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Intelligent Measurement of Void Fractions in Homogeneous Regime of Two Phase Flows Independent of the Liquid Phase Density Changes

Abdullah M. Iliyasu [1,2,*], Farhad Fouladinia [3], Ahmed S. Salama [4], Gholam Hossein Roshani [3,*] and Kaoru Hirota [2,5]

1 Electrical Engineering Department, College of Engineering, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia
2 School of Computing, Tokyo Institute of Technology, Yokohama 226-8502, Japan
3 Electrical Engineering Department, Kermanshah University of Technology, Kermanshah 6715685420, Iran
4 Faculty of Engineering and Technology, Future University in Egypt, New Cairo 11835, Egypt
5 School of Automation, Beijing Institute of Technology, Beijing 100081, China
* Correspondence: a.iliyasu@psau.edu.sa (A.M.I.); hosseinroshani@kut.ac.ir (G.H.R.)

Abstract: Determining the amount of void fraction of multiphase flows in pipelines of the oil, chemical and petrochemical industries is one of the most important challenges. Performance of capacitance based two phase flow meters highly depends on the fluid properties. Fluctuation of the liquid phase properties such as density, due to temperature and pressure changes, would cause massive errors in determination of the void fraction. A common approach to fix this problem is periodic recalibration of the system, which is a tedious task. The aim of this study is proposing a method based on artificial intelligence (AI), which offers the advantage of intelligent measuring of the void fraction regardless of the liquid phase changes without the need for recalibration. To train AI, a data set for different liquid phases is required. Although it is possible to obtain the required data from experiments, it is time-consuming and also incorporates its own specific safety laboratory consideration, particularly working with flammable liquids such as gasoline, oil and gasoil. So, COMSOL Multiphysics software was used to model a homogenous regime of two-phase flow with five different liquid phases and void fractions. To validate the simulation geometry, initially an experimental setup including a concave sensor to measure the capacitance by LCR meter for the case that water used as the liquid phase, was established. After validation of the simulated geometry for concave sensor, a ring sensor was also simulated to investigate the best sensor type. It was found that the concave type has a better sensitivity. Therefore, the concave type was used to measure the capacitance for different liquid phases and void fractions inside the pipe. Finally, simulated data were used to train a Multi-Layer Perceptron (MLP) neural network model in MATLAB software. The trained MLP model was able to predict the void fraction independent of the liquid phase density changes with a Mean Absolute Error (MAE) of 1.74.

Keywords: artificial intelligence; capacitance sensor; homogeneous; fractional; two-phase flow; experimental validation

Citation: Iliyasu, A.M.; Fouladinia, F.; Salama, A.S.; Roshani, G.H.; Hirota, K. Intelligent Measurement of Void Fractions in Homogeneous Regime of Two Phase Flows Independent of the Liquid Phase Density Changes. *Fractal Fract.* **2023**, 7, 179. https://doi.org/10.3390/fractalfract7020179

Academic Editors: Giuseppe Failla, Wojciech Sumelka, Jacek Leszczynski and Tomasz Blaszczyk

Received: 13 December 2022
Revised: 6 February 2023
Accepted: 9 February 2023
Published: 10 February 2023

1. Introduction

Several types of two-phase flows such as water–oil or gas–oil exist in the oil, gas, chemical and petrochemical industries [1]. Flow metering of two-phase flow is a difficult task because the existing mixtures are inherently very complex. On the other hand, measuring these flows is extremely important in many cases such as repository management, financial metering, procedure control etc. [2]. General method of two-phase flow measurement is very expensive and time-consuming because it requires breaking the separation process. This method works by first separating the two mixed phases and then the flow of each one is calculated separately [3]. It is very important to detect the type of flow, which cannot be provided by the traditional methods. Therefore, design and construction of flowmeters can be very useful to detect the type of flow, flow rate of each phase and also the amount of void fraction without interrupting the process [4,5]. Void fraction is calculated by dividing the section of the pipe which contains gas by the cross-section of the whole pipe. There are some methods to measure the void fraction. Radiation attenuation [4,5], ultrasonic [6], impedance manner using capacitance [7], wire mesh sensors [8] and open and close valves to measure volume [9] are the most commonly used methods.

