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Measurement and analysis of water/oil multiphase flow using Electrical Capacitance Tomography sensor

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ABSTRACT

The paper investigates the capability of using a portable 16-segmented Electrical Capacitance Tomography (ECT) sensor and a new excitation technique to measure the concentration profile of water/oil multiphase flow. The concentration profile obtained from the capacitance measurements is capable of providing images of the water and oil flow in the pipeline. The visualization results deliver information regarding the flow regime and concentration distribution of the multiphase flow. The information is able to help in designing process equipment and verifying the existing computational modeling and simulation techniques.

1. Introduction

An Electrical Capacitance Tomography (ECT) system is able to obtain information about the contents of vessels, based on measuring variations in the dielectric properties of the flowing material inside the vessel [1]. ECT can be used with vessels of any cross section, but most work to date has used circular geometries [2]. A typical ECT system consists of a sensor built up from 8, 12 or 16 electrodes, capacitance measurement circuit, central control unit and control PC [3]. The electrode, which is normally built from conductive plate, acts as the sensing surface that directly contains the measuring volume. The capacitance measuring circuit detects permittivity variations and the signal conditioning circuit converts the analog measurement readings to digital format. A central control unit is designed to synchronize all the operations and to transfer the data to a control PC. The control PC receives the measurements, stores the acquired data, reconstructs images from the integral measurements and takes feedback action to control the flow [4]. In this work, a sixteen segmented electrodes sensor was developed and mounted symmetrically on the outer surface of an insulating horizontal pipeline.

An ideal capacitance measuring system will have a very low noise level, a wide dynamic measurement range and a high immunity to stray capacitance. Stray capacitance is a type of noise where the leakage capacitance is due to connection between the circuit and the cable to the electrode [2]. In a practical ECT system, there are three main sources of stray capacitance which affect the capacitance measurement: screened cable, CMOS switches and sensor screen. A 1 m long screened cable connecting the sensing electrode to the measuring circuit introduces about 100 pF of stray capacitance [5]. Additionally the stray capacitance may vary with cable movement, ambient temperature changes, component variation and external or internal electric field changes [6]. Typical measurement capacitance values are in a range between 0.01 and 0.5 pF. Consider that the measurement error should be better than 1% for all capacitance measurements [7].

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In most of previous research regarding ECT, the signals from the sensor electrodes are usually connected to the signal conditioning circuit by using coaxial cable. The coaxial cable is able to shield disturbance or stray capacitance external to the system. However, the cable connecting the measuring electrode and signal conditioning circuit introduces most of the stray capacitance. Therefore, the connecting cables should be made as short as possible. In this project we propose a better solution by completely removing the use of cables to connect the electrode plates directly to the signal conditioning circuit. The signal conditioning circuit which is built on the electrode sensor becomes an ECT sensor module. This module not only reduces the noise, but can also work independently of other modules.

Furthermore, a known challenge in ECT systems which are categorized as soft field tomography is that the sensor is less sensitive at the center of the pipe [7]. This is due to the sensitivity of adjacent electrode pairs being much higher than the sensitivity of opposing electrode pairs, resulting in the higher measurement sensitivity near the wall as compared to the central area. The use of external sensors also produced nonlinear changes of capacitance measurements in function of material permittivity. Hence, a new method is developed to enhance the situation of nonlinear potential distribution and less sensitivity in the ECT measurement central area. A differential potential excitation scheme is used instead of the conventional single excitation technique.

2. Brief literature review of two phase flow visualization

Bolton [8], is among the pioneers in imaging liquid/liquid (water/oil) flow using ECT in two-phase flow systems. Their system consisted of a PTL-200 and 12 parallel capacitances that operated at a high frequency of 1.25 MHz. Moreover, they employed an LBP algorithm for image reconstruction. An alternative calibration procedure was applied with kerosene as the low permittivity fluid, whereas the higher permittivity fluid was emulsion of ~40% of water and with 60% of kerosene. They found that the ECT system distinguished hold-up images between 25% and 50% distribution with increasing water flow in the kerosene continuous phase.

