Received 13 May 2023, accepted 26 May 2023, date of publication 31 May 2023, date of current version 21 June 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3281754

RESEARCH ARTICLE

A Novel Smart Optimized Capacitance-Based Sensor for Annular Two-Phase Flow Metering With High Sensitivity

RAHMAD B. Y. SYAH[1], (Member, IEEE), ARYAN VEISI[2], ZAINAL ARIFIN HASIBUAN[3], MUSTAFA A. AL-FAYOUMI[4], MOHAMMAD SH. DAOUD[5], AND EHSAN EFTEKHARI-ZADEH[6]
[1]PUIN-Faculty of Engineering, Universitas Medan Area, Medan 20112, Indonesia
[2]Electrical Engineering Department, Kermanshah University of Technology, Kermanshah 6715685420, Iran
[3]Faculty of Computer Science, Universitas Dian Nuswantoro, Semarang 50131, Indonesia
[4]Department of Cybersecurity, King Hussein School of Computing Sciences, Princess Sumaya University for Technology (PSUT), Amman 11941, Jordan
[5]College of Engineering, Al Ain University, Abu Dhabi, United Arab Emirates
[6]Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, 07743 Jena, Germany

Corresponding author: Ehsan Eftekhari-Zadeh (e.eftekharizadeh@uni-jena.de)

This work was supported in part by the German Research Foundation Projekt under Grant 512648189, in part by the Open Access Publication Fund of Thueringer Universitaets- und Landesbibliothek Jena, and in part by the Excellent Centre of Innovations and New Science-UMA.

ABSTRACT Accurately determining phase fractions in two-phase flows is among the most significant issues in Industries related to the production and processing of petroleum and petrochemicals. There are numerous sensor types and configurations for measuring the void fraction. In this respect, the capacitance-based sensor is commonly recognized as one of the most precise and widely utilized sensors. In this essay, COMSOL Multiphysics software, which has been benchmarked, was used for simulations with various electrode architectures for measuring oil-air two-phase flow in an annular pattern. The initial electrode configurations were helix, double ring, concave and parallel plates. Finite element analysis utilizing COMSOL Multiphysics was executed to compare the electrode configurations. Results exposed disparate sensitivities for different electrode geometries. To get better results, a new electrode geometry called arrow-shaped which was optimized with Artificial intelligence (AI) was proposed and compared with the others. The sensor responses presented demonstrated that the proposed arrow-shaped capacitance-based sensor had 21% higher sensitivity than the best-performing sensor among four other existing sensor designs, including concave, helix, double ring, and parallel plates. These results indicate the superior performance of the arrow-shaped sensor and its potential for use in high-sensitivity applications.

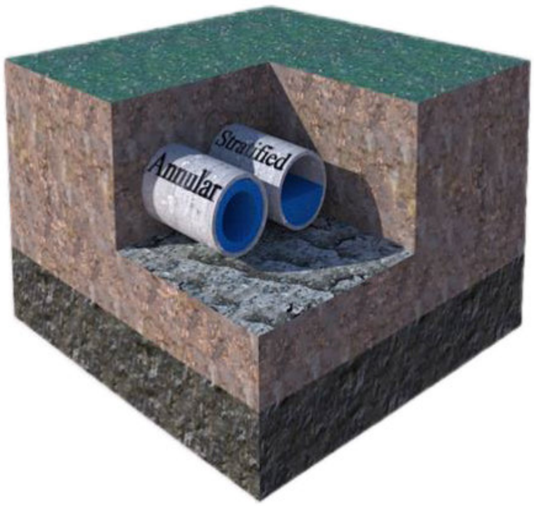
INDEX TERMS Annular regime, arrow-shaped, capacitive sensor, artificial intelligence, concave, optimization, sensitivity, two-phase.

I. INTRODUCTION

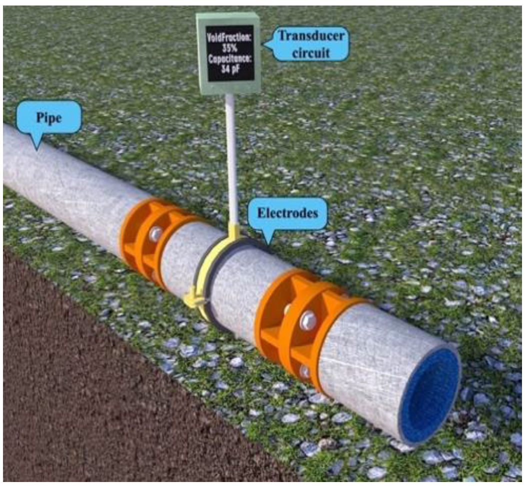
When it comes to the planning and construction of large-scale research facilities, understanding the attributes of two-phase gas-liquid flow patterns is essential. Nevertheless, it might be challenging to accurately Determine the flow of a combination comprising two phases [1]. Several types of commercially accessible meters use diverse measurement principles. [2], [3]. Each of these meters has some limitations. Almost all of them are flow regime dependent and the majority could only achieve acceptable accuracy with homogeneous flows. Flow-mixing instruments are typically used to address this issue [4]. One of the most ordinary measurements of gas-liquid two-phase flow is the segregation method, where the phases are separated and each flow measured separately. This method necessitated costly apparatus and had the potential to cause a disruption in the continuity of industrial processes besides, traditional methods cannot achieve the flow regime [5]. Accurate modeling of two-phase systems is required precise evaluation of pore space and discernment of

The associate editor coordinating the review of this manuscript and approving it for publication was Alon Kuperman.