The electric capacitor-based method is a suitable way to measure the void fraction inside the pipe as there is no need to interrupt the process or separate the phases for measuring. In capacitive sensors, type of electrodes and measuring circuit are two main parts for measuring. In this type of sensors, measurement precision highly depends on the configuration of electrodes. On the other hand, there is a direct relationship between the type of liquid inside the pipe and the configuration of electrodes. In order to measure flows in the pipe with two-phase liquid–liquid conductive fluid, the concave electrode is recommended [10–16]. There are three known different kinds of flow regimes, called stratified, annular and homogeneous. Various papers have studied different regimes with a two-phase fluid inside the pipe. Li and his coworker [17] researched about measurement error and presented that homogeneous sensitivity of the capacitive sensor reducing the measurement error. Many experiments have been performed to improve and develop a structure for ensuring homogeneous sensitivity and it was found that a helical electrode has more homogeneous sensitivity [18–24]. In [20] by Jaworek and Krupa, five different configurations such as helix, concave, and double ring were used to investigate two-phase water-air flow. The concave configuration showed the best sensitivity. Moreover, in [21], the highest and lowest sensitivities of the capacitance sensor in two-phase water-air flow were obtained for the concave and double ring configuration, respectively. Air–solid two-phase flow has investigated in [22] by Kendoush and Sarkis. In this work, different electrodes such as concave, parallel plate, ring and helical have been investigated. It was found that the concave electrode has the best sensitivity. For two-phase liquid/gas non-conductive fluid, Sami and Abouelwafa [23] used six different capacitors. The capacity of each capacitor has been measured by a capacitor meter. Studies have been carried out on oil–gas two-phase flow, and the helical electrode had best sensitivity among all electrodes. Moreover, the concave electrode has provided best results for the annular regime. Tollefsen and his coworker [24] studied two-phase oil–water mixture. Capacitance dependence to type of regime and distribution are main weakness of capacitive sensors using direct plate surfaces, and accurate results can only be obtained if components have been well mixed. If dimensions of bubbles are less than the volume of substance, the obtained mixture is almost homogeneous. In [25], Ahmed used a capacitive sensor to measure void fraction and detect the type of regime. In that research, investigations were carried out on air–oil two-phase fluid in a horizontal pipe. Concave and ring electrodes have been investigated, and it was shown that the ring electrode has more sensitivity. Among the existing limitations for measuring the amount of void fraction, the effect of the type of configuration on measured response has been mentioned. Artificial Neural Network (ANN) is one of the most powerful mathematical tools, which is widely used in a wide variety of fields, for instance, electrical engineering, control engineering and so on [26–39]. Performance of capacitance-based two phase flow meters highly depends on the fluid properties. Fluctuation of the liquid phase properties such as density due to temperature and pressure changes would cause massive errors in determination of the void fraction. A common approach to fix this problem is periodic recalibration of the system, which is a tedious task. The novelty and aim of this study is in proposing a method based on artificial intelligence (AI), which offers the advantage of intelligent measuring of the void fraction regardless of the liquid phase changes without the need for recalibration. To train AI, a data set for different liquid phases is required. Although it is possible to obtain the required data from experiments, it is time-consuming and also incorporates its own specific safety laboratory consideration, particularly working with flammable liquids such as gasoline, oil and gasoil. So, COMSOL Multiphysics software was used to model a homogenous regime of two-phase flow with five different liquid phases and void fractions. To validate the simulation geometry, initially an experimental setup including a concave sensor, a pipe consists of a homogeneous regime which is modelled by several straws with different void fractions created by filling some of them [40]. After validation of the simulated geometry for the concave sensor, a ring sensor was also simulated to investigate the best sensor type. It was found that the concave type has a better sensitivity. Therefore, the concave type was used to measure the capacitance for different liquid phases and void fractions inside the pipe. Finally, simulated data are used to train a MLP neural network model.

2. Experimental Setup

There are three main flow regimes, named annular, stratified and homogeneous in oil, chemical and petrochemical industries, which are shown in Figure 1. In this section, an experimental sample was established to evaluate the results from COMSOL Multiphysics software for a two-phase water-air flow. Since the homogeneous regime occurs at high pressures and specific condition in such a way that the two phases in the pipe are completely mixed, some straws were used to apply a homogeneous regime in the experiments.

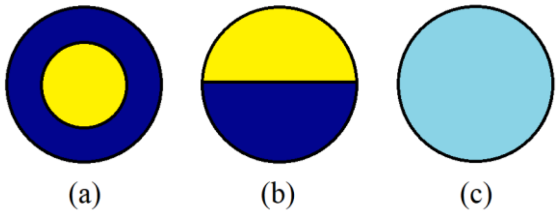

Figure 1. Different two-phase flow regimes (**a**) annular (**b**) stratified (**c**) homogeneous.

A pipe with a radius of 3.2 cm, length of 18 cm and thickness of 6 mm was made using a 3D printer and PLA material with relative permittivity equal to 3.4. As be shown in Figure 2, a copper plate with a thickness of one millimeter was used for the two electrodes of the concave sensor which were cut by CNC. The distance between the electrodes, the length of each electrode and the electrodes width are 5 mm, 12 cm and 9.55 cm, respectively which are shown in Figure 3. The straws used in the manufactured phantom have a radius of 2.75 mm, a length of 18 cm and a negligible thickness of 0.1 mm. In order to generate different percentages of void fraction in the experiments, specific numbers of straws were filled with water for each percentage and the rest were remained empty. Figure 4 shows the schematic and real mode of fabricated homogeneous phantom in every void fraction percentage. Filled straws with water for different void fractions have been shown with blue color and the rest which were empty or filled with air have been shown with yellow color. In order to measure the capacitance of the fabricated sensor, the measuring was carried out for every generated void fraction from 0% to 100% (21 samples). An LCR meter was used in order to measure the capacitance of each case, which has been shown in Figure 5. To measure the capacity of the fabricated sensor in every void fraction percentage, the voltage and frequency values of the LCR meter were set to 2 volts and 200 kHz, respectively. To check the spatial distribution, the experiments were performed several times with different positions of full straws in every void fraction, and there was a little difference between the obtained results in every void fraction.