Jaworski [9], who performed an experiment using external and internal electrodes that employed a commercially available PTL-300 ECT system, continued the study of Bolton et al. [8]. The imaging of uniform water/oil mixes with distilled water as a continuous phase. The internal electrode sensor tended to overestimate the amount of oil, whereas the external electrode sensor underestimated the amount of oil. Overall, the ECT sensor exhibited nonlinear behavior, particularly for high-permittivity media and a thick pipe wall.

Hasan and Azzopardi [10] have conducted an investigation on the imaging of stratified liquid/liquid flows in horizontal and inclined pipes using an ECT system. The calibration was applied with kerosene as the low permittivity medium and water as the high-permittivity medium. Their study claimed that in a liquid/liquid flow, the phases within the pipe are distributed in several fundamentally different flow patterns or flow regimes that primarily depend on the flow rates of the two phases and the angle of inclination as shown in Fig. 1.

The research development above indicates that the application of ECT for imaging a spatial distribution in a pipe cross-section is reliable and has great potential. Therefore, the present work aims to image the stratified liquid/liquid flows in a horizontal pipeline specifically for the two-phase flow of water/oil mixes. This analysis is intended to verify the flow patterns along the pipeline that could be recognized by the image of the proposed segmented ECT system.

3. ECT system development

This research aims to investigate the use of a portable sensor design in an ECT system. As shown in Fig. 2, the project can be divided into 3 stages, which are the portable sensor design, the central control unit design and software programming.

ECT systems are usually comprised of 8, 12 or 16 electrodes. The size of each electrode decreases relatively to the growing number of ECT sensor electrode [7]. The sensor provides excitation signals and converts the measured capacitances into voltage signals, which are conditioned and then digitized for data acquisition.

In this research, 16 segmented electrodes have been fabricated onto the 110 mm diameter pipeline. It is very important that the pipeline material must be pure insulator to minimize measurement error as the detected signals are received from the excited electrode, and not from the current that flows through the pipe. The thickness of the pipeline and the permittivity (ε) of the material will influence the measured value of standing capacitance. However, other factors, such as the requirements of corrosion, abrasion, temperature resistance, and the temperature stability, may limit the selection of the pipeline material [11]. Fig. 3 shows an arrangement of 16 electrodes sensor on pipelines that has been designed in this project to cover 110 mm acrylic pipe in diameter with wall thickness of 5 mm, R_1 is inner pipeline radius 50 mm, R_2 is outer pipeline radius, 55 mm and electrode stretch angle θ is 22.5°.

The smaller radius-electrode ratio, the more serious effect of pipeline thickness will arise. Pipelines thickness has significant influence not only on capacitance but also on image. The maximum capacitance change is at $\rho = 0.85$, which is beneficial for

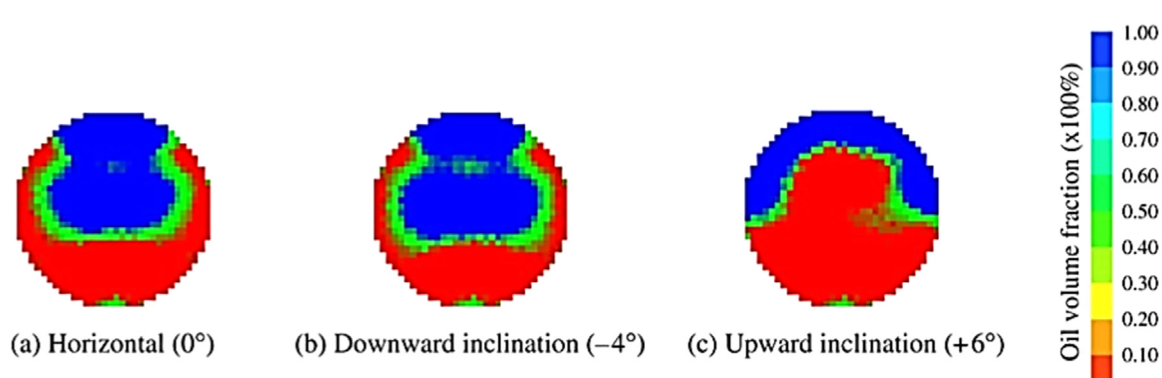


Fig. 1. Phase distribution in a pipe cross-section for mixture with input oil fraction 70% at different angles of inclination taken from Hasan et al. [10].

