occur, especially in the wellhead and oil pipelines. Besides, in most cases, conditions for creating such flows are not under the control, to ensure the design calculations such as pressure drop, multi-phase flow regime type and Gas to Liquid Ratio (GOR) should also be carefully determined. The old method of fluid flow measurement is separation of phases and their measurement by single-phase flow meter that in addition to a lot of inconvenience and expense, needs enough manpower to the continuous repair and maintenance as well. However, this equipment is not capable of continual monitoring and measurement and it cannot provide data obtained from the well for moment to moment as well. In addition, it did not also specify the output flow regime from the well. Among the multi-phase flow measurement methods because of the stability, reliability, simplicity, non-weaving, cheap price and low-safety needs the capacitor electrical method has been taken into consideration. But still, there are questions about the procedure, for example which is the best type of electrode configuration? In this study, types of important electrode configurations such as helix, concave and ring were assessed using the COMSOL application with finite element method based on the sensitivity of the response, phase distribution dependency. In short, they were the best choice for measurement of GOR of the helix type electrode and for identification of a concave configuration flow regime. Also, based on numerical simulation a new arrangement of electrodes called trifid was proposed that has the most sensitivity.

Key words: Two-phase flow, oil well, electrical capacitance method, electrode configuration, numerical simulation

INTRODUCTION

A study of gas and liquid flow in pipes and wells in order to accurately calculate pressure drop on them is important for the oil industry. Since due to the combination of the flow of the wells after the separation process in the operation unit, determination of flow rates of each phase is not possible for any of the well therefore, data relating to the production wells necessitates separation of output flow of each well before the operation and measurement of flow rate of each phase. For this purpose, the mobile separator is used. A disadvantage of the mobile separators is that this equipment is not capable of monitoring and measuring continuously and in situ data cannot be obtained. The problems in the development of fields in areas with difficult access to production systems are more obvious (Salehi and Abbas, 2013). An alternative option for this method that is today gradually expanding is the use of the multi-phase flow meters. This technology has solved some of the industry's needs in the area of multiphase flow measurement as well as other problems and limitations with the conventional methods. The multi-phase flow meter is used for simultaneous measurement of oil production rates, the percentage of producing water and gas to oil ratio in the oil and gas wells.

Various researchers have used the electrical methods to obtain the volume fraction of a liquid/gas mixture. Due to the ease of use and creation of continuous signal, methods of measurement of an electrical resistance have been considered. These methods have been applied due to the fact that the liquid and gas phase have different dielectric conductivity and constant and based on the fluid characteristics are the two types: electrical conductivity and constant.The electrical conductance method is used for liquid materials that conduct

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electricity flow like water but the capacity method is used for liquids that do not conduct electricity such as oil and coolants.

It is clearly evident that the electrical resistance of an empty liquid is different from its two-phase fluid. The first works were presented by Olsen (1967). Olson found that the annular type of electrodes located inside the flow is the best, although now a days, the electrodes that have been located outside the flow are of more attention. After that, band-shaped electrodes were used by Ma *et al*. (1991) examined changes in volume fraction of the two-phase gas/liquid flow with electrical resistance in coming from copper electrode that is placed on an insulating pipes. Yang *et al*. (2003) used, the electrical resistance measurement (Impedance method) to determine the volume fraction. Jaworek *et al*. (2004) obtained a volume fraction in the water/steam flow using a capacitive sensor. Also, they assessed the different geometrical effects of the electrodes on the sensitivity of the capacitive sensor. Emerson studied and corrected the effects of temperature change on capacity assessment and correction of the sensor. Ahmed (2006), studied two major geometries (Concave and Ring type) of capacitive sensors in oil/air system in the horizontal pipe and they concluded that capacitive sensors with the ring geometry are a higher sensitivity to the volume fraction compared to a concave geometry. Their results were different from they are in contravention with Jaworek *et al*. (2004), although system that they studied was different. Ahmed and Ismail (2008) placed capacitive sensors inside the pipe and calculated the volume fraction. While they attained good results but the used sensor was intervened with the flow. The next studies on measurement of volume fraction using a capacitive sensor were often on a two-phase system of oil and water (Strazza *et al*., 2011; Tan *et al*., 2015).

