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# Development of Low-Cost, Non-Obtrusive Electrical Impedance Tomography Device for Liquid-Gas Flow Visualization

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*Abstract*—**The high cost of flow visualization equipment on the market hinders more active exploration in flow science. This paper presents a development of low-cost, non-obtrusive electrical impedance tomography (EIT) device for two-phase (liquid-gas) flow visualization. The device consists of three main hardware; an Arduino microcontroller as processor and communicators between components, a customized printed circuit board to control current injection and voltage measurement, and sensors band which consists of sixteen copper electrodes. During testing, the sensors band was enclosed around a cylindrical phantom tank filled with water. The sensing field then was stimulated by injecting current to the sensors of copper electrodes. Next, the measured voltage values were imported to MATLAB and interfaced with electrical impedance tomography and diffuse optical tomography reconstruction software (EIDORS) software for reconstruction of test images. The system capitalized on the different conductivity values of water and air, with the reconstructed images showed excellent agreement with the test images.**

*Index Terms*—**electrical impedance tomography, flow visualization, tomography**

## I. INTRODUCTION

### A. Background

Multiphase flow processes are often encountered in various industries. In multiphase flow, as the flow regimes and speed distribution change significantly over time, the measurement of medium distribution becomes very complex. In order to control and enhance understanding of the complex fluid dynamics, the visualization of flow regime is highly desirable. Furthermore, flow visualization is also useful to detect any hidden obstruction or deposition in a fluid system such as pipe.

A variety of methods have been deployed to visualize the multiphase flow in pipe, and one of them is called tomography. The word 'tomography' originated from the Greek word "tomos" which means slice or section, while "graphein" means representation [1]. Hence tomography refers to a technique of visualizing the inner cross-section based on the internal structural information. The internal information is obtained by stimulating the physical process involved within an object such as by injecting a current to the gas-liquid flow within pipe. As the current is injected to the medium of interest, the resulting voltage measurement will be measured by sensor [2]. The information then will be fed to appropriate software and mathematical model developed in the software will be applied to visualize the internal cross section.

Tomography principle has been widely applied to various medical scanning activities such x-ray, magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) that are used for body scan. There are also specialized equipment such as Positron Emission Tomography and ultrasound that are meant for brain scanning and mammography, respectively [3]. Visualization of internal cross section study was developed in early 1970's by Hounsfield's research team at the EMI Central Laboratories [4]. This innovative research revealed that X-ray computerized axial tomography (CAT) may be utilized to scan human tissue and the underlying bone structure in non-invasive manner. Based on this early work, medical imaging began to develop into an extensive industry and led to the parallel field of process tomography.

The same tomography principle can be extended to the non-medical process tomography capable of providing real-time internal structure information [5]. NMR and computed tomography (CT) have been useful to resolve industrial problems including materials characterizations, and inspection of flaws in non-destructive testing. Other instances include electrical resistivity tomography (ERT) and electrical capacitance tomography (ECT) that have been used to monitor the multiphase flow regime in pipe, hydrocyclone, and turbine plumes, while optical tomography has been utilized for flame analysis [6]. ERT equipment also has been utilized in detecting the location of any stuck debris or contaminants inside pipe. Electrical tomography too can be used for core porosity calculation, flow rate measurement and determining the flow velocity distribution.

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Among the tomography techniques, electrical tomography is widely used due to its cost efficiency and non-invasive capability [7]. Electrical process tomography comprises of electrical impedance tomography (EIT), ECT, electromagnetic tomography (EMT), and ERT. In EIT, as impedance is a measurement of reactance (imaginary part) and resistance (real part), the real component of EIT is the dominant properties of materials in an ERT process application. EIT is applied for a process with a conductive continuous phase while ECT detects the permittivity distribution in non-conductive continuous phase. In EMT, measurable current is induced under a magnetic field which mainly applied for highly conductive fluids. In the meanwhile, Mohadeseh *et al*. [6] in his report compiled various efforts in the development of ERT application for multiphase flow monitoring. The most conclusive result, however, can be retrieved from a multiphase flow measurement system patent [8], which stated that ERT is incapable of measuring continuous phase flow rate and in its current form undergo complexities in determining an absolute value. Current multiphase flow measurements are very limited and cannot accurately measure flow rates in all multiphase flows, particularly where the phase distributions and velocity profiles are highly complex and non-steady, such as inclined oil water flows in which internal waves intermittently form and decay. Gamma ray attenuation and electrical impedance method are the most commonly used techniques for measuring gas water two phase flow, but it imposes safety issues and high cost setup. Thus in this paper, EIT device was chosen for the two phase flow visualization.