fluid movement patterns. The amount of gas that is contained within a pipe is proportional to the entire capacity of the pipe. This proportion is referred to as the void fraction [6]. Several techniques can be used to measure void fractions, such as Conductive sensing probes, impedance or capacitance sensing, quick-closing valves, and Radiative absorption (x-rays or γ-rays). However, interferometric probes cause disturbances in the flow field, and radiation attenuation methods can be costly and difficult to implement from a safety perspective. In contrast, the technique of measuring impedance is economical and feasible [7]. Additionally, capacitive technology is utilized in the process of determining the thickness of a liquid film [8]. In order to estimate real-time hold-up, a capacitance-based sensor system has been proposed [9]. This technique is on the basis of the diverse electrical qualities of each phase with different combinations and quantities in the tube, producing different permittivity distributions [10]. To detect these shifts, a capacitor is formed with electrodes on the tube's exterior [11]. One major benefit of capacitive sensing is that it is not obtrusive and does not cause any disruptions to the flow regime [12]. To gather hold-up measurements or tomographic reconstructions, capacitance-based sensors have advanced and shown good results for gas-liquid and liquid-liquid flow [13], [14]. Additionally, with regard to the gas-solid system [15]. Kendoush and Sarkis proposed a new method to improve the accuracy of void fraction measurement using capacitance sensors in two-phase flow, which involves taking into account the influence of electrode shape, electrode spacing, and dielectric constant of the fluids [16]. Abouelwafa et al. evaluated the outcomes of a comparison of numerous capacitance setups in gas-liquid two-phase tubes. In a Quantified flow regime, it has been determined that a structure composed of four concave plates is superior for increased sensitivity and manufacturing convenience [17]. Ahmad et al. examined the ring and concave type of capacitance sensor. An equivalent capacitance circuit was used to represent the phase fraction and evaluate the sensitivity of both ring and concave sensors. Furthermore, decreasing the distance among electrodes increases the sensitivity of the ring sensor. Additionally, the ring sensor exhibits greater sensitivity compared to the concave sensor at the same resolution [18]. Zhai et al. proposed a double helix capacitance sensor for the noninvasive measurement of liquid holdup in horizontal oil-water two-phase flow pipes, which offers a potential solution to the challenge of accurate measurement of two-phase flow in oil and gas production processes [19]. Jaworek et al. evaluated the vacancy fraction by utilizing five unique sensor designs with a radio frequency resonance circuit operating at a frequency of 80 MHz [20]. Elkow and Rezkallah developed capacitance sensors for measuring the void fraction in gas-liquid flows under both normal gravity and microgravity conditions, highlighting the versatility of this sensing technology in different operating environments [21]. Dos Reis and da Silva Cunha conducted an experimental study to investigate different configurations of capacitive sensors for measuring volumetric concentration in two-phase flows. The results showed that the sensitivity and accuracy of the sensors were influenced by the sensor configuration, electrode shape, and electrode material. The authors concluded that a careful selection of these parameters could lead to an optimal capacitive sensor design for measuring the volumetric concentration in two-phase flows [22]. Tollefsen and colleagues aimed to improve the sensitivity and accuracy of a helical capacitive sensor's independence to flow regimes by utilizing Finite Element Method (FEM) modeling to simulate the sensor. The researchers validated their simulation by employing various sensors and flow regime measurements, which demonstrated the highest discrepancy of 5% among the simulated and experimental outcomes [23]. Salehi and his colleagues conducted experimental and simulation studies to investigate architecture factors on the capacitance output for the concave and ring types of sensors. A linear association was discovered between output capacitance and porosity. Additionally, Salehi introduced a capacitive sensor system for measuring the phase fraction of a gasoline two-phase flow arrangement in 2017 [24]. In comparison to each other, double-ring and concave electrodes were employed. Observational conclusions demonstrated that concave architecture depends on flow regimes. Salehi et al. examined the new shape of electrode formations in different regimes for two-phase oil-air flow measurement [25]. The results demonstrate that each electrode shape has varied sensitivity. In the annular structure, the concave configuration exhibited higher sensitivity compared to the other shapes. Salehi and his co-workers proposed a new shape of electrode named TRFLC to identify the pattern of flow in two-phase oil-gas horizontal tubes [26]. Computational and mathematical calculations, combined with Digital Signal Processing (DSP) techniques, specifically Artificial Neural Network (ANN), are being extensively used as a highly effective mathematical tool to solve complex engineering problems in various fields such as electrical engineering [27], [28], [29], [30], civil engineering [31], [32], instrumentation and control engineering [33], [34], Nano electronic [35], [36], chemical, and petrochemical engineering [37], [38], [39], [40], [41], [42]. Recent research has focused on hardware acceleration for electrical tomography systems. Meribout et al. proposed a hybrid FPGA-GPU-based hardware accelerator for 2D Electrical Impedance Tomography [43], while Tiwari et al. developed a neural network-based data acquisition system [44]. Tiwari et al. reviewed electrical tomography hardware systems for real-time applications [45], while Teniou et al. designed a pipelined parallel hardware architecture for 2-D real-time electrical capacitance tomography imaging [46]. Saied et al. developed a real-time two-dimensional imaging system using electrical capacitance tomography [47]. These hardware systems offer significant improvements in imaging speed and accuracy. Also have potential applications in medical diagnosis, industrial monitoring, and environmental sensing. In our previous work, the COMSOL simulation was



(a)



(b)

FIGURE 1. (a) Stratified and annular flow regimes in a pipe. (b) Schematic view of a capacitance-based flow meter.

validated through experimental studies, and an artificial neural network (ANN) model was developed to accurately predict void fractions in various fluids [48]. The characteristics of gas-liquid two-phase flow patterns can give rise to different flow regimes, where the most common ones are stratified and annular, as demonstrated in Figure 1(a). Electrodes and a transducer circuit are the two components that make up capacitance-based sensors, as shown in Figure 1(b).

The novelty and main contribution of our paper specifically focus on proposing and improving a novel optimized arrow-shaped electrode geometry for capacitance-based sensors. This paper proposes a new type of capacitance-based sensor with an arrow-shaped design, which has demonstrated higher sensitivity than other sensor shapes for measuring gas-liquid two-phase annular flow patterns. The study further investigates the ideal construction of the proposed sensor by examining the sensitivity domain of the arrow-shaped sensor using the finite element method (FEM) through COMSOL Multiphysics software.