There is a difference of opinion about the performance of the electrodes and the researchers obtained from different and sometimes opposite results (Ahmed, 2006; Abouelwafa and Kendall, 1980; Reis and Cunha, 2014). Because electrode configuration has the basic impact on the response of the sensors and any kind of electrodes also has its own properties, selection of the appropriate electrode for any work is required and the inappropriate or incorrect selection can cause a large error in the output response. Based on previous studies, there are three major types of configuration of the electrodes, concave, double ring and double helical or helix (Reis and Goldstein, 2005).

In this study, electrodes are assessed based on the parameters of the response sensitivity, phase distribution-response dependency. To assess the sensitivity, two types of sensitivity are defined as follows: the overall sensitivity to changes the capacity when the pipes are filled with oil and gas:

$$\Delta C_{os} = C_o - C_g \tag{1}$$

where, Oc_{os} is the overall sensitivity according to unit of pF and C_o and C_g of and capacity between the electrodes when the pipe has been filled with oil and air (pF unit). And element sensitivity can be defined as:

$$Se = \frac{C_o - C_m}{C_0 - C_g} \tag{2}$$

where, C_m is oil and gas mixture capacity between the electrodes. The element sensitivity is dimensionless. The element sensitivity can be obtained with fixed changes in permittivity due to the subdomain changes in the volume fractions different from gas ($1<\alpha<0$).

MATERIALS AND METHODS

Theory: A capacitive sensor has been composed of exciting electrode and measuring electrode and screen. The screen is applied for isolating electrodes and connected electronic circuit to minimize the effect of environmental noises. The electric field enters the exciting Electrode Alternatively (AC) and sinusoidal and after passing through the electrode through inside the tube is gathered by the measuring electrode and ready to be processed.

Due to the complex nature of this process, Definition of a specific function for a description of the connection between the sensor output and the sensor parameters is difficult. For this reason, finite element method was used for assessing the efficiency of the sensor. At first, we evaluated the simplest type of electrodes, i.e., the concave electrode. By knowing the distribution of permittivity between the electrodes, the shape of the electrodes and electric potential boundary conditions between the electrodes can be achieved by solving Poisson's equation:

$$\nabla^2\varphi = -\frac{\rho}{\varepsilon} \tag{3}$$

where in two-dimensional form, it is as:

$$\nabla^2\varphi\,(x,y) = \frac{\partial^2\varphi}{\varphi x^2} + \frac{\partial^2\varphi}{\partial y^2} = -\frac{\rho(x,y)}{\varepsilon(x,y)} \tag{4}$$

and in the three-dimensional form, it is as:

$$\nabla^2\varphi(x,y) = \frac{\partial^2\varphi}{\varphi x^2} + \frac{\partial^2\varphi}{\varphi y^2} + \frac{\partial^2\varphi}{\varphi z^2} = -\frac{\rho(x,y,z)}{\varepsilon(x,y,z)} \tag{5}$$

where, φ is an electrical potential distribution between the electrodes, permittivity distribution and ρ is an electrical charge distribution between the electrodes. Due to the complexity of solving this equation using analytical method to get the electric potential distribution (Tollefsen and Hammer, 1998), the Finite Element Method (FEM) can be used. By obtaining the electric potential between the electrodes, quantities of capacity between the electrodes can be calculated using the following relation:

$$C = \frac{Q}{V_C} = \frac{\oint_S \varepsilon(x,y,z)\nabla\varphi(x,y,z)ds}{V_C} \tag{6}$$

where, V_C shows the potential difference applied between the electrodes and s shows the surface of the electrodes. To solve the mentioned equations with the FEM, the COMSOL Software was used.

RESULTS AND DISCUSSION

Now, we assess the concave electrode response to the flow passing through the inside of the pipe optionally and for instance, a flow of oil-gas just a layer. Figure 1 displays a view of concave electrode that is installed outside the pipe. Pipe diameter is 6 cm, length of electrodes is 12 cm and the distance between electrodes is 5.0 cm. Figure 1 displays electrode configuration on the external wall of the pipe.