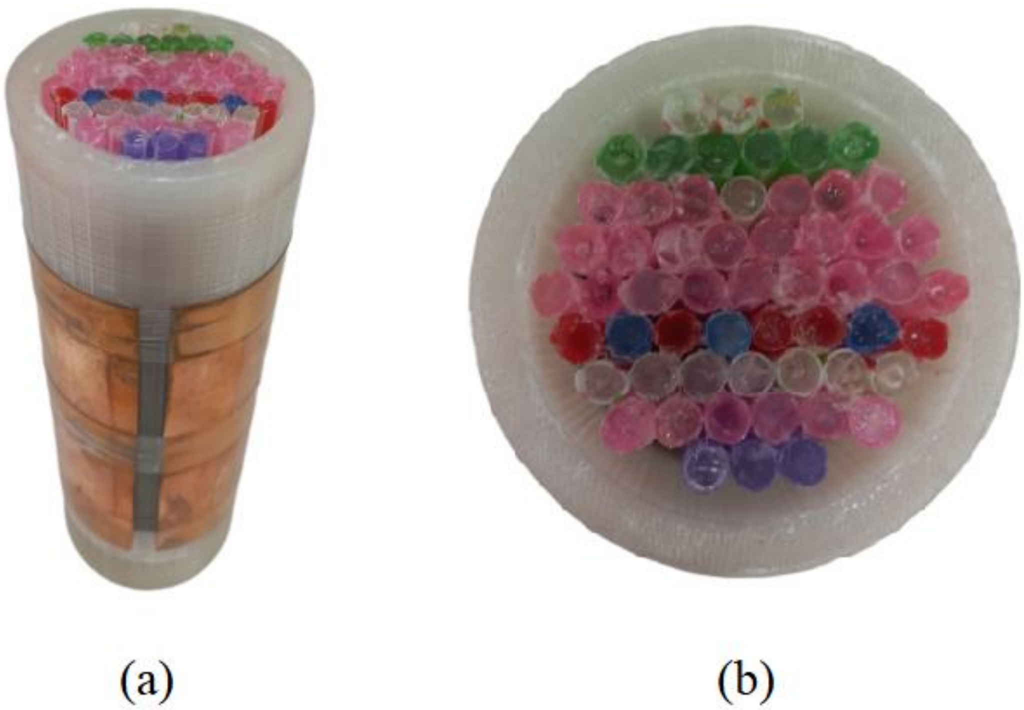

Figure 2. (**a**) fabricated concave sensor (**b**) straws in the pipe for creating homogeneous regime phantom.

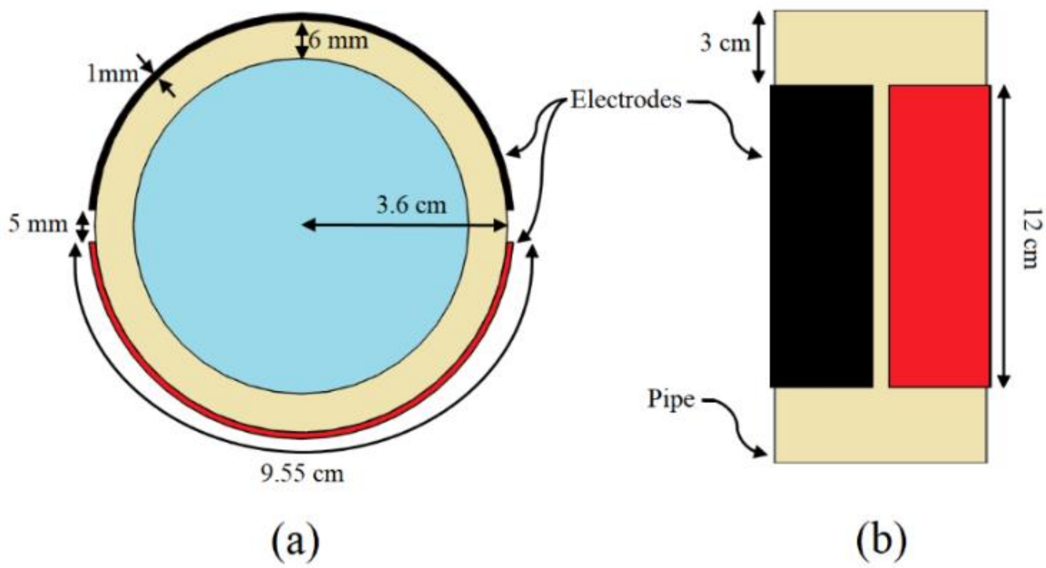

Figure 3. Fabricated concave sensor (**a**) top view (**b**) side view.

