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Identification of Liquid-Liquid Interface using Electrical Resistance Tomography

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Abstract — *Finding interfaces among liquids in a process tank is crucial in some applications. Various industrial sectors have deployed expensive, invasive, and hazardous techniques to achieve this. In this paper, an Electrical Resistance Tomography (ERT) technique comprises a phantom tank surrounded by 16 copper electrodes. A 50 kHz, 5 mA AC signal was used as an input, and the output response in terms of voltages was fed to EIDORS reconstruction algorithm. The 2D images show the domain containing two poorly conducting liquids, i.e., water and oil, although not accurate, but showing ERT as a possible promising technique for analyzing liquid-liquid interfaces.*

Keywords — *Liquid-Liquid Interface, Electrical Resistance Tomography, EIDORS, Arduino.*

I. INTRODUCTION

Determining interfaces within liquids in industrial vessels of process plants such as oil and gas, wastewater treatment, nuclear and mineral processing, petrochemical industries, etc., is a significant requirement. For instance, finding the interface between crude oil and water in a refinery tank is important to avoid the distillation column's water. Although one can separate liquids based on their varying density and specific gravity, differentiating and identifying the interface between them is difficult. Various imaging techniques have been used in identifying interfaces within liquids, such as nuclear magnetic resonance imaging (NMRI), x-ray tomography, gamma-ray tomography, and others [1]. However, these methods are expensive, invasive, and hazardous. In this paper, Electrical Resistance Tomography (ERT) imaging technique is applied to identify liquid-liquid interfaces in the process tank. It provides information relating to conductivity around the process tank and determines each liquid's structural behavior and presence within it. An image of conductivity distribution is obtained using EIDORS software. ERT promises to be a beneficial technique for its portability, inexpensiveness, safe use, and non-invasiveness. However, further work should be carried out towards the images' spatial resolution (better results).

II. LITERATURE REVIEW

The utilization of Gamma-ray for industrial process measurements dates to 1962, where a gamma scan was applied to diagnose mechanical problems, like tray damage and other process-related problems. Gamma-ray Grid Scan Technique was applied to provide information regarding the average density along a packed column. This technique was also applied to monitor the distribution of fluidized solids during catalyst cracking [2]. The history of imaging the hydrodynamic properties of a slurry bubble column and three-phase fluidized bed by means of x-ray imaging was reported in 1995. They measured the bubble sizes and velocities within the column. The radiographic technique was employed in which x-ray pulses were passed through a reactor amplified by a cesium-iodide image intensifier, which was later captured on a video camera. The solid phase in the reactor was zirconia of diameter 38 µm. The liquids used were water and water-glycerol mixtures. The fluidizing gas was typically nitrogen, although helium was used for some high-pressure experiments [3]. NMRI technique was used to characterize the pore spaces in a packed bed of particles.

A 4.5 cm inner-diameter glass column containing a 6 mm glass sphere and water was imaged. A three-dimensional data set was acquired to identify the pores. The pore size distribution and the pore volume as a function of pore surface area were calculated [4]. Further incorporation of short (4.5 cm) and tall (970 cm) packed beds with 5 mm diameter glass sphere was studied. NMRI technique was applied in their study. The columns were filled with de-ionized water with all air bubbles removed, and a seal was formed to prevent air from entering the system during imaging. A constant flow of water passed through the column as the images were obtained. The focus of this study was to obtain velocity images. The flow velocity was then correlated with the bed's structure to visualize the flow around individual glass spheres. These techniques typically involved ionizing radiations from x-ray and other radiation sources and therefore were considered unsuitable for mainstream process applications continuously due to their cost and safety measures. Most of these techniques consumed extensive contact time, which implies that processes' active measurements would be impractical [5].

Alternatively, the Electrical Resistance Tomography (ERT) technique uses a certain number of electrodes placed on a medium at equal intervals surrounding the domain to be imaged. A constant, low frequency and low magnitude alternating current (AC) is injected through the electrodes, and the potential differences, i.e., the function of unspecified conductivity distribution, are measured between several pairs of electrodes. The internal conductivity distribution is calculated based on voltage measurements corresponding to various current injection patterns. This data is processed through an image processing algorithm in the computer that subsequently provides the image that can be used to monitor and control the processes automatically [6]. ERT is a straightforward and rapid monitoring technique associated with an extensive series of research and development applications, for instance, measurement and control of process tanks, identification of liquid interfaces, an inspection of mixing processes, and study of a solid-liquid filtration process, etc. [7]. Apart from many benefits, its limitations, such as low spatial resolution, vulnerability to noise, and electrode errors, can disrupt the images' quality [8].