A view of layer inside the pipe with the appropriate mesh (Fig. 2) is displayed. The gas volume fraction is considered to be 10%. Using the finite element, fluid element flow has been divided into 12520 three-dimensional tetrahedral elements. The software voltage entering the exciting electrode is 1 V. Figure 3 shows the potential field distribution around the pipe by streamline. As the figure shows, the flow field around the electrodes in out of the pipe is very regular but potential field inside the pipe also can be assessed by displaying contour that it is more hopeful. Figure 4 shows

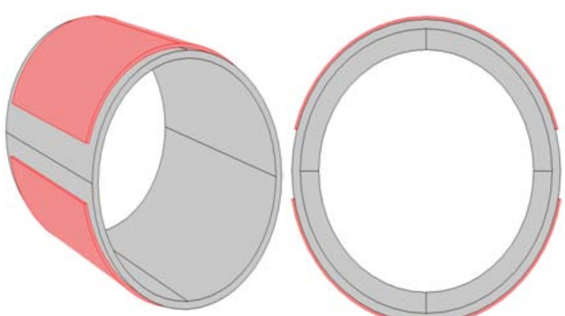

Fig. 1: A concave electrode configuration of the pipe: a) View from the front; b) Side view

the contour display on the inside of the pipe. As can be seen in Fig. 4, contours within the flow are very regular but at the joint surface, their slope is changed severely. In fact, the field lines are dependent on the kind of the fluid passing through the pipe and over to change it, these lines will be changed as well. This property may be used to get the percentage of each of the fluid elements inside the oil transfer pipe.

Figure 5 displays the ring layer type electrode of for Layer flow. Figure 6 and 7 show, respectively the potential field with flow lines and ring type electrode contour. As Figure 6 shows ring type electrodes with a more dispersed and less order, compared to the concave type, create flow lines the outside of the pipe. But the distribution of contours inside the pipe is annular and completely different with concave type. This ring lines

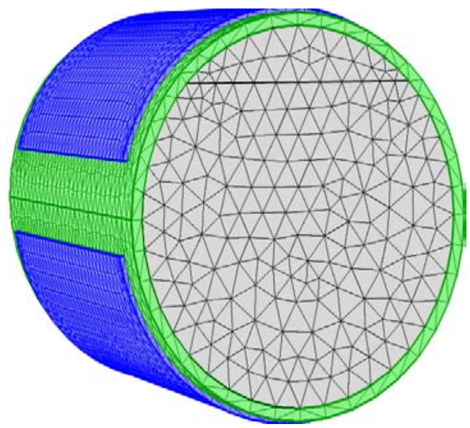

Fig. 2: Meshing model of electrodes and the fluid flow inside the pipe

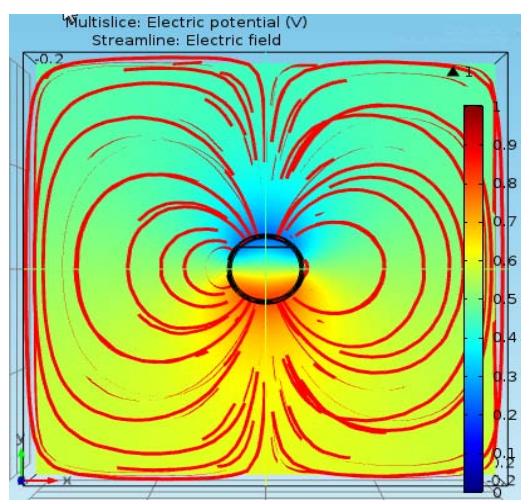

Fig. 3: Numerical simulation of potential field distribution around the pipe in a concave type electrode (a = 10%)

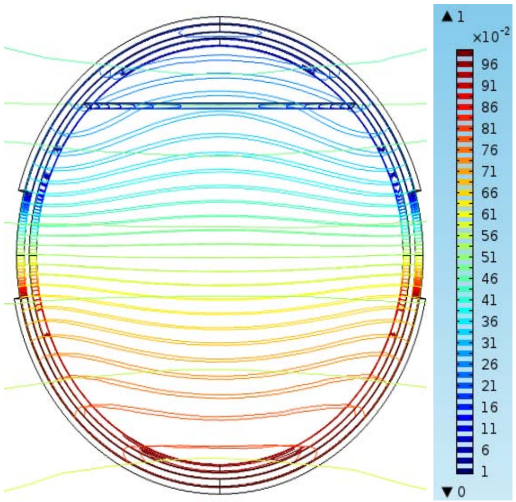

Fig. 4: Numerical simulation of distribution ofcontour inside the pipe in a concave type electrode (a = 10%)