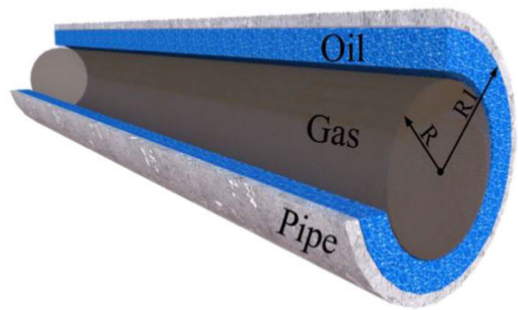


FIGURE 2. Two-phase annular flow pattern structure.

II. VOID FRACTION MEASUREMENT TECHNIQUES

The geometric distribution of the components inside a flow may impact the momentum, mass and energy transfer rates. Additionally, the flow inside each component or phase depends on the flow regimes, which is deemed a particular form of geometric distribution for the constituent [49]. In this project, an electrical capacitance-based sensor was used to provide Precise measurement outcomes using non-engaging and non-invasive methods. In multiphase flow, the dimensionless quantity of void fraction is regarded as the most crucial factor. Although void fraction was first used in the 1940s, it continues to be utilized today. The term ‘void fraction’ in multiphase flow refers to the fraction of a geometric domain engaged by a different phase, as illustrated in Figure 2, which depicts related polyphase flow terminology. The phase fractions for the two-phase oil-gas regime in annular flow were described using Equations (1) and (2). Several studies have explored various techniques for estimating void fraction values. Among these studies, Zehtaban and colleagues investigated void fraction in two-phase flows [50], while Giang T. T. Phan et al. focused on predicting void fraction [51]. Robert Hanus et al. conducted research on void fractions in basic flow regimes [52]. Barbosa et al. studied the characteristics of void fraction [53]. Fouladi et al. utilized an artificial neural network to predict void fractions in different fluids [54]. Additionally, Shahsavari et al. focused on the effect of different orientations in stratified two-phase flows [55].

$$Vgas = \frac{\pi R^2}{\pi R1^2} = \frac{R^2}{R1^2} \tag{1}$$

$$Vwater = \frac{\pi R1^2 - \pi R^2}{\pi R1^2} = \frac{R1^2 - R^2}{R1^2} \tag{2}$$

III. VALIDATION OF SIMULATION

In this paper, the capacitance-based sensors used for simulating polyphasic flows were created using COMSOL Multiphysics tools. To ensure accuracy, the simulations were initially benchmarked against the reference [48].

To validate the COMSOL reconstruction, both an investigational study and an arithmetical study were conducted, as described in reference [48]. The present study involved

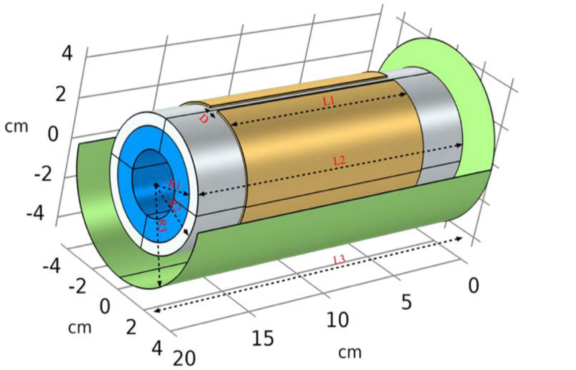


FIGURE 3. A diagrammatic representation of the configuration employed to authenticate the COMSOL Multiphysics simulation.

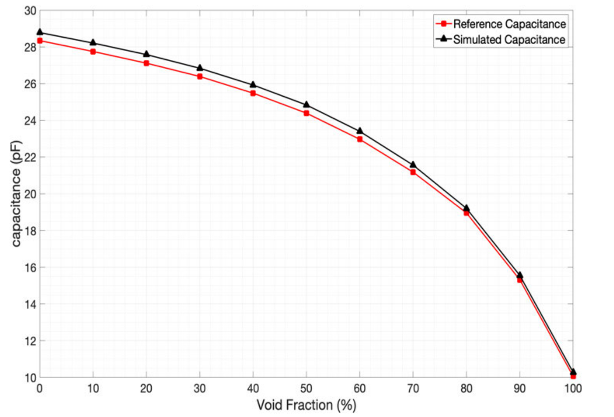


FIGURE 4. The validation of the simulation based on a comparison of the findings obtained by COMSOL Multiphysics with [39].

conducting experimental investigations and numerical examination on diverse electrode arrangements to measure the two-phase flow of air and water in annular patterns. In the current investigation, a concave capacitive sensor with the arrangement determined in [48] was first simulated. Soft copper electrodes with a thickness of 0.1 cm were used, with one electrode for exciting and the other for measuring. The interior pipe radius was R1 = 2.6 cm, the exterior pipe radius was R2 = 3.2 cm, and the radius of the considered earth was R3 = 4.5 cm. The electrode length was L1 = 12 cm and the pipe length was L2 = 18 cm. L3 = 20 cm was the length considered for Earth and the spacing between electrodes was D = 0.5 cm. The relative permittivities of air, water and the pipe wall were adjusted to 1, 81, and 3.3, respectively. Figure 3 depicts the simulated structure used to validate the COMSOL simulation. Simulations were run using void fractions of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 for the annular air-water two-phase flow. The comparison between the COMSOL simulation and the outcomes that were demonstrated in reference [48] is shown in Table 1 and graphed in Figure 4. The comparison demonstrates a good agreement between the two. The mean relative difference between the reference capacitance and the simulated capacitance was 0.022, which is a negligibly small number. This small difference could be due to the considered earth or size of the meshed model. These findings imply that the simulated outcomes have been validated.

TABLE 1. Comparison of the COMSOL Multiphysics simulation's calculated results with [48] to validate the simulation.