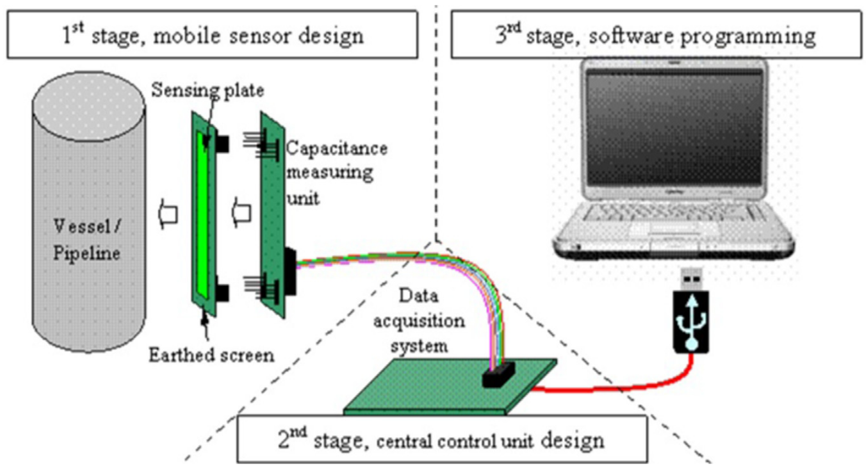


Fig. 2. Overview of the project.

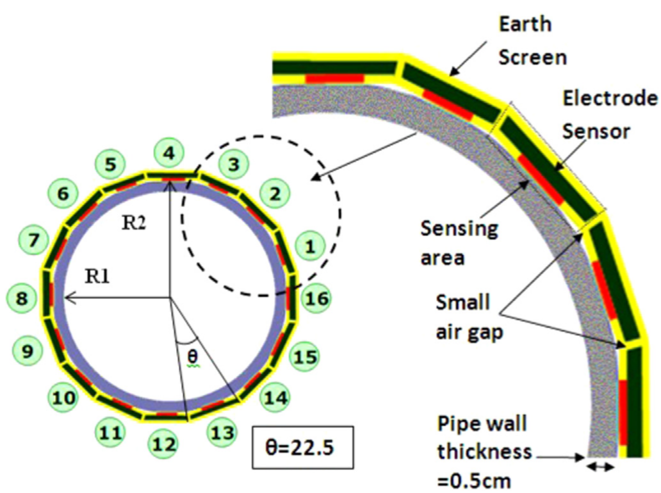


Fig. 3. Cross-sectional view of the ECT sensor with 16-segmented portable electrodes.

capacitance measurement and image reconstruction [12]. In this research the radius electrode ratio, ρ is 0.9 which also can be accepted.

The spatial resolution of a tomographic imaging system depends on the number of independent measurements and the fineness of sensitivity focus for each measurement. The measured values or data are manipulated to reconstruct the cross sectional image of the pipeline by computer programming [13].

4. Portable electrode sensor design

Typical ECT sensors must have a high level of mechanical stability, because any small movement between electrodes will change the values of inter electrode capacitances. In the previous research in ECT, all the electrode sensors were built fixed on the vessel. The electrode plate cannot be moved to other vessel, and the installation must be done on the actual vessel. This research has broken the limitation, starting a new generation in the ECT world; a portable ECT system that can be mounted on any vessel. The number of the electrode sensors can be selected depending on the diameter of the pipeline. The material of the electrode must be a highly conductive material. Copper has been chosen because it can be found on any bare Printed Circuit Board (PCB).