EIT has wide application prospect in multiphase flows with conductive continuous phase such as water and gas. EIT is applied to achieve flow visualization by using electrode sensors array to acquire the instantaneous distribution of electrically conducting materials with different conductivities. The basic idea of EIT relies on the fact that different medium have distinct conductivities [9]. The operation mechanism of EIT is to provide the sensing field with exciting current and multiple impedance measurements are taken at the periphery of a pipe and combined to provide information on the electrical properties of the process volume. The sensing field is built by applying the current to a pair of electrodes. Along the flow in pipe, as the conductivity distribution changes, the current field distribution will change, followed by the potential field, and finally the boundary voltage measurement. Hence, the medium distribution can be distinguished by using the acquired conductivity distribution of the sensing field. A typical EIT system consists of a sensor array equally spaced around the object periphery being imaged, an effective data acquisition system or printed circuit board, and a computer with image reconstruction software [6].

### *B. Motivation of Study*

EIT analyzes the compositions and inner structure of objects by examining it with excitations such as electricity in a cross sectional manner [10]. Proposed by Webster in 1978, the impedance distributions of internal structure are recovered from pair wise impedance measurements of surface electrode surrounding an object [11]. Compared to other tomographic methods as x-rays, gamma ray, and MRI, EIT offers non-obtrusive application at relatively lower cost. However, most of the existing flow visualization systems available are bulky and expensive with price ranging from $30,000 to $1,000,000. Numerous EIT studies have been conducted since its introduction in early of 1980s [12]. Starting with the EIT application on biomedical field, researchers extended its application for industrial flow visualization studies due to its many capabilities [13].

Thus, this study describes the efforts to create a small, low-cost and non-obtrusive EIT device, the one that could be integrated on pipe or any suitable region of interest. However, it is to be noted that achieving these design traits comes at the cost of reduced precision and resolution compared to the industrial EIT systems. Nonetheless, the developed system is still able to resolve considerable detail image reconstruction of tested subjects.

### *C. EIT Design Concept*

Previous works in this area include Chitturi *et al*. [14] who designed an EIT system for modelling and diagnosis of pulmonary disease. Similarly, Montellano *et al*. [15] came out with a device to sense morphological changes in tissues. Their work revolved around a phantom tank with electrode array wrapped around it, filled with a saline solution and test material which consists of objects with different sizes and shapes. Then the uniformity in the reconstructed image was acquired, representing certain homogeneity in liquid composition. Aside from that, Zhang and Harrison [12] developed an EIT device for hand gesture recognition. A phantom tank filled with water and a bottle were used in their preliminary studies. The results show that their EIT devices provide clear image representing the water and bottle location. Based on these three medical related research, it was concluded that EIT can provide distinct representation of water and air phases.

In terms of the hardware aspect of a typical EIT device, the key factors that should be considered in designing a sensor array includes; the number of electrodes, the size of the electrodes, materials used to construct the sensor, and economic factor [2]. Hoyle *et al*. [16] stated that electrodes are usually made of metals. The two factors considered in the material selection are the electrical and chemical characteristics. The physical properties need to meet practical implementation such as to minimize the contact resistance between the electrodes and the medium effectively, and to improve the distribution of sensitivity field on the verge of flat field. The number of electrodes is a trade-off between image resolution and system complexity. A trade-off system will help to provide a certain desired outcome at the expense of other system factors. In the case of selecting the number of electrodes, higher quantity will lead to better spatial resolution as more measurements taken but would cause more current flow through the near field and lower sensitivity to the center as a result of reduced distance between two adjacent electrodes. Since more measurement is taken, hardware requirement needs to increase accordingly in order to sustain the same real time performance. Commonly used electrodes in ERT and EIT system are stainless steel, copper, brass and silver palladium alloy.