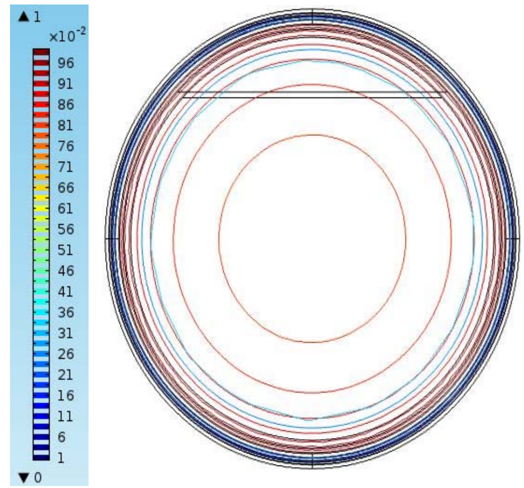

Fig. 7: Numerical simulation of distribution ofcontours inside the pipe in ring type electrode in layer flow (a = 10%)

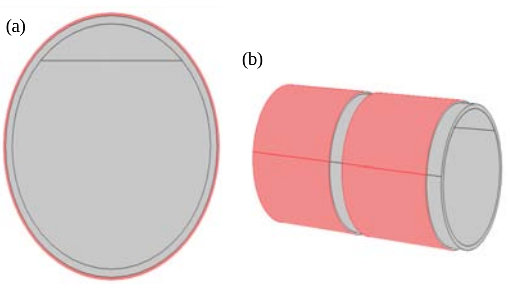

Fig. 5: A ring electrode configuration of the pipe: a) View from the front; b) Side view

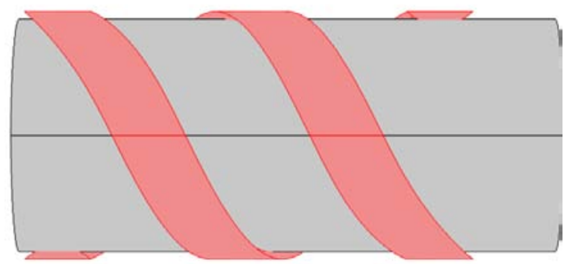

Fig. 8: Configuration of helicaltype electrodes on the pipe

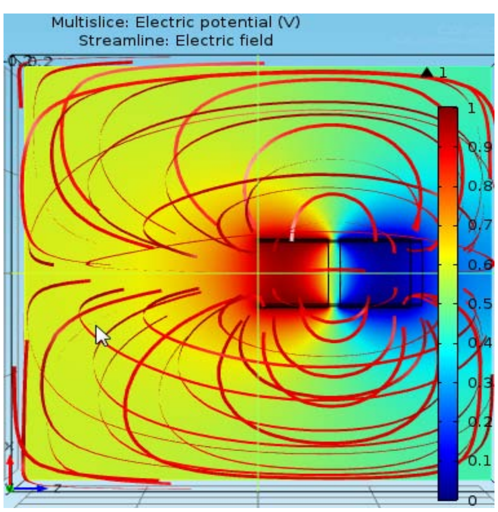

Fig. 6: Numerical simulation of potential field distribution around the ring electrode pipe in layer flow (a = 10%)

may be linked to a more linear response to this type of electrode compared to the concave type in annular flow as we expect.