A comprehensive study employing ERT to a 36 m^3 production pressure filtration tank was performed to provide real-time information on the final stages of filtration and drying, limitation in the filter block, and solvent displacement of the mother liquor. This work exhibited that an ERT system could be employed on large pressure filtration vessels. Moreover, the work proved ERT's capability to abide by the intrinsic safety regulations rendering the technique eligible for the most hazardous and explosive environment [9]. A laboratory-scale experiment was conducted to observe the ERT system's effectiveness for modeling and analyzing pharmaceutical mixing processes. A 3.5 l glass-coated tank consisting of 65 platinum electrode sensors (4 rings carried 16 electrodes each along with a ground electrode) was produced. The operation was executed over a wide range of temperatures with minimal electrode projection, fine chemical compatibility, and fine optical admittance [10]. A new radial flow reactor was designed to show the flow pattern through a radial flow-packed bed reactor to verify the effectiveness of ERT. The reactor with an inner diameter of 914 mm consisted of a cylindrical flow collector elevating 1 m situated at its center. It was filled to a height up to the collector's peak with spheres of 10 mm diameter in a thin outer region while the rest was filled with the spheres of 3 mm diameter. To sustain the flow distribution, a disc was placed on top of the collector, and the final cover of the 10 mm sphere was placed above the spheres [11]. An image with a high spatial resolution was achieved by overcoming ill-posed aspects of the inverse problem by converting it into the well-posed inverse problem by integrating additional information. They used a system magnetic resonance ERT (MRERT) based on magnetic resonance current density imaging (MRCDI) techniques, where the current was injected in an electrically conducting medium that produced a magnetic field along with the electric field. The magnetic field transformed the ill-posed problem into a well-posed inverse problem. The images had better resolution, but it was non-portable with the expensive MRI scanner requirement and took longer processing time [12].

A study on the estimation of phase boundary in ERT with weighted multilayer neural networks (WMNN) was carried out by developing ERT to visualize real-time binary mixture fields that are generally experienced in standard and unexpected circumstances for dual-phase flow in different industrial applications. A high nonlinearity relationship was found between the measured electric potentials through the electrodes and the Fourier coefficients; thus, the FEM method was used to compute electrode potential as a function of the Fourier coefficients. Several comparisons were carried out between the proposed WMNN and normalization methods, i.e., boundary potential and the modified Newton-Raphson (mNR) method alongside Levenberg-Marquadt regularization in terms of the performance, and it was observed that the estimation performance with the charged boundary potential was depreciated. Simultaneously, moderately improved estimation performance was produced by mNR after ten iterations but required a long computation time. The suggested WMNN with the normalization technique showed the best boundary estimation performance in accuracy and online computation [13]. A rotational ERT (RERT) system was developed to improve reconstructed image quality using a plastic container whose inner surface was surrounded by 16 rotating compound electrodes attached to a moveable ring and driven using a micro-stepper motor. Every compound electrode consisted of a current and voltage electrode, as can be seen in Fig. 1.

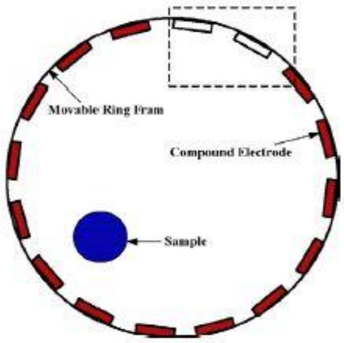

Fig 1: Moveable ring consisting of 16 compound electrodes for RERT system [14]

Images were reconstructed using MATLAB EIDORS software and validated using the FEM method, which further proved that results obtained by RERT were better than conventional ERT using SVD. The study suggested the attachment of electrodes to the mixing impeller to analyze the mixing process using RERT.

A new technique, i.e., capacitively coupled ERT (CCERT), was developed that employed FEM as the primary sensor to measure two-phase flow's conductivity. A serial sampling model was employed in the DAS that acquired 66 pairs of DC voltages during one measuring cycle. Compared with traditional ERT, this system's data acquisition rate was 30 frames per second, which was possibly due to the use of a low pass filter that required low settling time. However, the image's quality compared to the traditional ERT image was not better [15]. Another new method to carry out the separation of the gas phase from that of the liquid was proposed. A double-plane ERT system was used where both planes comprised eight titanium electrode sensors (6 mm high and 4 mm wide) equally spaced around and fastened onto the circumference of an 85 mm thick Perspex pipe. On receiving the measured data through the USB interface, the computer recorded and displayed the cross-sectional phase distribution visuals at 50 fps. The flow rate of water was different in ten groups of experiments and was slowly reduced. For the same flow rates of water and gas, 2000 frame data in 40 seconds were sampled. The collected data from eight electrode sensors was transformed into time series, which is quite non-identical from those acquired by the conventional time-averaged and lesser order statistical methods. Several specific flow regimes were presented and compared with respect to the reconstructed images of ERT. The gas and liquid phases' flow rate was estimated by measuring the two sensor arrays' transit time through the separate cross-correlation of the signals indicating the phases of gas and liquid. The experimental outcomes acquired by the new technique showed fine conformity with the real material processes. Combined with the phase distribution, the comparison with ERT information led to the estimation of flow rates of various physical phases [16].