Basically in EIT system, electrode will act as both electrode and sensor. The current is injected to one electrode then voltage or impedance values are measured on the remaining electrodes. All electrodes will be attached to one sensor which will measure the impedance values. Based on the previous EIT research, the most commonly used EIT sensor is Impedance Measurement System-On-Chip AD5933 [12], [17]-[19]. Montellano *et al.* [15] used National Instrument data acquisition card NI USB-6008 with LabVIEW software in their EIT study. The current is injected to electrodes mounted on the domain and the voltage drop across a pair of electrodes will provide the measurement of impedance.

Next, for data acquisition strategy, four different types of strategies commonly used are Adjacent Strategy, Opposite Strategy, Diagonal Strategy, and Conducting Boundary Strategy. During data acquisition phase, electrode will electrodes play two roles during the acquisition process which are for current excitation and impedance measurement. Adjacent Sensing Strategy is when the exciting current is initially injected into a neighboring pair of electrodes and voltages measurement is conducted on consecutive pairs of adjacent electrode [20]. The process is repetitive whereby the current is injected to the following couple of electrodes and the voltage is measured until all independent measurement completed. By considering the problem of contact impedance between electrolyte and electrode, voltage measurement is not conducted at electrode which the current is currently injected. This strategy provides the measurement formula of ($N$-3)/2 where $N$ represents the total electrodes number. Adjacent strategy requires a minimal hardware capacity and when the requirement is meet, image reconstruction can be done relatively fast [2].

In the Opposite Strategy, current is injected to diametrically opposite electrodes. The voltage measured at electrode next to the current injecting electrode is determined as voltage reference. By excluding the current-injecting electrode, the voltage references are measured with respect to the reference of all the electrodes for an individual pair of current-injecting electrodes. After one complete measurement is done, the voltage reference electrode location is switched accordingly as the current injection changes to the next couple of electrodes in clockwise direction. This strategy is less sensitive to conductivity changes compared to adjacent strategy as the current flows to the center point of domain. This will give increment of evenly distributed currents which can lead to better image characterization.

According to P. Hua *et al.* [21], Diagonal Strategy or the cross method is where the current is applied between a large distances separated electrodes. This yields a more consistent current distribution in medium to be imaged as compared to adjacent strategy. The way the method operates can be visualize in the following example. By using a 16-electrode ERT as an example, current is applied on electrode 1 and voltage reference is set at electrode 2. The voltages are measured at all electrodes with reference to electrode 2 except the current injecting electrodes. The current is then injected to electrode 3 and electrode 4 is set as voltage reference. This sequence will be repeated until all the electrodes have been set as the current injecting electrode. For a 16 electrodes EIT / ERT system, 91 measured data will be acquired from 13 voltage measurements and 7 independent current electrode pairs for respective couple of current injecting electrodes. This strategy would produce 182 data points whereby 104 data are independent. As compared to adjacent strategy, this technique has the benefit of providing better sensitivity over the intact region and enhanced matrix conditioning. As this strategy is not as sensitive to measurement error, better quality image can be produced. However, the limitation of the strategy is it has a lower sensitivity in the boundary relative to the same reference.

The Conducting Boundary Strategy as explained by Aw *et al.* [2] is designed to for the EIT application on electrically conducting domain material. The strategy utilizes only two electrodes for measurement. With the purpose to decrease the common-mode voltage across the measurement electrodes, larger surface area of the conducting boundary is set as the current sink. Therefore, earthed floating measurement method and common-mode feedback are not required. The effect of electromagnetic interference is also reduced via the earthed conducting boundary. This strategy considers the resistance of the conducting phantom tank from affecting the voltage measurement which will later be used in reconstructing the images. The measured voltages will be corrected by considering the conducting boundary resistivity values.

