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Planar Imaging of Stagnant and Hydrodynamic Fluid using Miniaturized ECT Device

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Abstract:
This paper discusses the development of an on chip planar capacitance tomography (ECT) for stagnant and hydrodynamic multiphase fluid monitoring. The 8-electrode planar ECT device is developed based on Lab-on-chip (LOC) or microfluidic device concept. The ECT with LOC application is an improved design to allow ECT to be portable and small scaled measurement. To reconstruct images, ECT measures the permittivity variation within the sensing area. Eight-planar electrodes with dimension of 5.00 mm × 2.08 mm (length × width) are fabricated on printed circuit board (PCB). These electrodes are aligned to circulate 16 mm diameter of sensing area. For stagnant sample, the design of the chamber is simpler from the hydrodynamic flow. The hydrodynamic flow consists with two inlets to allow multiphase flow testing. Fan beam projection technique is utilized with Linear Back Projection (LBP) algorithm to reconstruct images of the substance within the chamber. Time is an important item for hydrodynamic flow compared to stagnant sample to ensure that the data taken is useful to the user. For stagnant experiment, the ECT system able to produce image reconstruction for water – air, oil – water and yeast – glucose samples. For hydrodynamic flow, the test conducted for immiscible water – oil sample, and miscible water – glucose solution is done. The results show the system produce the best result when one liquid is dominating the sensing area.

Keywords: Planar, ECT, static and hydrodynamic flow, miniature ECT

1. Introduction

Process Tomography (PT) is a technique that produces cross-sectional images of an enclosed pipeline [1]. The system operates without obstructing and affecting the flow inside it. These cross-sectional images within the pipeline system are obtained by using various types of sensing array. The images produced from sets of data obtained during the inspection. There are many types of PT in industrial and medical application such as Ultrasonic Tomography (UT), Electrical Resistance Tomography (ERT), Positron emission tomography (PET), Electrical Impedance Tomography (EIT) and Electrical Capacitance Tomography (ECT) [1,7,8]. The selected PT type is based on application and purpose of the analysis. Among items to be considered are the environment, the material inside the inspection area, the size of the sample and the sensing element.

Electrical Capacitance Tomography (ECT) is one of the electrical tomography besides EIT and ERT. ECT allows user to inspect the flow distribution inside a closed vessel by detecting the permittivity variation. Although ECT suffers from soft-field effect, it remains prominent system as it provide low cost setup, fast response and radiation free system [1]. Apart from the drawback, the ECT soft-field measurement is sensitive in multiphase of different permittivity [2]. In addition, ECT provides non-invasive and non-intrusive measurements, which allows the test material flows naturally. The ECT system is divided into two components; hardware and software. The hardware component comprises of sensors and data control system. Signal reconstruction system and the display and interpretation facilities are the software component used in the system for imaging and data processing [3].

The basic tomography setup is often bulk and sophisticated, which contribute to high material and setup cost. The bulky size also limits its usage for in-situ application. There are many study conducted for

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miniature tomography to cater various applications such as teaching instruments and onsite inspection. The miniature tomography adopted lab-on-chip (LOC) application which able to provide high throughput and low cost setup [4]. In addition, LOC application uses small amount of sample. At the same time applies small quantity of reagents or chemical solution. LOC application includes in biotechnology, medical diagnostics and environmental monitoring [5].

This paper discusses the ECT adopted LOC application for stagnant and hydrodynamic flow. For LOC platform, the configuration of the electrodes are arranged in a planar where all electrodes are at the base of the sensing area [4] where the electrode configuration is shown in Fig. 1.

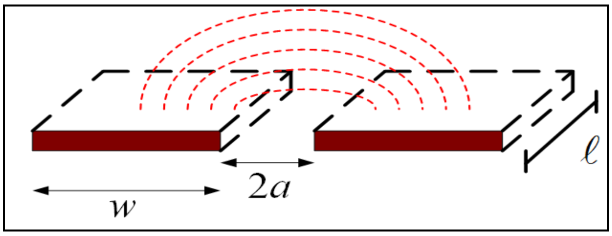

Fig. 1 Illustration of dimension and electrical field line formed by planar electrodes

The capacitance measurement for planar electrode configuration is defined as the measurement of charge between two plates (conductive electrode) inside the capacitor system. In miniaturized planar electrode sensor, the capacitance, C_x is calculated based on equation (1) [4] where the field line of planar electrodes is formed above the electrodes when current is supplied to the excitation electrode.