An inexpensive ERT system for monitoring industrial processes by imaging the inner part of the conductive domain was developed that explained that current injection is carried out by injecting a precise amount of current into the domain’s boundary, voltages are measured around the domain’s boundary, stored in PC and images are reconstructed using different algorithms in MATLAB software. They further stated that precision in ERT instrumentation is crucial for the final quality of the image. Despite its inexpensive components, the proposed hardware contained high output impedance current source with a pulse generation element along with other elements, all of which were tested accurately. Apart from the successful implementation of the inexpensive ERT system, the VCCS part of the system is preferred for the project, as it involved economical and effective components and ICs, specifically LF412 [17].

Comprehensive research was carried out categorizing most of the previous ERT research conducted to show the gradual acceptance of the spectacular technique in becoming a recognized measurement system for monitoring pilot plant vessels. The research mostly comprised ERT applications based on the process tanks unit operations in chemical engineering. This included the operations associated with pipes, mixing vessels, bed reactors, and separators, etc. It was stated that for imaging a vessel using ERT measurements, the vessel's diameter happens to be a key aspect. The ERT measurements are also provided in calculating various crucial process parameters, i.e., pathologies detection, mixing time, flow rates and phase hold-ups, etc. It was also mentioned that the research done for process tanks had been limited to the lab-scale equipment, whereas further investigation is needed for monitoring, detection, and analysis for industrial scale [18]. It was stated that it is possible to visually inspect the mixing process through ERT inside opaque mixing tanks or solutions. So, one can notice that broad research for diverse mixing analysis has been carried out of ERT applications, but the only restrain the installation of industrial ERT system to be studied for the regulation of all the various described aspects collectively. A similar research study had been carried out in ERT measurement for phase distribution and analysis. The difference in conductivity between various phases offers ERT to monitor and analyze the phase distribution within the object of interest. This potential of ERT can be widely used in the void fraction analysis, i.e., gas phase holds up, and similarly solid-phase hold up, solid concentration, and oil volume fraction analysis.

Having noted the number of aspects of ERT technique, it is undergoing many research and rapid modifications to suit different applications daily. It has a wide range of applications, so there’s room for improvement constantly. It is a very popular technique in the medical field, but it is still limited to the laboratory scale and development in industrial applications, as can be observed from the researches carried out. Compared to the researches and struggles been done to provide a better medium for the development of efficiency and reliability of ERT technique, this work has been undertaken to enhance the development of ERT technique further and provide a base application for identifying interfaces within liquids in process tanks as well as to monitor and control the process.

III. MATERIALS AND METHOD

An ERT system was developed in which 16 copper electrodes were firmly and equidistantly fastened using nuts and washers against the plastic container's inner surface with a height of 18 cm and a diameter of 23.5 cm. The electronic instrumentation comprised of a constant current injection block (CCI) comprising a voltage controlled oscillator (VCO) and voltage-controlled current source (VCCS), and an electrode switching module (ESM), which was implemented by means of multiplexers and a USB based data acquisition system carried out by Arduino Mega 2560 microcontroller. The complete block diagram of the developed ERT system is shown in Fig. 2.

A 50 kHz constant sinusoidal current of 5 mA was injected into the domain through a pair of exactly opposite electrodes (position-wise) called current electrodes (EC), and the root-mean-square potential on the rest of the pairs of electrodes called voltage electrodes (EP) was measured. The low-frequency sinusoidal signal was produced by constructing the VCO circuit using IC L8038 that supplied the input to the VCCS circuit, which was developed with IC LF412 dual op-amp ICs. On getting the input voltage, VCCS gives out a low-frequency sinusoidal AC current to be fed to the automatic electrode switching module (ESM), which consists of two high-speed CMOS analog multiplexers, IC CD4067BE. At this stage, through automatic switching, the AC current is passed onto the pair of opposite electrodes to inject current into the domain, while the rest of the electrodes were assigned for voltage measurements for the first cycle. The next cycle commences with the switching of the next opposite pair of electrodes for current injection while the earlier electrodes, along with the rest of the electrodes next to each other, measure voltages. This continues in a cyclic manner. The whole process is controlled by Arduino Mega 2560 microcontroller. Upon successful current injection, during the switching interval for the next cycle, the voltage measurements that are taken by the voltage electrodes are sent to the microcontroller that is stored in MATLAB software as a .mat file. One complete cycle acquires 13 x