For current and voltage measurement switching method, the electrode current switching was developed by Chitturi *et al.* [14] using CD4067 multiplexers. In another study, Zhang and Harrison [12] used ADG1608 8-to-1 multiplexer as their EIT system consists of 8 electrodes. In another work, Trivedi *et al.* [22] selected HCF 4051 and ADC 0809 multiplexer in their sixteen electrodes EIT device. Based on the literatures, the multiplexers selected in our study were CD4067BE, a high-speed complementary metal-oxide-semiconductor (CMOS) analogue multiplexers. For sixteen electrode EIT system, two 1:16 multiplexers (MUX1 and MUX2) were used to develop an automatic switching system for current to inject into the adjacent pair of electrodes after completing one set of voltage measurements. In the same system, Arduino microcontroller provided instructions for multiplexer functioning.

EIT image reconstruction steps consist of forward and inverse problems. The Electrical Impedance and Diffuse Optical Tomography (EIDORS) toolkit is crucial due to the complexity in solving an EIT problem. EIDORS is a customized MATLAB toolbox for reconstruction using electrical impedance values obtained from a specific sequence of connection over an array of electrodes [23]. Forward problem or computation is solved to determine impedance distribution arising from the current pattern injection onto the object by using Finite Element Model in EIDORS simulation while inverse problem or computation is solved to study the image reconstruction steps and to determine the conductivity distribution by using the measured voltage and developed sensitivity matrix. Stacey *et al*. [24] highlighted that EIT inversion problem is a nonlinear, ill-posed problem that is very computationally intensive. In solving forward computations, EIDORS package utilizes a finite element model. A regularized nonlinear solver is included in EIDORS to gain a unique and stable inverse solution [25-26]. Chitturi *et al*. [14] and C. Montellano *et al*. [15] both used EIDORS in reconstructing the image of EIT system. The package is equipped with a mesh generator, several standardized EIT methods, a graphical output, and supports two-dimensional and three-dimensional EIT systems. The first step in using EIDORS is to create finite element model of the domain and electrodes. With the set of currents and FEM, forward problem can be solved. Then, the real measured impedance data has to be fed to the software to solve the inverse problem. EIDORS solves the inverse problem by using different methods to acquire a stable and unique inverse solution. Lastly, the final image can be displayed post the solving of the forward and inverse problems.

## II. METHODOLOGY

EIT comprises two main areas of development which are the hardware assembly of EIT prototype and the software study. The hardware assembly deals with components used and fabrication of printed circuit board, while the software study describes the application program for impedance measurement and image reconstruction process.

### *A. Materials*

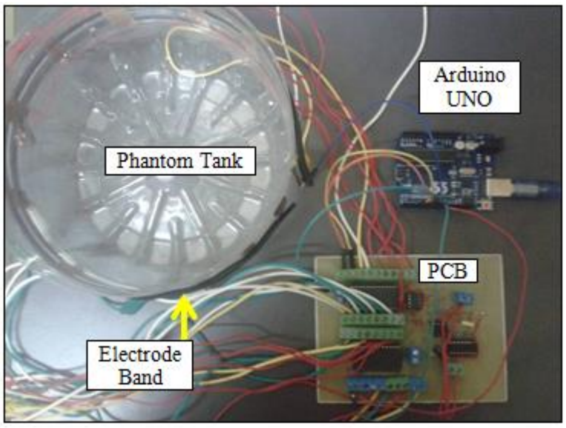

Fig. 1. EIT hardware components used in the study.

A phantom tank was constructed from a shallow plastic bucket filled with water. To add a fraction of air phase, an empty plastic bottle was introduced into the tank. An array of sixteen copper electrodes was fixed over the external wall of phantom tank in the form of electrode sensor band. In the meanwhile, the EIT device was basically made of a 12V AC DC adaptor, an Arduino UNO microcontroller, a printed circuit board (PCB) which consisted of CD4067 multiplexer, ICL8083 and TL071 function generator, and wires. The electrodes attached to the external wall of phantom tank were connected to the multiplexers of the PCB for the automatic current switching module and to the analogue pins of Arduino microcontroller for extracting the voltages. The components are shown in Fig. 1.