$$C_X = \frac{2\varepsilon_r \varepsilon_o \ell}{\pi} \ln\left[1 + \frac{w}{a} + \sqrt{\left(1+\frac{w}{a}\right)^2 - 1}\right] \qquad (1)$$

Where ε_r is the dielectric constant, ε_o is the electric constant, ℓ is the length of the electrode, w is the width of the electrode and a is half gap between electrode. Equation (1) shows that the capacitance response depends on the dielectric and electric constant, and the geometry of electrode sensor. In this paper, the device development and the image reconstruction for stagnant and hydrodynamic samples using the device is discussed

2. Design and Fabrication of 8-electrode Planar ECT

The sensors of the miniaturized ECT are made by copper where the electrical conductive (σ) is 5.69×10^7 S/m at 20 °C. Copper is relatively cheap as compared to other metal and it is easy to obtain and fabricate. The planar electrodes were fabricated on single sided PCB using the conventional PCB etching technique. The PCB layout was transferred using heat transfer machine. Later, ferric chloric acid is used to remove the unwanted copper layer. Fig. 2 indicates the configurations of the electrodes and measurement of the ECT planar electrodes.

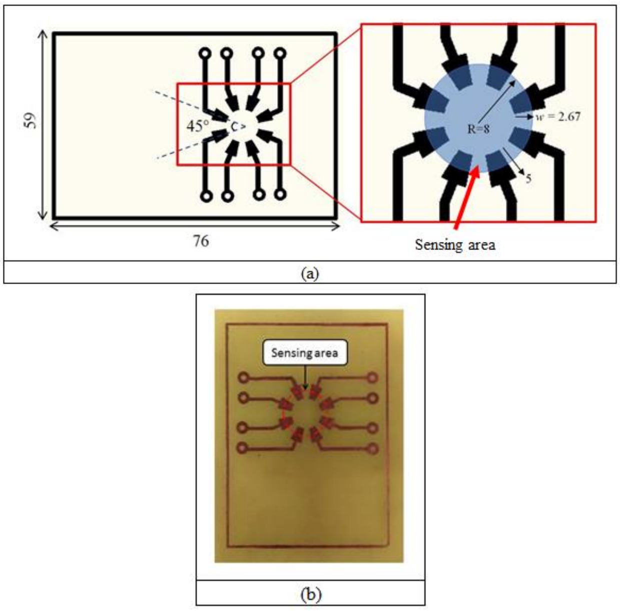

Fig. 2 8-planar electrode (a) dimension and arrangement and (b) fabricated electrodes

From Fig. 2(a), the overall size of the device is 76 mm × 59 mm where an eight-copper-electrode array is fabricated on. The electrodes array with each electrode size 5.00 mm × 2.08 mm is distributed equally on the sensing area with the interval angle between electrodes is 45°. The diameter of the sensing area is 16 mm and the length of the electrode exposed in the sensing area is 2.67 mm. The fabricated 8-electrode planar array sensor is shown in Fig. 2(b) where the red dotted line indicates the placement of the sensing chamber.

The microchannel is developed for both stagnant and hydrodynamic flow channel. Fig. 3(a) shows the Polydimethylsiloxane (PDMS) chamber for stagnant sample and Fig. 3(b) shows the channel for hydrodynamic flow for the same 8-electrode ECT system. The development of micro the chamber and channel is important to hold and to flow two-phase sample into the sensing area. PDMS is used for the fabrication of the micro channel as it offers several beneficial characteristics such as biocompatible. In addition, it is transparent at optical frequencies where the state of samples in sensing area can be observed easily. The PDMS micro channel was fabricated using molding technique to create structure of the PDMS micro channel using the PDMS elastomer kits where the prepolymer resin and the curing agent are prepared with the ratio of 10:1 (w:w) and are mixed thoroughly. The mixture is then poured on a master replica template and cured in the oven at 60 ºC for 1 hour.

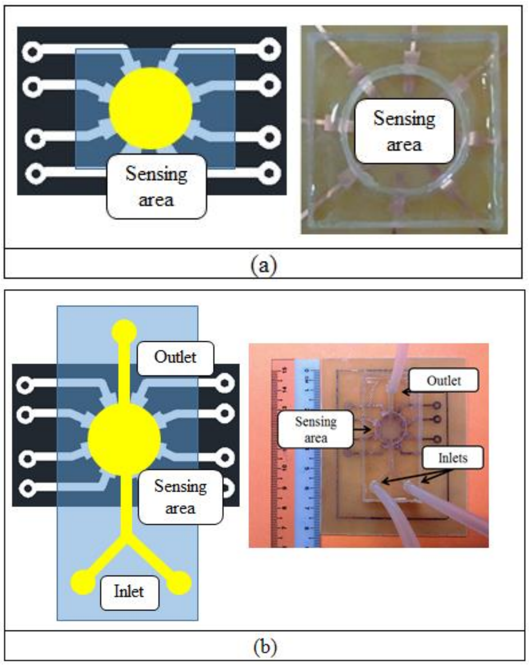

Fig. 3 PDMS chamber for (a) stagnant sample (b) hydrodynamic flow.