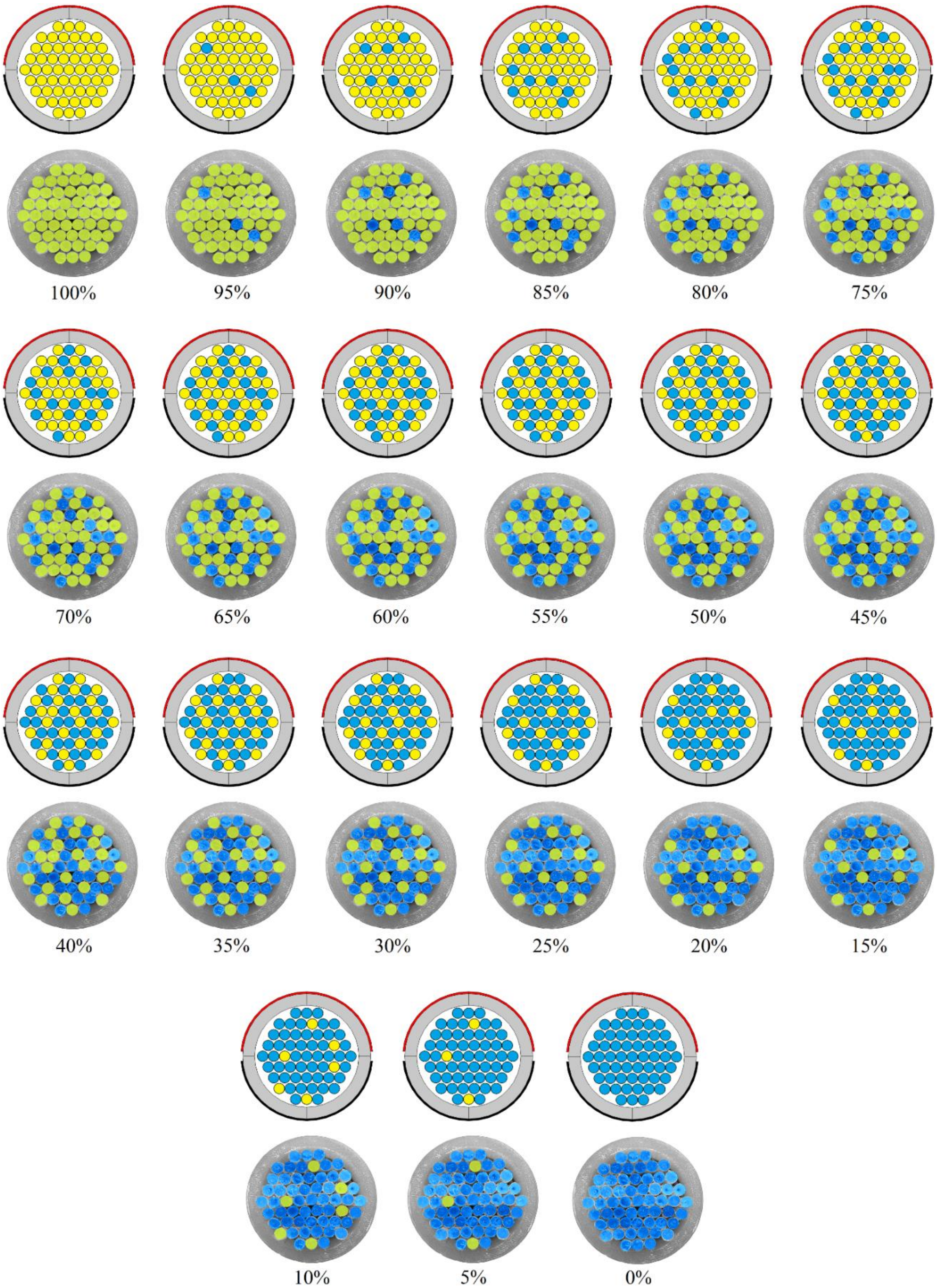

Figure 4. Different modelled void fractions for homogeneous regime in schematic and real mode using full and empty straws.