Void fraction (present)	Reference capacitance [48] (pF)	Simulated capacitance with COMSOL (pF)	Relative difference
100	10.067	10.277	0.020
90	15.317	15.553	0.015
80	18.957	19.204	0.013
70	21.178	21.561	0.018
60	22.967	23.398	0.018
50	24.391	24.837	0.018
40	25.481	25.923	0.017
30	26.389	26.836	0.017
20	27.113	27.58	0.017
10	27.749	28.208	0.016
0	28.341	28.779	0.015

IV. CONFIGURATION OF THE SUGGESTED SNSOR

The presented arrow-shaped sensor consisted of five components: an insulating pipe, an earthed screen, a transducer circuit, an exciting electrode, and a measuring electrode. The sensor's electrode design was optimized through a passive approach based on the study of existing sensors. Also, artificial intelligence was utilized to improve the design. The arrow-shaped sensor is shown in three dimensions in Figure 5(a), while Figure 5(b) illustrates a cross-sectional

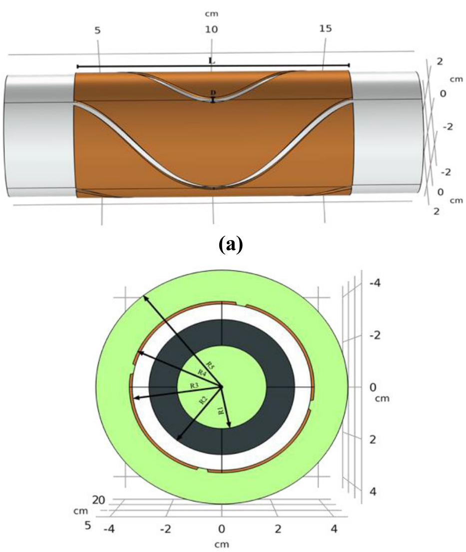
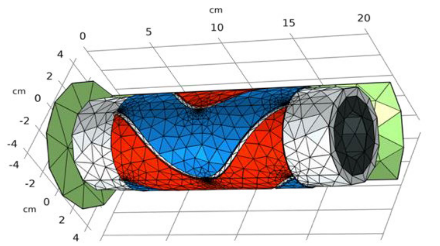
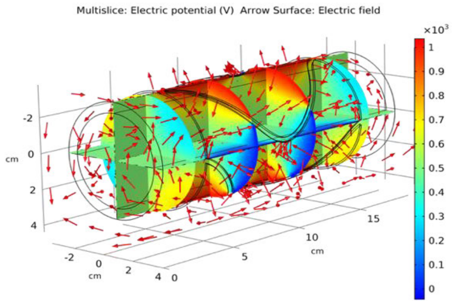


FIGURE 5. (a) Three dimensions view of the proposed sensor. (b) Diagrammatic section of the arrow-shaped sensor which has been located in the center of the pipe.



(a)



(b)

FIGURE 6. (a) Mesh representation of the suggested sensor. (b) An instance of a FEM simulation of the arrow-shaped sensor for an annular flow pattern.

view of the sensor, with the fluid mixture inside the pipe represented by the central area. The length of the electrode, the radius of air inside the pipe, the internal radius of the pipeline, the external radius of the pipeline, the external radius of the electrode and the radius of the earthed screen as L, R1, R2, R3, R4, R5, respectively. To Simulate the proposed sensor, soft copper plates were utilized as electrodes, quartz glass as the pipe material, and oil and air as the fluid and gas phases, respectively. The finite element mesh model of the arrow-shaped sensor is shown in Figure 6(a), while Figure 6(b) depicts the outcomes of the FEM simulation.

V. SENSITIVITY FIELD OF THE ARROW-SHAPED SENSOR

Configuration of the electrodes is a crucial criterion for capacitance computation since it influences the electric field's susceptibility distribution. Using a 3-D arithmetical finite element examination, the effect of the arrow-shaped sensor's geometry on output response was investigated. The meshed FEM was drawn using the COMSOL Multiphysics 5.5 software. In the model documentation, Electrostatics was selected, and the fluent ingredient was subdivided towards 19280 3-D tetrahedral pieces. In the finite component computation, the sensitivity of the arrow-shaped electrode was estimated in the annular flow pattern. A 3D geometry was used to calculate the capacitance differences caused by the sub-domain permittivity shift to estimate the electrode sensitivity sphere. The retort of the arrow-shaped sensor in an annular regime qualified to obtained by repeating the process at every particular test spot in the measured area. Equation 3 provides the definition of the overall sensitivity.

$$S_o = C_o - C_g \tag{3}$$

In this equation 3, C_o and C_g represent the computed capacitances of the pure oil and gas in the pipes, respectively, and were used as reference values to calculate the void fraction in the two-phase flow. In the calculation, the interior radius of the tube was set to R2 = 2.6 cm, the exterior radius of the tube was set to R3 = 3.2 cm, and the overall length of the electrode was set to L = 12 cm. The dielectric constants of air (ε_{gas}) and oil (ε_{oil}) are set to 1 and 2.2, correspondingly, while the dielectric constants of the tube wall are set to 3.3. The capacitance value between the stimulating and measuring electrodes inside the pipe can be determined using electromagnetic theory. How potential is distributed throughout a three-dimensional electrostatic field is outlined by equation 4.

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

where V(x, y, z), ρ(x, y, z), and ε(x, y, z) were the spatial variation of electric potential, the charge distribution, and the permittivity dispersion of the medium among the measuring and exciting electrodes, respectively. If how the charges are spread out in a three-dimensional electrostatic field is ignored, Laplace's equation can be used to describe how the electrical potential is spread out. Due to the difficulty of the mathematical solution required to determine the potential dissemination [19], the finite element approach is favored. When the potential distribution within the sensor has been determined, the capacitance value can be calculated using equation 5.

$$C = \frac{Q}{V_c} = \frac{\oint_s \varepsilon(x, y, z)\nabla V(x, y, z)ds}{V_c} \tag{5}$$

In this scenario, s stands for the electrode surface, and V_c represents the potential difference between the two electrodes. The capacitance value between the stimulating and measuring electrodes can be determined using the Gauss law by applying a voltage between them (1 volt applied to the stimulating electrode and zero volts applied to the detector electrode). The impact of sensor characteristics on the sensitivity field was studied. The findings obtained using the FEM and Artificial intelligence (AI) are depicted in Table 2 and Figure 7. Table 2 shows that under the same condition, the four-blade sensor had the maximum sensitivity when compared to others. The

TABLE 2. The comparison of blade numbers and sensor overall sensitivity.