### *B. Hardware Assembly and Configuration*

The electronic circuit was used to provide a platform of current injection and switching module of current injection and voltage measurement was designed on Proteus software.

The schematic drawing was converted to ARES drawing layout which represents the real size and shape of components used their connection with each other based on the electronic circuit designed. The ARES drawing is shown in Fig. 2.

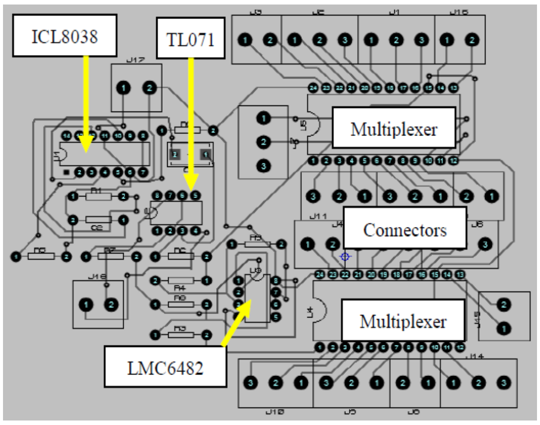

Fig. 2. ARES drawing of PCB design.

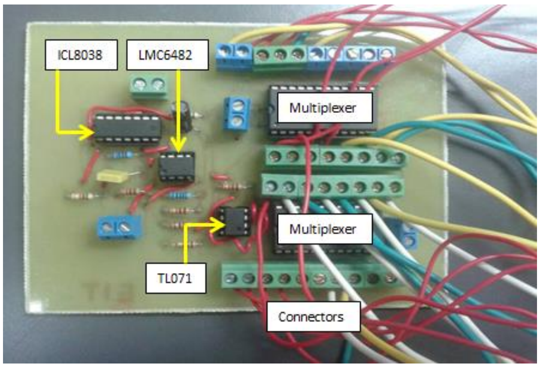

Fig. 3. Fabricated printed circuit board (PCB) used in this study.

Prior to the development of full PCB board, ARES drawing was printed on a glossy paper. Next, the layout paper was laminated to FR4 board by using photoresist material in order to transfer the image of PCB layout to board and to stick the photoresist at the surface of PCB. The board then was placed in UV Light Exposer machine. The machine exposed UV light onto the surface of photoresist dry film to create the circuit track that will stick on PCB. Afterwards, the board was placed on developer machine to remove the unwanted photoresist film from the PCB surface followed by the etching process to remove the unwanted copper at the surface of PCB. Upon completion, the board was treated with acid and left for several minutes for drying. Next, the board was drilled to make a hole for the component leg. Subsequently, the components and ICs used were mounted to the board and soldered accordingly. The fabricated PCB used in this study was shown in Fig. 3.

The connection between multiplexer on PCB to electrodes was made by using a single core with an alligator clip. For the voltage measurement part, jumper wires were used to connect the multiplexer input pin to Arduino UNO analog pin. Four input pins of Multiplexer 1 (MUX 1) were connected to D2, D3, D4 and D5 analog inputs of Arduino for current injection command to electrodes. Another four input pins of Multiplexer 2 (MUX 2) were connected to D6, D7, D8 and D9 analog inputs of Arduino for voltage measurement system.

EIT system developed in this study adopted the adjacent current injection and voltage measurement strategy. Generally, four different types of strategies commonly used are diagonal strategy, adjacent strategy, opposite strategy and conducting boundary strategy. According to Suzanna *et al.* adjacent strategy requires a minimal hardware capacity but if that requirement is meet, image reconstruction can be done relatively fast [2].

Adjacent sensing strategy can be described by which the exciting current is initially injected into a neighboring pair of electrodes and voltages measurement is conducted on consecutive pairs of adjacent electrode [17]. The process is repetitive whereby the current is injected to the following couple of electrodes and the voltage is measured until all independent measurement completed. By considering the problem of contact impedance between electrolyte and electrode, voltage measurement is not conducted at electrode which current is injected. This strategy provides the measurement formula of $N(N-3)$ where $N$ represents the total electrodes number. In this study, 16 copper electrodes were used thus resulted in 208 measured voltages for a complete measurement. The concept adjacent current sensing strategy is depicted in Fig. 4.