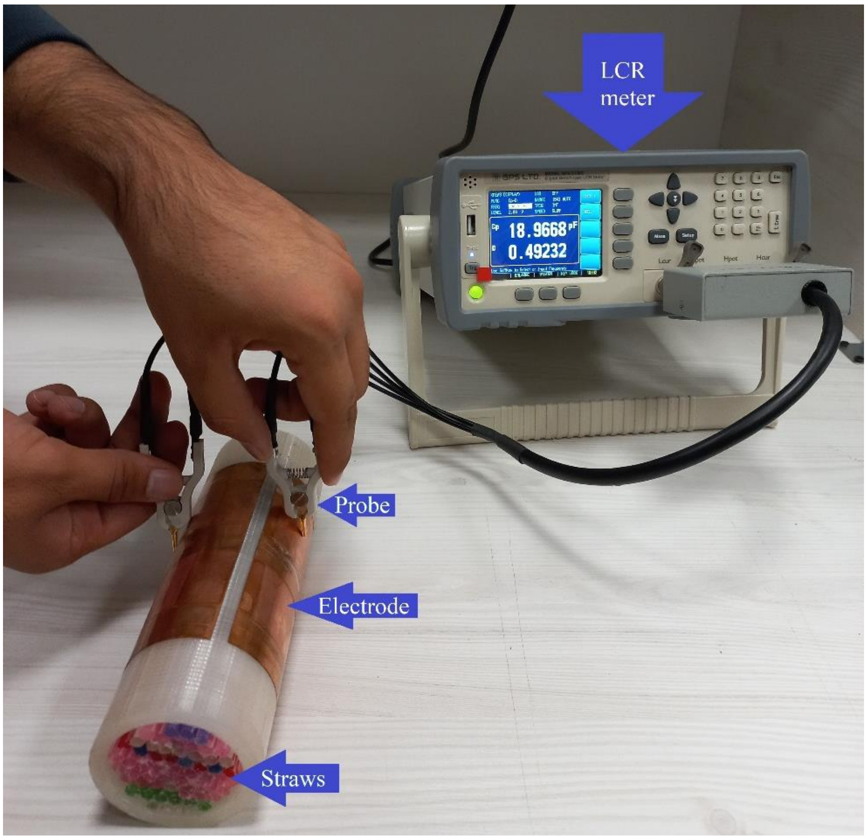

Figure 5. Measuring the capacitance of the sensor using an LCR meter.

3. Simulation

3.1. Simulation of the Concave Sensor in a Homogeneous Regime

In this part, the simulation procedure of the concave sensor in COMSOL Multiphysics software is discussed. All of dimensions of the manufactured sensor were used exactly in the simulation. Relative permittivity (ε_r) is the factor by which the electric field between the charges is decreased relative to the vacuum. In order to simulate the homogeneous regime in the software, different ε_r were assigned to the material in the pipe while in the manufactured sensor, the homogeneous regime was modelled with straws. Indeed, for each specific void fraction, a specific ε_r was assumed for the interior material. This equivalent ε_r was obtained using averaging. In the room temperature, the ε_r of air is equal to 1 and the ε_r of water is equal to 81 so the ε_r of homogeneous flow inside the pipe has been changed from 1 to 81 with the step of 4 for every 5 % decreasing of void fraction. The simulated model is presented in Figure 6. This simulated sensor has two electrodes with the same configuration as the fabricated one. The mesh settings for simulation were set on "Finer mode".

In order to validate the simulations, the obtained results from the software were compared with the results acquired from the fabricated sensor. Because the frequency of the LCR meter (200 kHz) is lower than the required level, all of the numbers are normalized and then compared with each other. A comparison of normalized experimental and simulated data is shown in Figure 7 and all of the normalized data are presented in Table 1. The mean relative difference is 4.457 % which demonstrates the simulated and experimental data are in good agreement, and the simulated geometry is reliable. In fact, the simulation was validated and can be used for generating new data. In the following, another type of widely used capacitive sensor (ring sensor) will be simulated in COMSOL software.

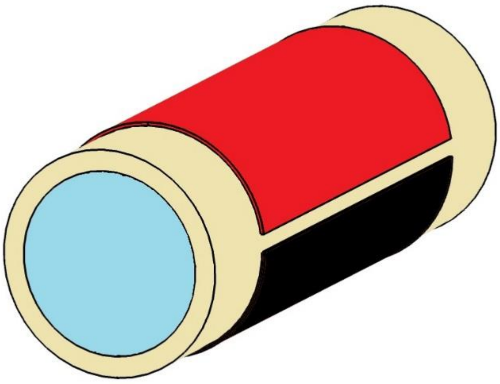

Figure 6. Implementation of the concave sensor in COMSOL Multiphysics software.

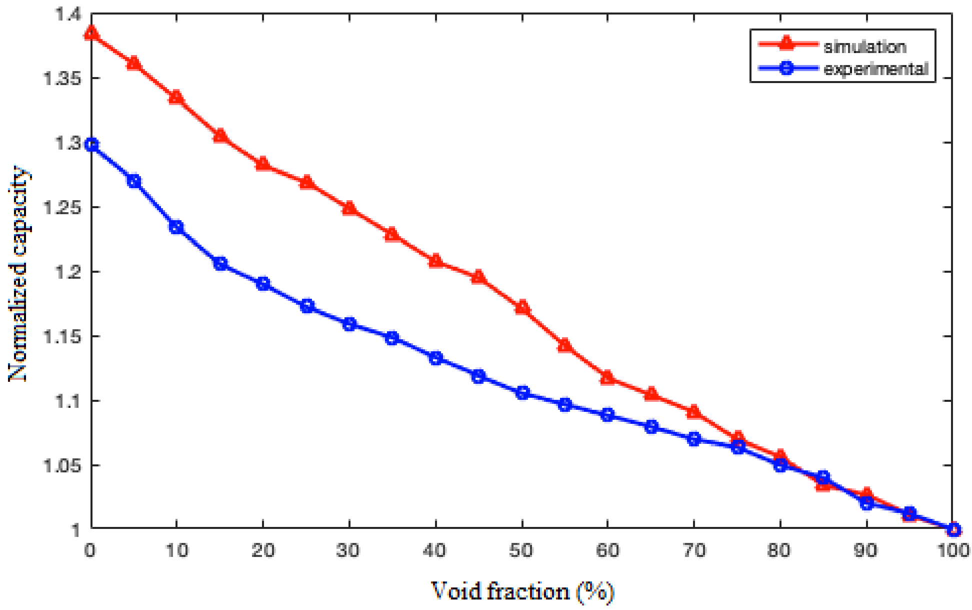

Figure 7. Comparison of normalized experimental data and simulated data in the homogeneous regime.