In an ideal ECT sensor, the electric field lines will be normal to the sensor axis. However, the electromagnetic field lines will spread out from the plates at the ends of the electrodes. The spreading could be reduced if the electrodes are shorter than the pipe's diameter, but this could lead to a reduced measurement sensitivity. Another method to prevent the electric field lines from spreading at the ends of the measuring electrodes is using driven guard, which has been integrated onto the electrode sensor in this project. The driven guard maintains a parallel electric field pattern across the sensor in the region of the measuring electrodes, by preventing the electric field lines from spreading axially at the ends of the measuring electrodes. This improves both the axial resolution and the sensitivity of the sensor.

Other than that, earthed guard electrode tracks may also be needed between adjacent measuring electrodes to reduce the standing capacitance between adjacent electrodes to a value low enough to avoid overloading or saturating the capacitance measuring system. These driven guard electrodes are connected to guard driving circuitry on the data acquisition module. Fig. 4 shows the driven electrode guard arrangement for electrode 1 and 2 for the 16 electrodes sensor. The rest of the electrodes are arranged in the same manner. The length of the guard electrodes is 33 mm on the left, and 43 mm on the right, as shown in Fig. 5. The guard is asymmetrical as the right part of the electrode is longer by 10 mm where the mounting screws will be placed and connected to the sensor jig. Externally, the measuring electrodes must be completely surrounded by an earthed metal screen so that the signals obtained in the signal conditioning circuit will not be influenced by external disturbances. In this research, the earth screen is located on the top layer of the electrode PCB as shown in Fig. 6 for ECT is created, by using special design PCB.

The sensor module is made by a double sided FR4 ($\varepsilon_r = 4.6$) PCB with the thickness of 1.6 mm. The FR4 is a widely used stiffener for flexible PCB and it is a cost efficient solution for high-end application involving impedance control and high frequency. Compared

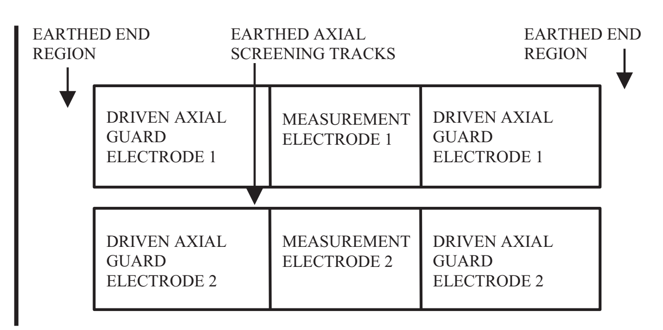


Fig. 4. Driven guard electrode design for an 16 electrode sensor.

Fig. 5. Electrode's dimension.

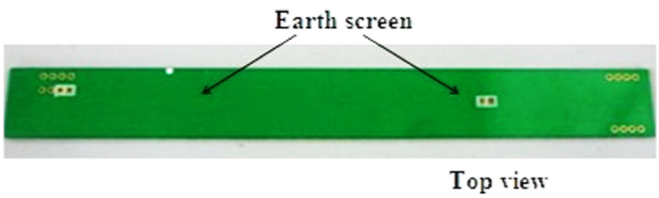


Fig. 6. The earthed screen is placed at the top layer of the electrode.

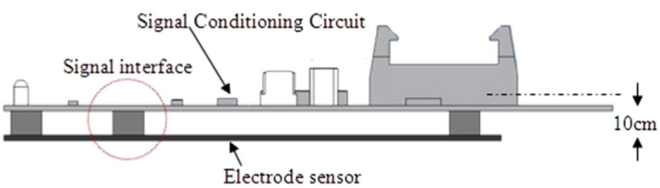


Fig. 7. Sensing module.