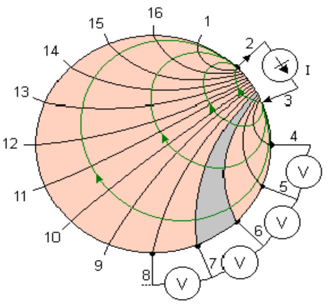

Fig. 4. Adjacent current injection and voltage measurement sensing strategy [8].

### C. Software Study

Arduino microcontroller was used to provide control to the operation of EIT device. For current and voltage measurement switching method, the electrode current switching was developed by using multiplexers. For sixteen electrode EIT system, two 1:16 multiplexers (MUX1 and MUX2) were used to develop an automatic switching system for current to inject into the adjacent pair of electrodes after completing one set of voltage measurements [14]. Arduino microcontroller provided instructions for multiplexer functioning by following the uploaded codes to the Arduino UNO board. The codes also instructed the Arduino to measure and save voltage.

Subsequently, the measured voltage was exported to EIDORS software for image reconstruction system. EIDORS is a MATLAB based free software used in forward and inverse solution of Electrical Impedance Tomography. The sequence of program developed for image reconstruction follows the description from block diagram shown in Fig. 5.

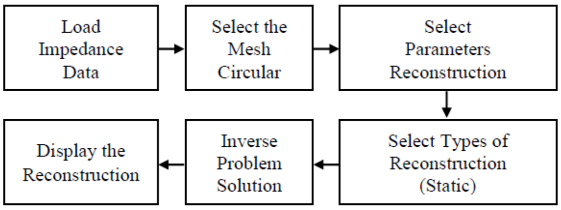

Fig. 5. Block diagram of EIDORS sequence actions

### D. Preliminary Tests

A series of preliminary tests was conducted as a foundation study prior to the application of EIT system on any multiphase flow facility. Preliminary tests including reliability test, suitability test, compatibility test and communication and connectivity test were conducted once the EIT prototype had been successfully fabricated. The purposes of preliminary test are shown in Table I. These tests were vital to ensure the prototype captures correct reading consistently, able to transmit data between the individual components, and interpret them into meaningful graphical representations.

TABLE I: PRELIMINARY TESTS AND THEIR PURPOSES

| Test | Purpose |
|---|---|
| Reliability test | To analyse the accuracy and consistency of the device in measuring the impedance values. |
| Suitability test | To ensure the suitability of each component used in the developed EIT device as well as their compatibility. |
| Compatibility test | |
| Communication / Interfacing test | To test the communication and interfacing of the device with the processing software. |
| Connectivity test | To study on how to feed the measured voltages from Arduino UNO to computer. |

## III. RESULTS AND DISCUSSION

The objective of developing a low cost and non-obtrusive EIT device for liquid gas flow visualization was achieved as the EIT device only cost roughly RM150 (40 USD) to build in individual quantity. The device can be applied simply around a pipe due to its non-bulky components and a simple image reconstruction process.

Based on the preliminary tests conducted, the EIT device was found capable to be used in visualizing multiphase flow in pipe. This was proven whereby all the components were able to communicate to each other. Furthermore, the currents were successfully injected and the resulting voltages managed to be measured through coding of the microcontroller. The measured voltages by the microcontroller were validated by measuring the voltages by using multimeter.

Some trials were performed in order to validate the voltage measurement and reconstructed images. Firstly, an image of empty phantom tank was reconstructed by using EIDORS software. The reconstructed image is represented in Fig. 6. As can be observed, the constructed image does not show any variation of color within the circular field that represents the tank. This indicates that the voltage values throughout the field were constant, which was expected from the empty tank with current injected into its homogeneous content, i.e.air.