Table 1. Relative differences between normalized simulation and experimental data.

Void Fraction	Normalized Simulation	Normalized Experimental	Relative Difference
100	1.000	1.000	0.000
95	1.011	1.012	0.132
90	1.026	1.020	0.647
85	1.034	1.040	0.571
80	1.056	1.049	0.630
75	1.069	1.063	0.571
70	1.090	1.069	1.982
65	1.104	1.079	2.299
60	1.117	1.088	2.673
55	1.142	1.096	4.157
50	1.171	1.105	5.925
45	1.194	1.119	6.781
40	1.207	1.133	6.566
35	1.228	1.148	6.931
30	1.248	1.159	7.699
25	1.269	1.172	8.251
20	1.281	1.189	7.731
15	1.304	1.205	8.223
10	1.333	1.233	8.088
5	1.360	1.270	7.111
0	1.383	1.297	6.637

3.2. Simulation of the Ring Sensor in a Homogeneous Regime

In addition to concave, a ring sensor was also modelled in the simulation in order to investigate the best sensor type. For implementation of the ring sensor in COMSOL software, a pipe with a radius of 3.2 cm, length of 18 cm and thickness of 6 mm (same as previous simulation for concave sensor) was used. Two electrodes were considered with 5.75 cm width and 21 cm length. For applying homogeneous liquid inside the pipe, the equivalent ε_r of homogeneous liquid inside the pipe was changed from 1 to 81 with step of 4. Figure 8. Shows the designed ring model. Moreover, the mesh settings were set on "finer mode".

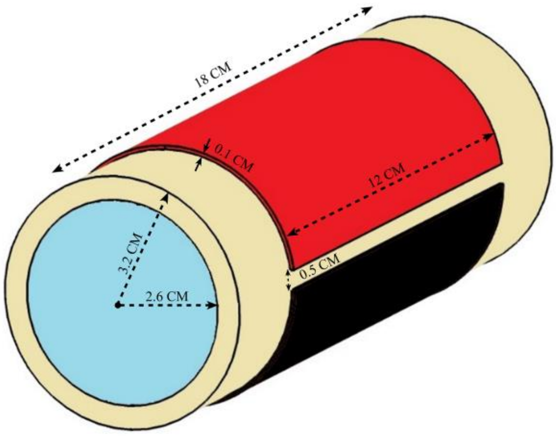

Figure 8. Implementation of the ring sensor in COMSOL software.

To compare performance of both sensors, their sensitivity relative to void faction changes was evaluated. As can be seen from Equation (1), to calculate the *overall sensitivity*, the measured capacity of liquid phase (C_{liquid}) when there is no air inside the pipe ($VF_{0\%}$), and the measured capacity of air (C_{air}) when the pipe is fully empty ($VF_{100\%}$), are required. Simulation results in Figure 9 show that the concave sensor has an *overall sensitivity* equal to 19.0594 pF and the ring sensor has an *overall sensitivity* of 13.5667 pF. Because of higher *overall sensitivity*, the concave sensor has better performance for the two-phase water-air homogeneous flow regime. For this reason, only the concave sensor's data were used to train the ANN.

$$Overall\ sensitivity = \frac{C_{liquid} - C_{air}}{VF_{0\%} - VF_{100\%}} \quad (1)$$

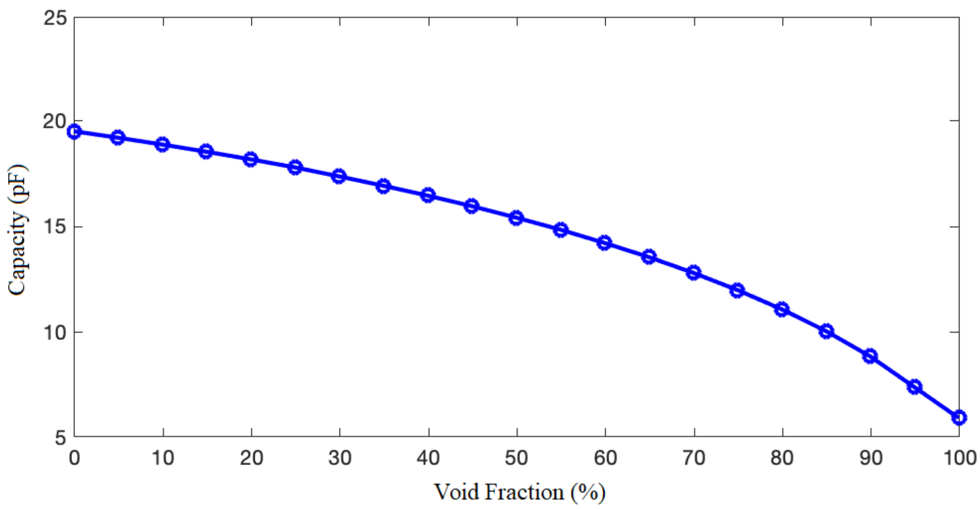

Figure 9. Simulation results of the ring sensor in COMSOL software.