16 = 208 sets of voltage readings. Finally, the stored data is processed in EIDORS. EIDORS is a MATLAB toolkit used for image reconstruction from voltage data obtained from the microcontroller. The image reconstruction method that is used in this project is called difference reconstruction, wherein the outcome is acquired by evaluating existing voltage readings from the electrodes against the voltage readings from the electrodes when the object has an entirely homogeneous medium inside.

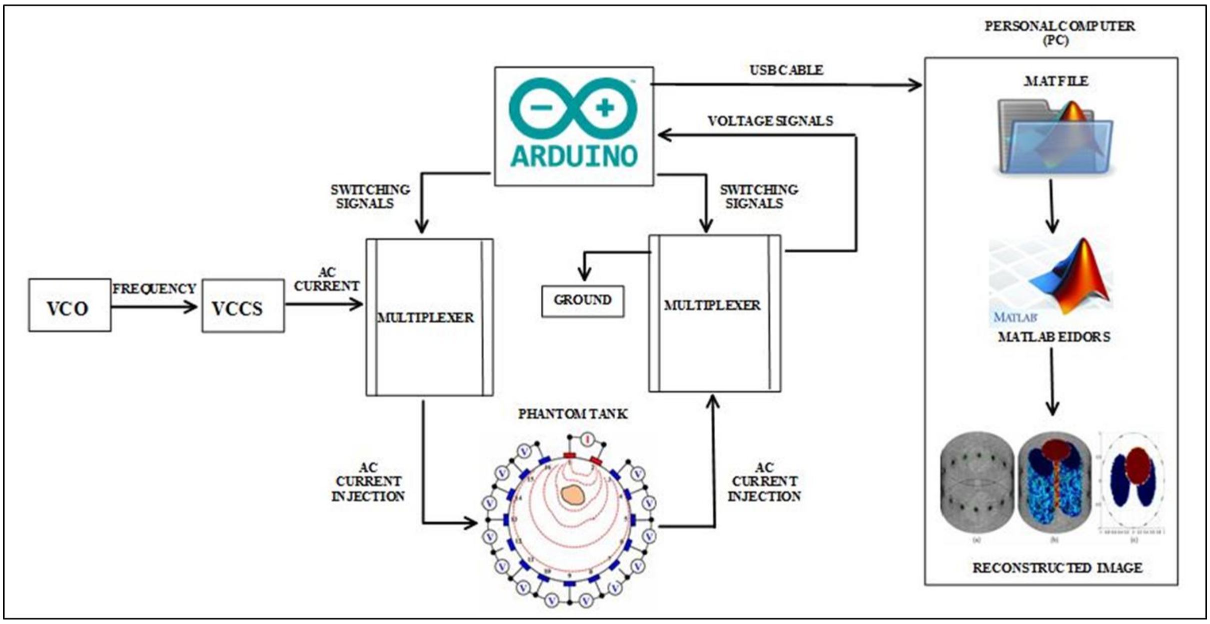

Fig 2: Block diagram of the proposed ERT system

IV. RESULTS AND DISCUSSION

A saline (NaCl) solution was added to the phantom to achieve uniform conductivity and hence to exhibit the interfaces more accurately. A color bar was used to identify the conductivity of the cavity. For instance, going down from white color implied the decrease in conductivity, while moving up from white color indicates the increase in conductivity. To facilitate the proper functioning of the system, all the components were tested for their individual functioning. A plastic container resembling a process tank was used as a domain to carry out the qualitative testing. The developed system, along with electronic instrumentation, is shown in Fig. 3. Initially, an empty bottle was introduced into the phantom to check the working of the system. Later, the phantom containing the liquids and the reconstructed image was obtained from the system, as shown in Fig. 4.