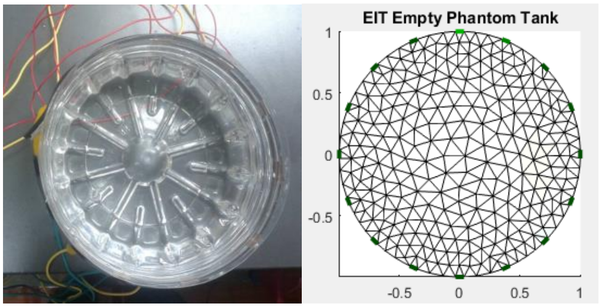

Fig. 6. Left image is the real empty phantom tank and right image is its EIDORS reconstructed image

TABLE II: MEASURED VOLTAGES FOR ELECTRODE 1 TO 8

| Electrode | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 |
|---|---|---|---|---|---|---|---|---|
| 1 | X | X | 0.955 | 0.419 | 0.392 | 0.380 | 0.445 | 0.429 |
| 2 | X | X | X | 0.955 | 0.419 | 0.392 | 0.380 | 0.345 |
| 3 | 0.955 | X | X | X | 0.955 | 0.419 | 0.252 | 0.180 |
| 4 | 0.419 | 0.955 | X | X | X | 0.955 | 0.419 | 0.252 |
| 5 | 0.252 | 0.419 | 0.955 | X | X | X | 0.955 | 0.419 |
| 6 | 0.180 | 0.252 | 0.419 | 0.955 | X | X | X | 0.955 |
| 7 | 0.145 | 0.180 | 0.252 | 0.419 | 0.955 | X | X | X |
| 8 | 0.129 | 0.145 | 0.180 | 0.252 | 0.419 | 0.955 | X | X |
| 9 | 0.124 | 0.129 | 0.145 | 0.180 | 0.252 | 0.419 | 0.955 | X |
| 10 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 | 0.252 | 0.419 | 0.955 |
| 11 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 | 0.252 | 0.419 |
| 12 | 0.180 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 | 0.252 |
| 13 | 0.252 | 0.180 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 |
| 14 | 0.419 | 0.252 | 0.180 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 |
| 15 | 0.954 | 0.418 | 0.352 | 0.352 | 0.345 | 0.338 | 0.323 | 0.328 |
| 16 | X | 0.955 | 0.419 | 0.420 | 0.480 | 0.445 | 0.429 | 0.424 |

TABLE III: MEASURED VOLTAGES FOR ELECTRODE 9 TO 16

| Electrode | Run 9 | Run 10 | Run 11 | Run 12 | Run 13 | Run 14 | Run 15 | Run 16 |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.424 | 0.429 | 0.445 | 0.480 | 0.452 | 0.419 | 0.954 | X |
| 2 | 0.329 | 0.324 | 0.329 | 0.345 | 0.380 | 0.352 | 0.458 | 0.955 |
| 3 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 | 0.252 | 0.419 |
| 4 | 0.180 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 | 0.252 |
| 5 | 0.252 | 0.180 | 0.145 | 0.129 | 0.124 | 0.129 | 0.145 | 0.180 |
| 6 | 0.419 | 0.252 | 0.180 | 0.145 | 0.129 | 0.124 | 0.128 | 0.145 |
| 7 | 0.955 | 0.419 | 0.252 | 0.180 | 0.145 | 0.129 | 0.123 | 0.129 |
| 8 | X | 0.955 | 0.419 | 0.252 | 0.180 | 0.145 | 0.128 | 0.124 |
| 9 | X | X | 0.955 | 0.419 | 0.252 | 0.180 | 0.145 | 0.129 |
| 10 | X | X | X | 0.955 | 0.419 | 0.252 | 0.180 | 0.145 |
| 11 | 0.955 | X | X | X | 0.955 | 0.419 | 0.252 | 0.180 |
| 12 | 0.419 | 0.955 | X | X | X | 0.955 | 0.418 | 0.252 |
| 13 | 0.252 | 0.419 | 0.955 | X | X | X | 0.954 | 0.419 |
| 14 | 0.180 | 0.252 | 0.419 | 0.955 | X | X | X | 0.956 |
| 15 | 0.345 | 0.380 | 0.352 | 0.338 | 0.955 | X | X | X |
| 16 | 0.429 | 0.445 | 0.480 | 0.452 | 0.419 | 0.956 | X | X |

Afterwards, an empty plastic bottle was fixed in the water container to investigate whether the developed EIT device and measured voltages were reliable to be used in liquid-gas flow visualization. Current was injected and the voltage measurements were recorded and saved in a MATLAB file format. The tabulations of measured voltages for the test setting are presented in Table II and Table III. It can be seen that the measured voltages at electrodes 15, 16 and 1 are higher compared to the other electrodes. This is due to the location of the empty plastic bottle around those electrodes increased the electrical resistivity near that region, causing slightly higher voltages sensed.