4. Artificial Neural Network

There are different types of Artificial Neural Networks (ANNs). One of the best ANNs, with various applications, is multilayer perceptron (MLP). The MLP ANN has been widely used and popular due to its powerful and very close approximation ability. So, this kind of ANN has been used by many researchers in their works. There are various methods to find the weights and biases in this type of network. The Levenberg–Marquardt (LM) algorithm was used to train the presented network in this study, which is the most widely used algorithm. This algorithm is derived from two methods, gradient descent and Gauss–Newton [41–43].

Presented MLP-LM network has two inputs and one output as be shown in Figure 10. The first input is the capacitance received from the sensor and the second one is the liquid number inside the pipe. Crude oil (ε_r = 2), oil (ε_r = 2.2), gasoil (ε_r = 2.4), gasoline (ε_r = 2.7) and water (ε_r = 81) were simulated and considered as second input. The output of the presented network is the amount of void fraction inside the pipe.

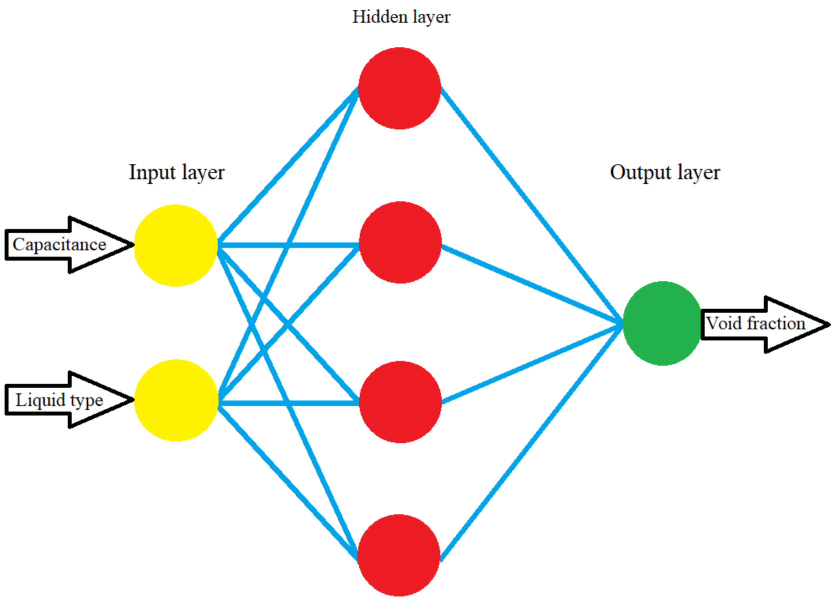

Figure 10. Architecture of the proposed network in order to determine void fractions.

A total of 105 different cases have been obtained from the simulations performed with COMSOL Multiphysics software. Void fractions have been changed from 0 to 1 with a step of 0.05 for 5 different liquids. In all, 73 cases were considered for training and 32 cases were considered for testing the performance of the presented network.

After examining multiple networks with different numbers of neurons and layers, the best structure was obtained. The best architecture has three layers: one input layer, one hidden layer and one output layer. Four neurons were used in the hidden layer of this network. The activation functions of the input and output layers were "purlin" and for the hidden layer it was "tansig". The number of epochs in the best case was equal to 500.

5. Results and Discussion

In the used neural network, the data were randomly divided between the training data and the test data, and 70% of the data were used for training and the rest were used for test data. Furthermore, the performance of the network was examined using the Mean Absolute Error (MAE) of test data. Using trial and error the best architecture was obtained and saved. In Figure 11a, a regression diagram of the training data and in Figure 11b a regression diagram of the test data were given. MAE for the training data and test data are equal to 1.74 and 1.33, respectively. To prevent over-fitting and under-fitting, the obtainable data are separated into two categories: training data and test data. The training data include the information seen by the neural network and is used to create the model. After the neural network has been trained, its performance may be evaluated using test data. As long as the neural network responds appropriately to these two data sets, as shown in Figure 11a,b, the proposed network will be safe from over-fitting and under-fitting problems, respectively.