The number of blades	*Overall sensitivity (pF)*
2	2.034
4	2.232
6	1.891
8	1.704
10	1.533

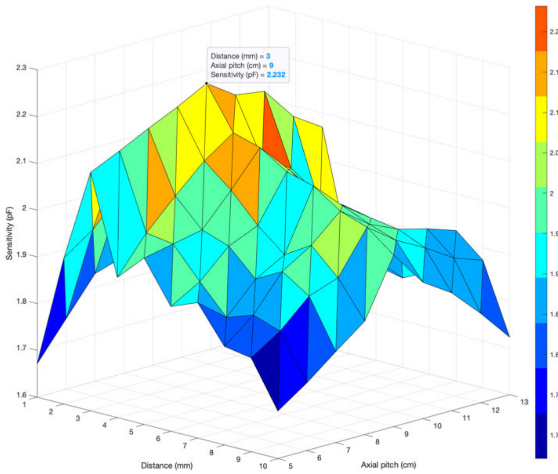


FIGURE 7. Sensitivity map of the arrow-shaped capacitance-based sensor.

sensitivity map of the arrow shape sensor is illustrated in Figure 7. According to Figure 7, sensitivity increases as the distance between each electrode blade decreases. Moreover, it shows that sensitivity decreases as distance decreases below 0.3 cm. As shown in Figure 7, another factor affecting the sensitivity stands the axial pitch. This sensor has the highest sensitivity, around 90 mm of the axial pitch.

VI. RESULT AND DISCUSSION

In this study, the implemented finite element method in COMSOL Multiphysics was utilized to optimize and compare different geometrical structures of capacitance-based sensors for phase fraction evaluation in two-phase flows. The arrow-shaped sensor was compared against concave, double ring, helix, and parallel plate configurations. The optimal physical arrangement of the arrow-shaped capacitance-based sensor was determined to be the distance between the sensor blades was 0.3 cm and the axial pitch was 9 cm. The capacitance at void fractions ranging from 0 to 100% was measured to evaluate the performance of the arrow-shaped sensor and the results are summarized in table 3. The overall sensitivity of the sensors was also compared and the results are presented in Figure 8. Notably, the overall sensitivity of the arrow-shaped sensor was found to be 22% higher than the concave, 264% higher than the double ring, 21% higher than the helix, and 234% higher than the parallel plates. Based on the obtained results, it can be concluded that the arrow-shaped sensor outperforms the other sensor configurations in terms of overall sensitivity. Thus, it may be a better choice for accurately determining phase fractions in two-phase flows in the petroleum and petrochemical industries. The findings of this study could contribute to the development of more accurate and reliable sensors for phase fraction measurement in various industrial applications.

TABLE 3. Measurement results were obtained using the arrow-shaped sensor in the annular oil-air flow regime, as calculated with COMSOL Multiphysics.

Void Fraction (%)	Recorded Capacitance (pF)
100	29.851
90	30.309
80	30.738
70	31.106
60	31.426
50	31.610
40	31.787
30	31.932
20	32.036
10	32.071
0	32.083

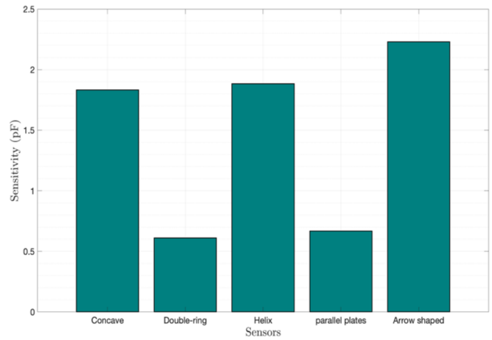


FIGURE 8. Comparison of the concave, double ring, helix, and parallel plate capacitance-based sensors, as calculated with COMSOL Multiphysics.

VII. CONCLUSION

This study identified the precise quantification of void fractions in two-phase flows in the petroleum and petrochemical sectors as a pressing issue. To address this issue, a novel arrow-shaped capacitance-based sensor was proposed and optimized with the aim of improving sensitivity. The sensitivity of the arrow-shaped sensor was computed using the implemented finite element method in the benchmarked version of COMSOL Multiphysics 5.5. The geometry of the arrow-shaped sensor was optimized with AI to achieve the possible maximum sensitivity. The optimal structures of the sensor were determined to include a blade distance of 0.3 cm, an axial pitch of the electrodes of 9 cm, and four blades. Based on the FEM results, the proposed sensor's overall sensitivity was 2.23 pF. The proposed sensor showed greater sensitivity in measuring phase fractions in oil-air filled tubes when using arrow-shaped surface electrodes, as compared to other electrode configurations. Additionally, the presented sensor responses showed that the proposed arrow-shaped capacitance-based sensor showed 21% higher sensitivity than the best sensor among the other four existing sensor designs, which include concave plates, helix, double ring and parallel plates. While our study focused on the annular flow regime, future studies could investigate the performance of the optimized capacitance-based sensor in other flow regimes to determine the optimal design parameters for those regimes and to further validate the applicability of the sensor in various flow conditions. These findings indicated that the arrow-shaped capacitance-based sensor shows significant promise in precisely determining phase fractions in two-phase flows within the industries related to the production and processing of petroleum and petrochemicals. The development of sensors with enhanced sensitivity and accuracy could significantly improve the efficiency and productivity of these industries.