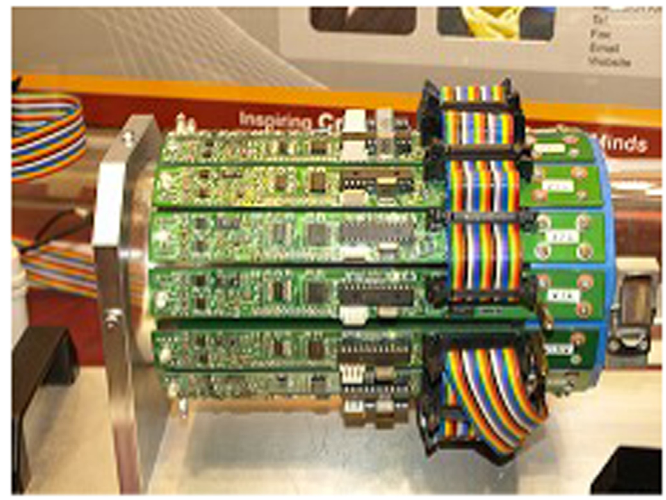


Fig. 9. Complete ECT sensing module.

to the past designed ECT system, the new electrode sensor no longer be bent and stuck on the pipe wall. This sensor is arranged symmetrically in hexadecagon format surrounding the pipeline. Each electrode sensor has 19 mm in width, and 100 mm in length sensor area. The length of sensor is chosen in accordance to the axial length of the electrodes which is related to inter electrode capacitance, signal bandwidth and measurement uncertainty of measured media. Longer electrodes produce an average signal over a greater axial length, which results in bad dynamic performance. Shorter electrode may result in capacitance values too small to be measured accurately [14]. The electrode length chosen is 100 mm which is the same as the pipe diameter.

5. Electrodes connecting techniques

An important issue with instrumentation design is the performance of the circuit in the presence of noise, which is generated

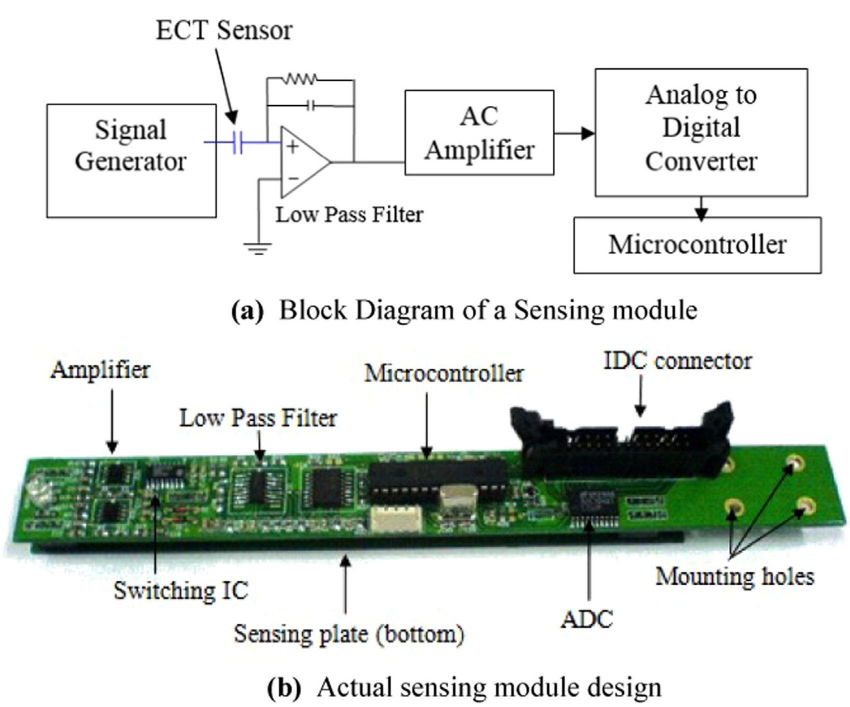


Fig. 8. (a) Block diagram of a sensing module. (b) Actual sensing module design.

Fig. 10. Horizontal water/oil flow rigs.