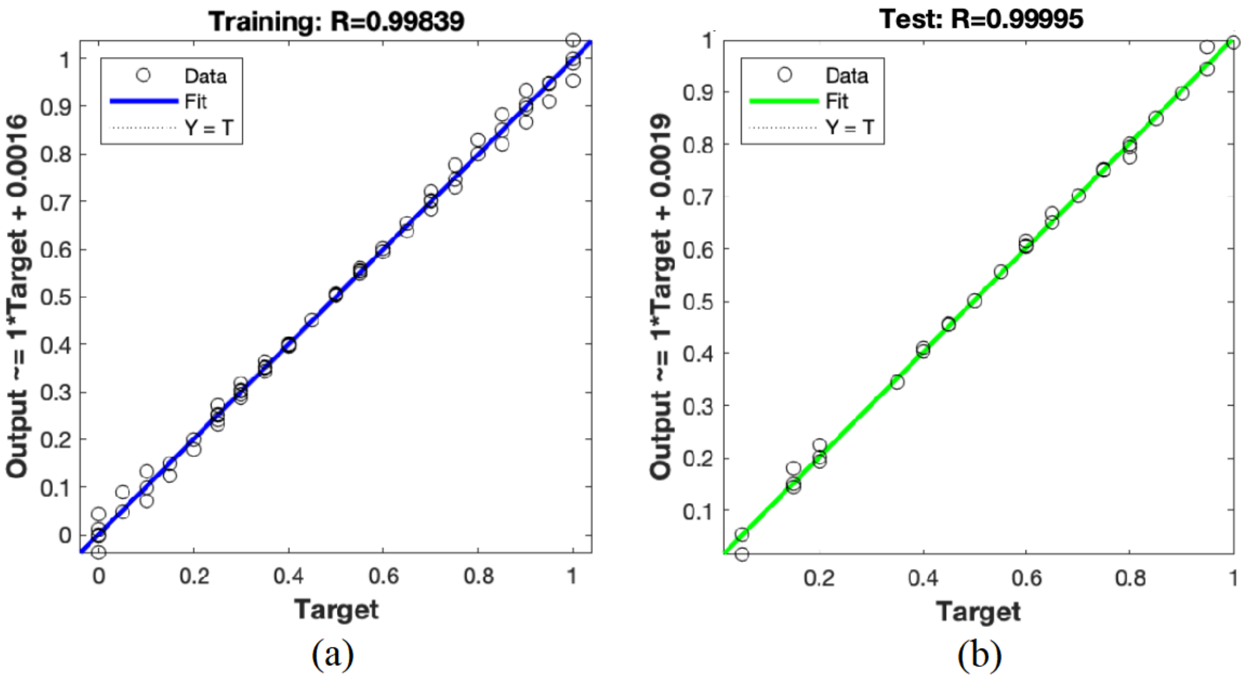

Figure 11. Regression diagram of (**a**) training data (**b**) test data.

The novel presented system in this study can predict the void fraction of different liquid–air homogeneous flows with various liquid phases. This important point was carried out using a concave sensor and designed ANN. In this regard, several experiments and simulations with mentioned structure were performed for the homogeneous regime. The simulations were verified using experimental results. The low difference between simulation and experimental results shows the validation of simulation. Required data for training the ANN were obtained from validated simulation. The low error of both test and training sets of ANN shows the correction and precision of the presented model. These results show that underfitting or overfitting have not occurred and the presented model is reliable.

6. Conclusions

In this study, the goal was predicting the void fraction of two-phase air-liquid homogeneous regime independent of liquid phase changes. At first, the results from COMSOL Multiphysics software for water liquid were validated by performed experiments. A concave sensor and an equivalent phantom of homogeneous liquid-air flow were fabricated, and the capacitance was measured. The low relative difference of simulated results with experimental results approves the simulations verification. For selecting the best sensor in proposed metering system, the ring sensor in the software was simulated and investigated as well. By comparing the sensitivity of this sensor with the concave sensor, the concave sensor showed a better performance and selected as the main sensor. Five industrial widely used liquids, i.e., crude oil, oil, gasoil, gasoline and water were simulated as the liquid phase and different void fractions were modelled inside the pipe. In all, 105 cases were simulated to provide required data set for training the MLP neural network. The output of the network was the void fraction of the flow for every different liquid. The output of the presented network had a very small error which shows the very good performance of the presented metering system.

Author Contributions: Conceptualization, A.M.I., A.S.S., G.H.R. and K.H.; Methodology, F.F. and K.H.; Software, A.M.I. and A.S.S.; Validation, F.F. and G.H.R.; Formal analysis, A.M.I.; Investigation, F.F. and A.S.S.; Resources, A.M.I.; Data curation, F.F.; Writing—original draft, A.M.I., F.F. and A.S.S.; Writing—review & editing, A.S.S., G.H.R. and K.H.; Supervision, G.H.R. and K.H. All authors have read and agreed to the published version of the manuscript.

Funding: This study is funded by the Deputyship for Research and Innovation of the Saudi Ministry of Education via its funding for the PSAU Advanced Computational Intelligence and Intelligent Systems Engineering (ACIISE) Research Group, Project Number IF-PSAU-2022/01/22246.

Data Availability Statement: The data is unavailable due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

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