Finally, Fig. 8 displays the cochlear type of electrode. Figure 9 and 10 show also a potential field with the streamlinesand contour of this electrode. Figure 9 shows the distribution of potential field around the helical electrode pipe. Like the ring type electrodes, streamlines did not have in great order out the electrodes. But the distribution of contours inside the pipe in Fig. 10 indicates a completely uniform and fit distribution in the whole cross-section of the pipe and not only in a certain direction. This type of distribution of the electrode potential for the helical type can be finally predicted as being a linear response in different regimes. Based on the previous description, it was shown that every electrode has its own properties that vary with the other. Here, for the first time based on numerical simulation a new electrode is introduced that has been foundin no reference so far. This electrodeis shown in Fig. 11. As it is clear from Fig. 11 each electrode is composed of three

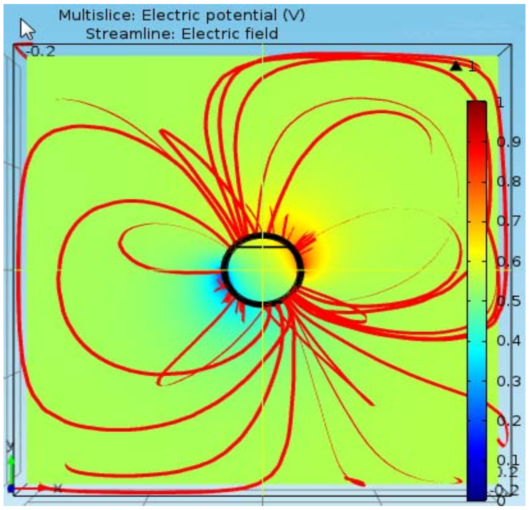

Fig. 9: Numerical simulation of potential field distribution around the pipe of helical type electrode in layer flow (a = 10%)

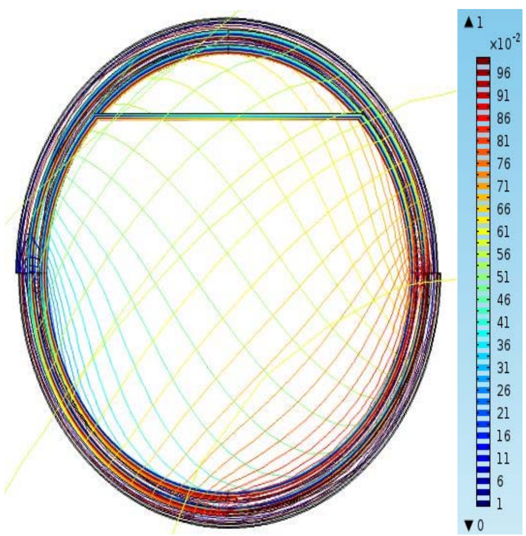

Fig. 10: Numerical simulation of the distribution of contours inside the pipe in helical type electrode in layer flow (a = 10%)

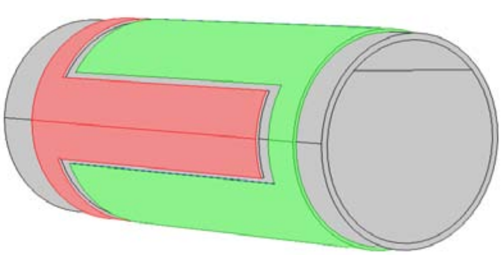

Fig. 11: Configuration of trifid electrode on the pipe

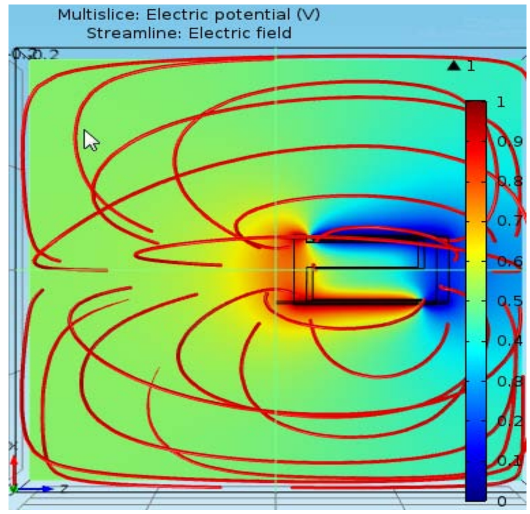

Fig. 12: Numerical simulation of the potential field distribution around the pipe on Three-jagged electrode in layer flow (a = 10%)