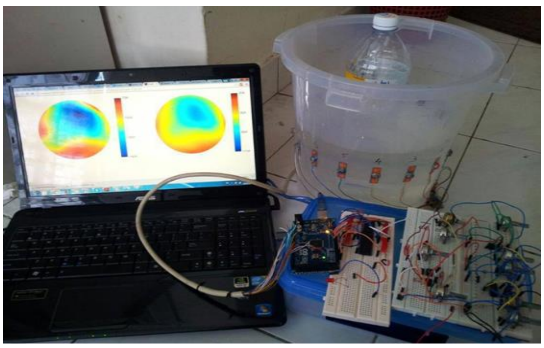

Fig 3: The complete developed ERT system

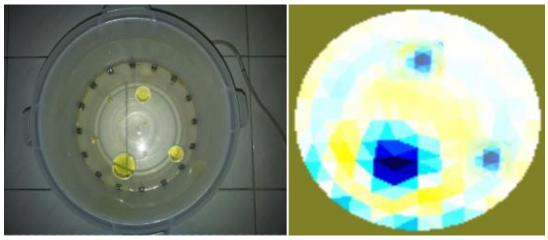

Fig 4: Reconstructed images showing the interfaces between oil and water

The 2D images are obtained based on the conductivities of water and oil. Oil, due to its poor conductivity, is seen with dark blue and white colors, while white and light blue color is that of water. The yellow color is of the unevenly mixed saline solution added to the water. The smaller patterns of oil are not visible due to the restriction of the system to detect objects smaller than 1 cm. This shows that the system can detect the layers of liquids and hence can also detect the interfaces between them.

Oil settles and floats on the water, as its density (~800 kg/m^3) is lesser than that of water (1000 kg/m^3). Fig. 5 shows the reconstructed images of the oil-water interface acquired at different intervals (the process is not real-time). Also, the resolution was found to be very poor due to contact impedance.

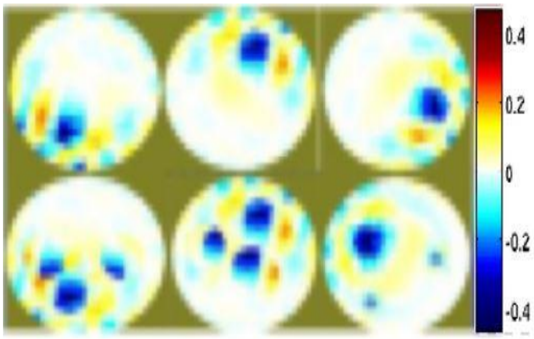

Fig 5: Reconstructed images showing the interfaces within oil (blue) and water (white) in the domain

To reduce the contact impedance issues from the image, different reconstructions algorithms were compared and tested inside the software itself using MATLAB programming. Consequently, the one with the best fit was selected and utilized for the application. The image results showed some improvement in resolution, but still, there was room for further improvement. Fig. 6 shows the images of the improved system.

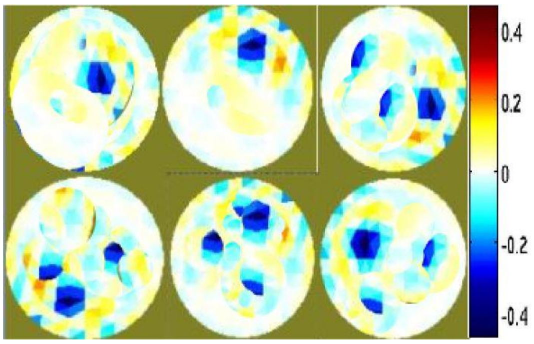

Fig 6: Reconstructed images showing the improved version of interfaces within oil (blue) and water (yellow and white) in the domain

There are few limitations in the developed ERT system that restricts the resolution of the reconstructed images. Such as problems relating to slow image processing, specifically in huge dimensional problems because hardware constraints were observed. Also, ERT was highly sensitive to electrode placement as well, i.e., quantity, size, and interspacing of electrodes. The resolution of the reconstructed image was quite poor, to an extent due to the noise factor, which is clearly visible in the results. When attempting to reconstruct images of objects of less than 1 cm in diameter, the system could not identify the object and provide the distorted image. The performance of image reconstruction algorithms was limited to the accuracy of the forward model along with the forward problem and inverse problem solver, due to which the prototype resulted in inaccurate images. There could be some limitations in terms of its industrial applications.

V. CONCLUSIONS

A technique for ERT monitoring and detection of interfaces within process tanks was developed. The technique was based on relatively safe and inexpensive components. The key motive of undertaking this work was to provide a better option to facilitate the simple assessment of ERT systems in the industrial field for cost-effective situations for which there currently no equipment available.

However, results showed that the exact shapes of these liquids were not quite clear due to the contact impedance issues. By using image reconstruction algorithms available in EIDORS, noise cancellation was possible, and hence, an improved reconstructed image was provided to be analyzed. Overall, the design from the initial concept till the actual implementation stage shows that the ERT technique could be a promising technique for liquid-liquid interface studies.

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