REFERENCES

[1] H. Ji, Z. Huang, B. Wang, and L. Haiqing, "Flow regime identification of mini-pipe gas-liquid two-phase flow based on textural feature series," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, May 2011, pp. 1–4.

[2] A. Ribeiro, "Developments in multiphase metering," in *Proc. Conf. Develop. Prod. Separat. Syst.*, London, U.K., 1993. pp. 4–5.

[3] R. Thorn, G. A. Johansen, and E. A. Hammer, "Recent developments in three-phase flow measurement," *Meas. Sci. Technol.*, vol. 8, no. 7, pp. 691–701, Jul. 1997.

[4] I. Ismail, J. C. Gamio, S. F. A. Bukhari, and W. Q. Yang, "Tomography for multi-phase flow measurement in the oil industry," *Flow Meas. Instrum.*, vol. 16, nos. 2–3, pp. 145–155, Apr. 2005.

[5] D. Wang, F.-C. Liang, Z.-Q. Peng, Y.-G. Wang, and Z.-H. Lin, "Gas–liquid two-phase flow measurements by full stream batch sampling," *Int. J. Multiphase Flow*, vol. 40, pp. 113–125, Apr. 2012.

[6] H. C. Yang, D. K. Kim, and M. H. Kim, "Void fraction measurement using impedance method," *Flow Meas. Instrum.*, vol. 14, nos. 4–5, pp. 151–160, Aug. 2003.

[7] D. Lowe and K. S. Rezkallah, "A capacitance sensor for the characterization of microgravity two-phase liquid-gas flows," *Meas. Sci. Technol.*, vol. 10, no. 10, pp. 965–975, Oct. 1999.

[8] M. R. Özgü, J. C. Chen, and N. Eberhardt, "A capacitance method for measurement of film thickness in two-phase flow," *Rev. Sci. Instrum.*, vol. 44, no. 12, pp. 1714–1716, Dec. 1973.

[9] N. Reinecke and D. Mewes, "Recent developments and industrial/research applications of capacitance tomography," *Meas. Sci. Technol.*, vol. 7, no. 3, pp. 233–246, Mar. 1996.

[10] J. J. M. Geraets and J. C. Borst, "A capacitance sensor for two-phase void fraction measurement and flow pattern identification," *Int. J. Multiphase Flow*, vol. 14, no. 3, pp. 305–320, May 1988.

[11] C. N. Strizzolo and J. Converti, "Capacitance sensors for measurement of phase volume fraction in two-phase pipelines," *IEEE Trans. Instrum. Meas.*, vol. 42, no. 3, pp. 726–729, Jun. 1993.

[12] W. Q. Yang and L. Peng, "Image reconstruction algorithms for electrical capacitance tomography," *Meas. Sci. Technol.*, vol. 14, no. 1, pp. R1–R13, Jan. 2003.

[13] A. M. Olmos, M. A. Carvajal, D. P. Morales, A. García, and A. J. Palma, "Development of an electrical capacitance tomography system using four rotating electrodes," *Sens. Actuators A, Phys.*, vol. 148, no. 2, pp. 366–375, Dec. 2008.

[14] E. dos Reis and L. Goldstein, "A non-intrusive probe for bubble profile and velocity measurement in horizontal slug flows," *Flow Meas. Instrum.*, vol. 16, no. 4, pp. 229–239, Aug. 2005.

[15] T. Dyakowski, R. B. Edwards, C. G. Xie, and R. A. Williams, "Application of capacitance tomography to gas-solid flows," *Chem. Eng. Sci.*, vol. 52, no. 13, pp. 2099–2110, Jul. 1997.

[16] A. A. Kendoush and Z. A. Sarkis, "Improving the accuracy of the capacitance method for void fraction measurement," *Experim. Thermal Fluid Sci.*, vol. 11, no. 4, pp. 321–326, Nov. 1995.

[17] M. S. A. Abouelwafa and E. J. M. Kendall, "The use of capacitance sensors for phase percentage determination in multiphase pipelines," *IEEE Trans. Instrum. Meas.*, vol. IM-29, no. 1, pp. 24–27, May 1980.

[18] H. Ahmed, "Capacitance sensors for void-fraction measurements and flow-pattern identification in air–oil two-phase flow," *IEEE Sensors J.*, vol. 6, no. 5, pp. 1153–1163, Oct. 2006.

[19] L. Zhai, N. Jin, Z. Gao, and Z. Wang, "Liquid holdup measurement with double helix capacitance sensor in horizontal oil–water two-phase flow pipes," *Chin. J. Chem. Eng.*, vol. 23, no. 1, pp. 268–275, Jan. 2015.

[20] A. Jaworek and A. Krupa, "Phase-shift detection for capacitance sensor measuring void fraction in two-phase flow," *Sens. Actuators A, Phys.*, vol. 160, nos. 1–2, pp. 78–86, May 2010.

[21] K. J. Elkow and K. S. Rezkallah, "Void fraction measurements in gas-liquid flows under 1–g and μ–g conditions using capacitance sensors," *Int. J. Multiphase Flow*, vol. 23, no. 5, pp. 815–829, Sep. 1997.

[22] E. dos Reis and D. da Silva Cunha, "Experimental study on different configurations of capacitive sensors for measuring the volumetric concentration in two-phase flows," *Flow Meas. Instrum.*, vol. 37, pp. 127–134, Jun. 2014.

[23] J. Tollefsen and E. A. Hammer, "Capacitance sensor design for reducing errors in phase concentration measurements," *Flow Meas. Instrum.*, vol. 9, no. 1, pp. 25–32, Mar. 1998.

[24] S. M. Salehi, H. Karimi, and A. A. Dastranj, "A capacitance sensor for gas/oil two-phase flow measurement: Exciting frequency analysis and static experiment," *IEEE Sensors J.*, vol. 17, no. 3, pp. 679–686, Feb. 2017.