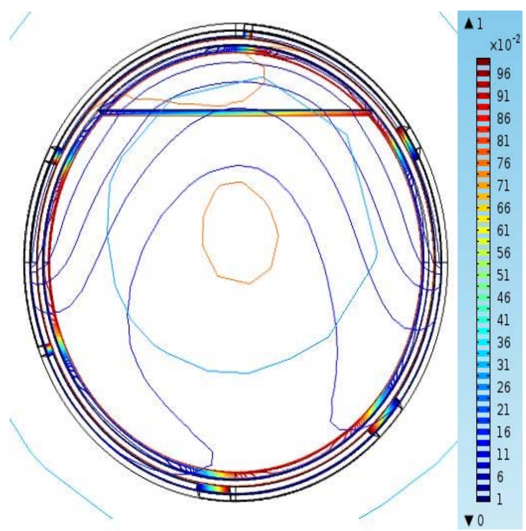

Fig. 13: Numerical simulation of contours inside pipe in three-jagged type electrode in the layer flow (a = 10%)

branches that are rectangular and have a base. All the branches on a regular basis and every other fallwithin each one. This electrode can be the name of the rectangular trifid or three-jagged electrode.

The distribution of potential field on the outside and inside of the pipes are displayed in Fig. 12 and 13, respectively. This distribution is very similar to the ring type electrode; however the internal distribution of contours inside the pipe is the difference and it seems that the three-jagged electrode is more sensitive to the change of the environment inside the pipe from the oil to gas

Table 1: The overall capacity calculated via simulation for a variety of electrodes at the α = 10%

Electrode configuration	Flow pattern	C_o (pF)	C_g (pF)	Δc_{ab} (pF)
Concave	Annular	09.23	7.00	2.23
	Layer	08.06	5.87	2.19
Double ring	Annular	06.53	5.50	1.03
	Layer	06.53	5.49	1.04
Helical	Annular	09.74	8.34	1.40
	Layer	09.74	8.34	1.40
Trifid	Annular	10.37	7.10	3.27
	Layer	10.33	7.04	3.29

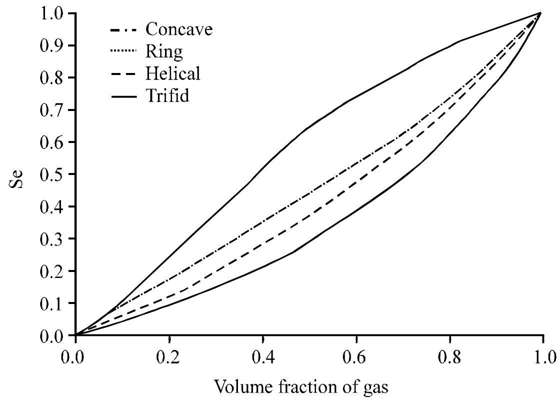

Fig. 14: The minor sensitivity of a variety of the electrode configuration in layer flow in the different volume fractions of gas

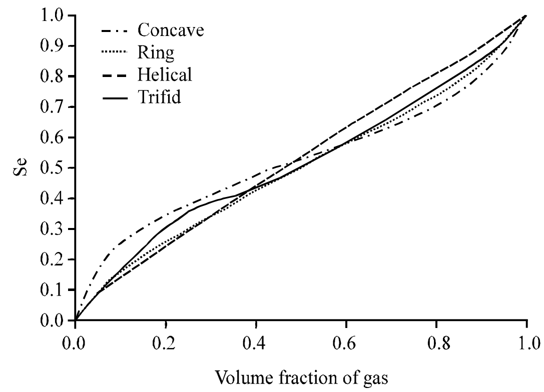

Fig. 15: The minor sensitivity of a variety of the electrode configurations in annular flow in the different volume fraction of gas

(Fig. 13) on the joint surface of oil and gas in the top half of pipelines). For a quantitative comparison, we can take advantage of sensitivity equations (Eq. 1 and 2). As mentioned in the case of having potential distribution, capacity between the electrodes can be calculated and finally the sensitivity values can be calculated for any type of electrode. The two annular and ring flow regime type layer was selected for comparing a variety of electrode shape and the answer depends to flow regime.

An example of the results of the simulation of volume fraction for 10% of the gas has been presented in the Table 1. In this Table 1, the overall sensitivity of all electrodes for two types of regime are compared with each The concave type has a high total sensitivity. Forms 14 and 15 show minor sensitivity to all types of electrodes respectively in the layer and ring flows as well.