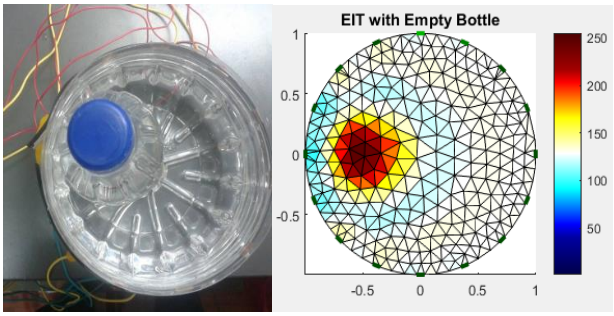

Fig. 7. Left image is the real phantom tank with empty plastic bottle and right image is its EIDORS reconstructed image

Final reconstructed image of the empty plastic bottle after simulation by EIDORS is shown in Fig. 7. It exhibits the variation of voltage distribution profile when an empty bottle (non-conducting material) was placed near to electrode 15, 16 and 1, in a tank filled with water (conducting material). The color reconstructed by EIDORS varies from blue to red, indicating low to high voltage measured. Based on Fig. 7, the presence of non-conducting material increases the voltages in that region.

Based on the image reconstructed in Fig. 6 and Fig. 7, it can be concluded that the developed EIT device and its auxiliary coding are capable of reconstructing the image of inner section of tested material. The developed EIT device in this study can be used by industrial practitioners in obtaining the visualization of the multiphase flow regime in pipe as well as to detect any contaminants stuck in the pipe. Due to non-obtrusive and simple nature of the device, it is possible to roughly monitor flow inside non-transparent pipe without halting ongoing operation.

The effort to make the flow monitoring to be online or real time should be the next course of action for research in this topic. Better algorithm and image reconstruction toolkit are necessary, not to mention faster and better integration between data acquisition system and image reconstruction software. These improvement can offers better functionality and higher resolution of reconstructed images.

## IV. CONCLUSION AND RECOMMENDATION

This study successfully developed a low cost, non-obtrusive and simple EIT device for liquid-gas two-phase flow visualization. It works by measuring the cross-sectional voltage or impedance values by using sixteen copper electrodes attached around the perimeter of cylindrical pipe/tank. During the test, the voltages measured by microcontroller were validated by using multimeter and were found reliable to be fed to the EIDORS software for image reconstruction process. The reconstructed images from EIDORS were able to resolve considerable detail image representation of the test images.

The developed EIT device in this study requires the manual image reconstruction process by which after a set of voltage measurement were completed, the measured voltages values has to be imported manually to the MATLAB interfaced with EIDORS software for image reconstruction. As it does not provide a real time image, it means the lead time of the process is relatively high. Moreover, in a dynamic flow system this device will probably reconstruct an outdated tomography of the fluid flow. Thus, real time image reconstruction is highly encouraged for future research. Apart from that, image reconstructed in this study does not represent the detailed size and shape of the test material which was placed inside the water container. Better algorithm and image reconstruction toolkit are suggested to be used for future research. Faster and better integration between data acquisition system and image reconstruction software also can offers better functionality and higher resolution of reconstructed images.

For further testing, it is imperative to conduct a measurement system analysis [27] to ensure accuracy, linearity, repeatability and reproducibility. This device can be applied in industry with some enhancement in selection of material and components, design of high precision current injection and voltage measurement system, as well as adopting a better image reconstruction method such as applying Linear Back Projection technique [28], [29].

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