In Fig. 3, a 16 mm diameter PDMS chamber is the sensing area for both stagnant and hydrodynamic sample. For stagnant sample, the chamber is opened where the sample can be loaded directly into the chamber (Fig. 3(a)), whereas for the hydrodynamic sample, a conventional Y-shape channel is used for transferring two fluid samples from the inlets into the enclosed sensing chamber. Same mixture of PDMS is prepared adhere the silicone tubes for the inlets and outlet. A very thin PDMS mixture is applied on the bonding area of PDMS channel and the bonding area of the planar electrodes. The chamber is aligned on the electrodes array and cure in the oven at 60 ºC for 1 hour.

For stagnant sample, the sample is placed on the sensing area, and capacitance values are measured. By using linear back projection (LBP) technique, the measured data is processed and image is reconstructed. For hydrodynamic flow, two fluid samples are delivered through the inlet by using micro pumps, the fluids are mixed and filled up in the chamber or the sensing area before exiting through the outlet. The image reconstruction for hydrodynamic flow is captured online as the flow changed.

The 8-electrode ECT planar is integrated with the hardware and software components to complete the system as shown in Fig. 4. The fan beam projection technique is used for the electrical configuration switching. The fan beam projection is selected for this experiment, where the transmitters and detectors can be alternately arranged until excitations of all electrodes are complete [6]. Thus, fan beam projection covers wider area of inspection and theoretically will produce better results of image reconstruction.

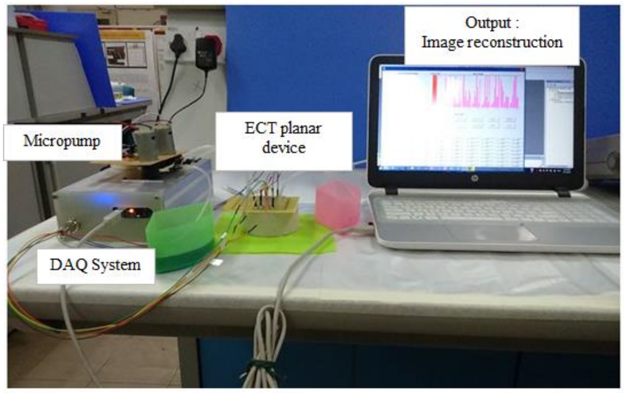

Fig. 4 Experimental set up for image reconstruction of two-phase fluid flow analysis.

The device is connected to the DAQ system for data collection and data processing. The data is sent to a control computer for image reconstruction. In addition, for hydrodynamic flow, a micro pump is used to supply the multiphase flow into the inlets and inspection chamber.

3. Result and Discussion

The image reconstruction is using LBP algorithm and 32 × 32 sensitivity map. The stagnant and hydrodynamic fluid within the sensing chamber is detected and reconstructed using the same planar ECT electrodes.

3.1 Stagnant samples

As for stagnant samples, the time taken for the detection and measurement process is not crucial and the image reconstruction can be done offline as the samples remain the same within the chamber as there is no movement or changes in the chamber. The image reconstruction results show that, various types of samples are easily reconstructed as shown in Fig. 5.

The stagnant samples consist of three different materials which are liquid – gas, liquid – liquid and solid – liquid. All three reconstructed images are able to resemble the real images from these combinations of materials which prove that the planar electrodes for the ECT device are able to reconstruct the images of these materials. The results are clearer for materials from different phase. Therefore a further study of the planar ECT system is by using hydrodynamic samples for liquid – liquid samples.