[25] S. M. Salehi, H. Karimi, R. Moosavi, and A. A. Dastranj, "Different configurations of capacitance sensor for gas/oil two phase flow measurement: An experimental and numerical study," *Exp. Thermal Fluid Sci.*, vol. 82, pp. 349–358, Jan. 2017.

[26] S. M. Salehi, H. Karimi, A. A. Dastranj, and R. Moosavi, "Twin rectangular fork-like capacitance sensor to flow regime identification in horizontal co-current gas–liquid two-phase flow," *IEEE Sensors J.*, vol. 17, no. 15, pp. 4834–4842, Aug. 2017.

[27] S. Roshani and S. Roshani, "Design of a compact LPF and a miniaturized Wilkinson power divider using aperiodic stubs with harmonic suppression for wireless applications," *Wireless Netw.*, vol. 26, no. 2, pp. 1493–1501, Feb. 2020.

[28] M. Hookari, S. Roshani, and S. Roshani, "Design of a low pass filter using rhombus-shaped resonators with an analyticalLC equivalent circuit," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 28, no. 2, pp. 865–874, Mar. 2020.

[29] T.-C. Chen, S. M. Alizadeh, A. K. Alanazi, J. W. G. Guerrero, H. M. Abo-Dief, E. Eftekhari-Zadeh, and F. Fouladinia, "Using ANN and combined capacitive sensors to predict the void fraction for a two-phase homogeneous fluid independent of the liquid phase type," *Processes*, vol. 11, no. 3, p. 940, Mar. 2023, doi: 10.3390/pr11030940.

[30] A. Lalbakhsh, G. Mohamadpour, S. Roshani, M. Ami, S. Roshani, A. S. M. Sayem, M. Alibakhshikenari, and S. Koziel, "Design of a compact planar transmission line for miniaturized rat-race coupler with harmonics suppression," *IEEE Access*, vol. 9, pp. 129207–129217, 2021.

[31] M. Khaleghi, J. Salimi, V. Farhangi, M. J. Moradi, and M. Karakouzian, "Evaluating the behaviour of centrally perforated unreinforced masonry walls: Applications of numerical analysis, machine learning, and stochastic methods," *Ain Shams Eng. J.*, vol. 13, no. 3, May 2022, Art. no. 101631.

[32] N. Moradi, M. H. Tavana, M. R. Habibi, M. Amiri, M. J. Moradi, and V. Farhangi, "Predicting the compressive strength of concrete containing binary supplementary cementitious material using machine learning approach," *Materials*, vol. 15, no. 15, p. 5336, Aug. 2022.

[33] R. Hanus, M. Zych, and A. Golijanek-Jędrzejczyk, "Measurements of dispersed phase velocity in two-phase flows in pipelines using gamma-absorption technique and phase of the cross-spectral density function," *Energies*, vol. 15, no. 24, p. 9526, Dec. 2022.

[34] R. Hanus, M. Zych, and A. Golijanek-Jędrzejczyk, "Investigation of liquid–gas flow in a horizontal pipeline using gamma-ray technique and modified cross-correlation," *Energies*, vol. 15, no. 16, p. 5848, Aug. 2022.

[35] A. Mayet and M. Hussain, "Amorphous WNx metal for accelerometers and gyroscopev," in *Proc. MRS Fall Meeting*, vol. 30, Boston, MA, USA, Dec. 2014.

[36] A. M. Mayet, A. M. Hussain, and M. M. Hussain, "Three-terminal nanoelectromechanical switch based on tungsten nitride—An amorphous metallic material," *Nanotechnology*, vol. 27, no. 3, Jan. 2016, Art. no. 035202.

[37] E. Nazemi, G. H. Roshani, S. A. H. Feghhi, S. Setayeshi, E. E. Zadeh, and A. Fatehi, "Optimization of a method for identifying the flow regime and measuring void fraction in a broad beam gamma-ray attenuation technique," *Int. J. Hydrogen Energy*, vol. 41, no. 18, pp. 7438–7444, May 2016.

[38] G. H. Roshani, R. Hanus, A. Khazaei, M. Zych, E. Nazemi, and V. Mosorov, "Density and velocity determination for single-phase flow based on radiotracer technique and neural networks," *Flow Meas. Instrum.*, vol. 61, pp. 9–14, 2018.

[39] G. H. Roshani, E. Nazemi, and M. M. Roshani, "Intelligent recognition of gas-oil-water three-phase flow regime and determination of volume fraction using radial basis function," *Flow Meas. Instrum.*, vol. 54, pp. 39–45, Apr. 2017.

[40] G. H. Roshani, S. Roshani, E. Nazemi, and S. Roshani, ''Online measuring density of oil products in annular regime of gas-liquid two phase flows,'' *Measurement*, vol. 129, pp. 296–301, Dec. 2018.

[41] E. Nazemi, S. A. H. Feghhi, G. H. Roshani, R. G. Peyvandi, and S. Setayeshi, ''Precise void fraction measurement in two-phase flows independent of the flow regime using gamma-ray attenuation,'' *Nucl. Eng. Technol.*, vol. 48, no. 1, pp. 64–71, Feb. 2016.

[42] S. Hosseini, O. Taylan, M. Abusurrah, T. Akilan, E. Nazemi, E. Eftekhari-Zadeh, F. Bano, and G. H. Roshani, ''Application of wavelet feature extraction and artificial neural networks for improving the performance of gas–liquid two-phase flow meters used in oil and petrochemical industries,'' *Polymers*, vol. 13, no. 21, p. 3647, Oct. 2021.

[43] V. K. Tiwari and M. Meribout, ''A hybrid FPGA-GPU-based hardware accelerator for high throughput 2D electrical impedance tomography,'' Khalifa Univ., Abu Dhabi, UAE, Tech. Rep., 2023.

[44] V. K. Tiwari, ''A novel neural network-based data acquisition system targeting high-speed electrical tomography systems,'' Khalifa Univ., Abu Dhabi, UAE, Tech. Rep., 2023.