Figure 14 and 15 show minor sensitivity to each electrode has a strong dependence on the distribution of phases. For layer flow, trifid configuration has maximum sensitivity and the annular type has the lowest minor sensitivity in all volume fractions. Helix and concave types are close to each other; however, the sensitivity of a concave type is more. But in the annular pattern, concave type in volume fractions <5.0 has maximum sensitivity and in volume fractions >5.0 has the greatest sensitivity. Generally, the most linear trend of changes is

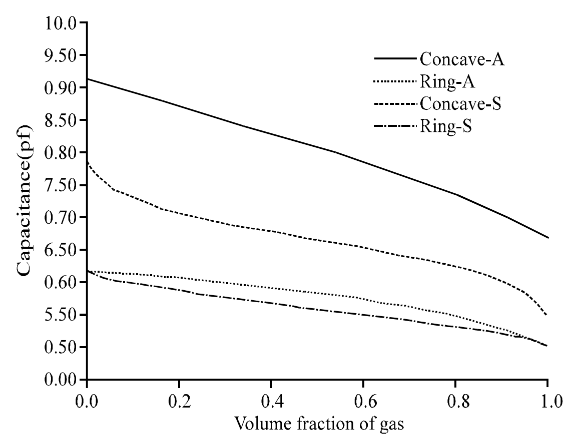

Fig. 16: Effect of flow pattern in the response of the capacitive sensor output with a concave and ring configuration: a) Ring pattern; b) Layer pattern

related to the helical configuration. But other useful charts are related to how the dependence of configurations of the types of the electrodes to the flow regime that is displayed in Fig. 16 and 17.

Figure 16 and 17 show, the response output of concave and trifid type configurations shows a lot of dependence to the distribution of phases, especially for concave type while the ring and helix types have much less dependence to the type of flow and distribution of

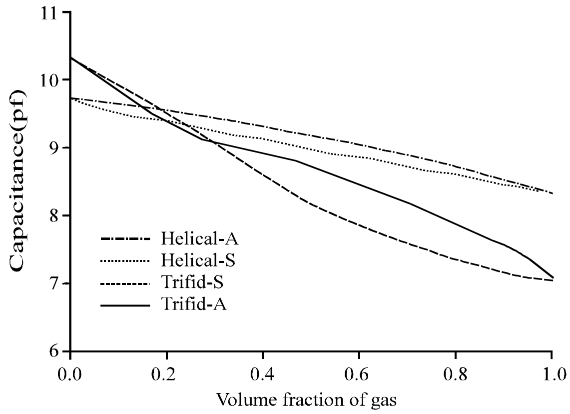

Fig. 17: Effect of flow pattern in the response of capacitive sensor output with the helical and trifid configuration: a) Ring pattern; b) Layer pattern

phases. In fact, this property of dependency to type flow for the mentioned configurations can be used to get the wellhead flow regime and the ring or helix type configurations can be used to measure the ratio of gas to oil coming out of the well.

CONCLUSION

Due to the special importance of electrode configuration in output response and the lack of agreement of earlier research on the best electrode configuration, a variety of important configurations were assessed using the FEM. Using the numerical simulator, a new type of electrodes was introduced that had more sensitive compared to other types of electrodes. The overall conclusion implies that: among the of concave, helix and ring configurations, concave type had the highest overall sensitivity. But its minor sensitivity had a lot of dependency on the type of the flow regime. In the case of layer flow, the trifid type and then the concave type had the most sensitivity; in the case of annular flow to a volume fraction of gas 5.0, concave type and then helix type showed the maximum sensitivity. In both types of layer and annular flow regimes, a minor sensitivity of helix type electrode changed almost linearly with the volume fraction of gas. The concave and trifid type electrodes showed greater dependence on flow regime and the helix and ring electrodes exhibited a lesser dependence. If the aim is to obtain the volume fraction of gas, helix type electrode, due to output response with low dependency on the type of distribution of phases and more sensitivity than the ring type is the best choice but if the aim is to obtain the flow regime, concave and trifid-type electrodes are appropriate, due to the high dependence of output responses to the type of the distribution of output phases.

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