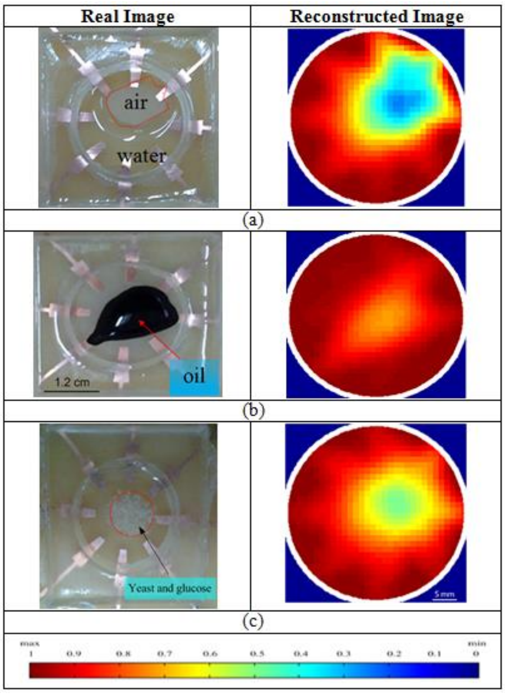

Fig. 5 Real and reconstructed images for stagnant samples (a) water-air (b) oil-water (c) yeast-glucose

3.2 Hydrodynamic flow samples

Hydrodynamic flow sample requires fast reconstruction algorithm for online monitoring. Liquid-liquid samples tested the limit of the planar ECT device in distinguishing the fluids via this non-optical image reconstruction method. Fig. 6 and 7 show the image reconstructed for two liquid-liquid samples at constant flow rate 12.03 ml/min.

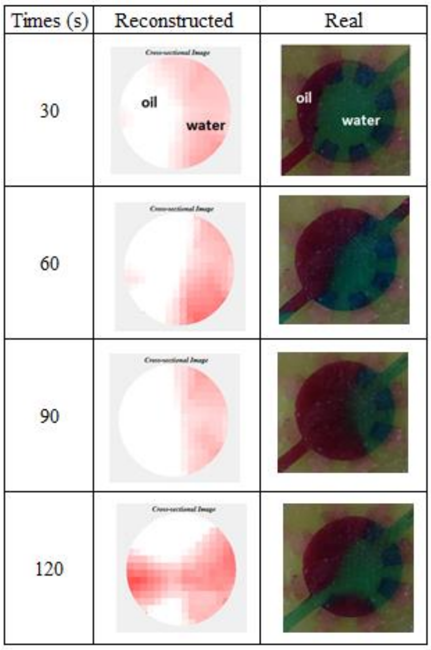

Fig. 6 Image reconstructions versus time at flow rate 12.03ml/min for immiscible water –oil sample

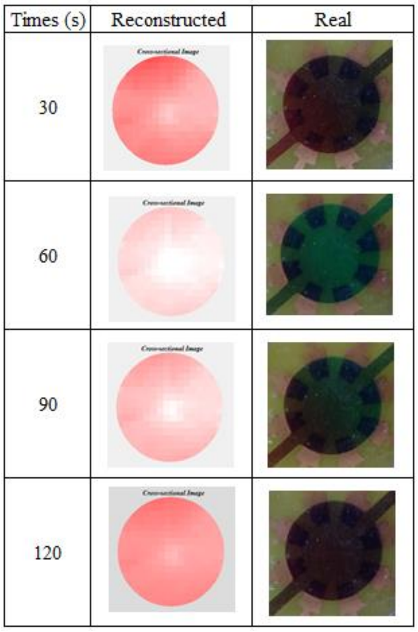

Fig. 7 Image reconstructions versus time at flow rate 12.03ml/min for miscible water –glucose sample

From Fig. 6, the reconstructed images for immiscible liquid-liquid samples show good distinction between the oil and water within the sensing chamber even though within a flow regime. Whereas, the reconstructed images for miscible liquid-liquid of water (blue) and 0.31 mol/L glucose solution (red) are not very clear (refer Fig. 7). However, the images shown are able to differentiate when one of the liquid is dominant in the sensing area; which is glucose.

4. Conclusion

The 8-electrode planar ECT developed able to detect the stagnant and hydrodynamic flow. For stagnant test, the time taking the data is an important variable as the sample stays at the sensing chamber. For stagnant sample, three experiments were conducted; water – air, oil – water and yeast – glucose. The results show that the ECT system able to detect the permittivity variation inside the sensing chamber.

For further study, the system is improved to test hydrodynamic flow measurements. For hydrodynamic flow, the data collection time is crucial to ensure the data collected is useful in flow monitoring. Thus, the experiment to capture image reconstructed versus time at flow rate 12.03 ml/min for immiscible water – oil sample, and miscible water – glucose solution is done. The system produces low quality image for miscible two multiphase flows, however, it is able to differentiate when glucose is dominating the sensor area.

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