[45] V. K. Tiwari, M. Meribout, L. Khezzar, K. Alhammadi, and M. Tarek, ''Electrical tomography hardware systems for real-time applications: A review,'' *IEEE Access*, vol. 10, pp. 93933–93950, 2022.

[46] M. Meribout and S. Teniou, ''A pipelined parallel hardware architecture for 2-D real-time electrical capacitance tomography imaging using interframe correlation,'' *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 25, no. 4, pp. 1320–1328, Apr. 2017.

[47] M. Meribout and I. M. Saied, ''Real-time two-dimensional imaging of solid contaminants in gas pipelines using an electrical capacitance tomography system,'' *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3989–3996, May 2017.

[48] A. Veisi, M. H. Shahsavari, G. H. Roshani, E. Eftekhari-Zadeh, and E. Nazemi, ''Experimental study of void fraction measurement using a capacitance-based sensor and ANN in two-phase annular regimes for different fluids,'' *Axioms*, vol. 12, no. 1, p. 66, Jan. 2023.

[49] C. E. Brennen, *Fundamentals of Multiphase Flow*. New York, NY, USA: Cambridge Univ. Press, 2005.

[50] M. Jamialahmadi, M. R. Zehtaban, H. Müller-Steinhagen, A. Sarrafi, and J. M. Smith, ''Study of bubble formation under constant flow conditions,'' *Chem. Eng. Res. Des.*, vol. 79, no. 5, pp. 523–532, Jul. 2001.

[51] M. Roshani, G. T. T. Phan, E. Nazemi, E. Eftekhari-Zadeh, N.-H. Phan, E. Corniani, H.-N. Tran, V. H. Duong, and G. H. Roshani, ''Performance comparison of capacitance-based flowmeter with gamma-ray attenuation-based two-phase flowmeter for determining volume fractions in an annular flow regime's components,'' *Eur. Phys. J. Plus*, vol. 136, no. 2, pp. 1–12, Feb. 2021.

[52] V. Mosorov, M. Zych, R. Hanus, and L. Petryka, ''Modelling of dynamic experiments in MCNP5 environment,'' *Appl. Radiat. Isot.*, vol. 112, pp. 136–140, Jun. 2016.

[53] P. R. Barbosa, K. C. O. Crivelaro, and P. Seleghim Jr., ''On the application of self-organizing neural networks in gas-liquid and gas-solid flow regime identification,'' *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 32, no. 1, pp. 15–20, Mar. 2010.

[54] A. M. Iliyasu, F. Fouladinia, A. S. Salama, G. H. Roshani, and K. Hirota, ''Intelligent measurement of void fractions in homogeneous regime of two phase flows independent of the liquid phase density changes,'' *Fractal Fractional*, vol. 7, no. 2, p. 179, Feb. 2023.

[55] M. H. Shahsavari, A. Veisi, G. H. Roshani, E. Eftekhari-Zadeh, and E. Nazemi, ''An experimental and simulation study for comparison of the sensitivity of different non-destructive capacitive sensors in a stratified two-phase flow regime,'' *Electronics*, vol. 12, no. 6, p. 1284, Mar. 2023, doi: 10.3390/ELECTRONICS12061284.

RAHMAD B. Y. SYAH (Member, IEEE) received the bachelor's degree from UNIKOM, Bandung, the Master of Informatics Engineering and Ph.D. degrees in computer science from Sumatera Utara University. He was the Head of the Excellent Centre of Innovations and New Science (PUIN), Universitas Medan Area. He is currently an Associate Professor with Universitas Medan Area. His research interests include modeling and computing, artificial intelligence, data science, business intelligent, metaheuristics, hybrid algorithms, and computational intelligent.

ARYAN VEISI was born in Kermanshah, Iran. He received the B.Sc. degree in electrical engineering from the Kermanshah University of Technology, Iran, in 2020, where he is currently pursuing the M.Sc. degree in electrical engineering: integrated electronic circuits. His current research interests include design and implementation of capacitance-based sensors, modeling and computing, and artificial intelligence.

ZAINAL ARIFIN HASIBUAN received the bachelor's (Ir.) degree in statistics from the Bogor Agricultural Institute (IPB) and the Master of Information Science (MIS) and Ph.D. degrees from Indiana University Southeast. He is currently a Professor, a Researcher, and an Academician with Universitas Dian Nuswantoro. His research interests include artificial intelligence, data science, information retrieval, digital library, e-learning, information systems, and IT strategic planning.

MUSTAFA A. AL-FAYOUMI received the B.Sc. degree in computer science from Yarmouk University, Irbid, Jordan, in 1988, the master's degree in computer science from the University of Jordan, Amman, Jordan, in 2003, and the Ph.D. degree in computer science from the Faculty of Science and Technology, Anglia University, U.K., in 2009. He is currently an Associate Professor of computer science and the Head of the Cybersecurity Department, Princess Sumaya University for Technology (PSUT). His research interests include computer security, cryptography, identification and authentication, wireless and mobile networks security, e-application security, intelligent applications, intelligent threat detection, machine learning, and other related topics.

MOHAMMAD SH. DAOUD received the Ph.D. degree in computer science from De Montfort University, U.K. He is currently an Associate Professor with the College of Engineering, Al Ain University, United Arab Emirates. His research interests include artificial intelligence, swarm systems, secured systems and networks, and smart applications.

EHSAN EFTEKHARI-ZADEH received the B.Sc. degree in physics from Shahid Chamran University of Ahvaz, Iran, in 2012, and the M.Sc. degree in radiation physics from Shahid Beheshti University, Tehran, Iran, in 2015. Afterwards, he gained a few years of professional experience in gamma irradiation industry in Iran. He has been a Doctoral Researcher in physics/photonics with Friedrich Schiller University Jena, Germany, as well as a Scientific Assistant with the Institute of Optics and Quantum Electronics, Jena, Germany, since 2019.