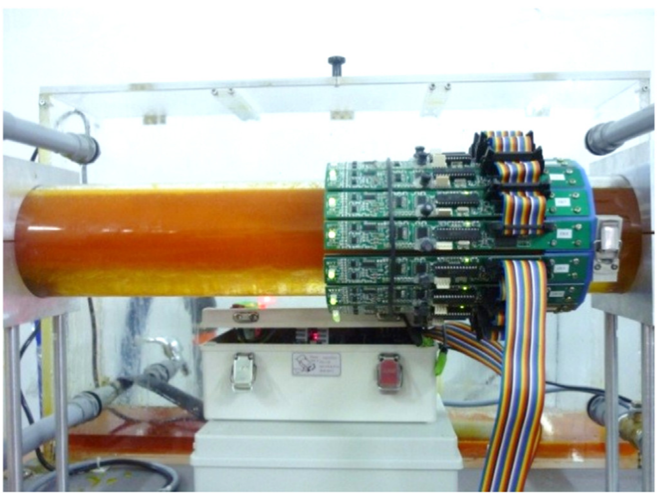


Fig. 11. Horizontal oil–water flows.

by external interference and thermal effects within components [6]. An ideal capacitance measuring system will have a very low noise level, a wide dynamic measurement range and high immunity to stray capacitance. The capacitance value measured would range from a few to hundreds femto farads.

In order to achieve the lowest resistance level for the connection between the measurement circuit and the electrodes, each of the electrodes is connected to a signal conditioning circuit via 1.0 mm pitch PCB connectors as shown in Fig. 7. Compared to the traditional method which uses coaxial cable, the sensor plate is now just located 10 mm away from the conditioning circuit. Output signal from the sensor plate which flows into AC based capacitance measurement circuit is measured in order to get the capacitance value between the excitation electrode and the receiving electrode.

Each of the signal conditioning circuits is identical and is able to work independently because all the measuring operations are controlled by a single microcontroller on the circuit. Each of the circuits consist of signal switching circuit, signal detection and amplifier circuit, absolute value circuit, low pass filter circuit, programmable gain amplifier (PGA), analog to digital converter circuit and microcontroller control unit. The desired sequence of operation of electrode's signal selection, measuring data and conversion data is dependent of the microcontroller programming. The electrodes sensor is designed in a way that it can be plugged directly onto the PCB sockets of the signal conditioning circuit and becomes a single sensing module.

These sixteen boards are interconnected by using a 26 way IDC cable. This design has eliminated the need to use cables to connect the electrodes and signal conditioning circuits. This design is able to cut down the maintenance cost of the system. In the case where only one sensing module is malfunctioning, users can simply change it by un-plugging the board and replacing it with a new board. Fig. 8(a) shows the block diagram of a sensing module and Fig. 8(b) shows the actual design. Fig. 9 shows the complete ECT signal conditioning system with 16 sensing modules.

6. Two excitation potentials technique for 16 sensor electrodes

In this work, we introduce a new scheme called two excitation potentials technique in order to improve the non-linear forward problem in soft field ECT [7]. In this case, two different excitation potentials are applied at different electrode pairs to produce an approximately uniform excitation field across the sensor, as opposed to using one excitation potential applied to each of the sensor electrodes in turn.

Using this technique, the excitation and measurement sequence is the same as the conventional single voltage source. However, the electrical potential used differs according to the position of the measured electrode pairs. A higher voltage is applied to the opposing electrode pairs and a lower voltage is applied to adjacent pairs. This technique is to improve the issue of less sensor sensitivity in the central area by increasing the potential measurement of opposing electrode pairs.

During this measurement phase, electrode 1 was injected by two differential excitation potentials/voltage sources (4 $V_{p\text{-}p}$ and 24 $V_{p\text{-}p}$) sequentially, where the lower excitation voltage source 4 $V_{p\text{-}p}$ will be excited to receive adjacent electrode pairs. For example: 1 and 2, 1 and 3, 1 and 4 also 1 and 14, 1 and 15 then 1 and 16, while an opposing electrode pair, in this case electrode 5 until electrode 13, will receive a high voltage excitation source of 24 $V_{p\text{-}p}$. In the next step, electrode 2 acts as excitation and electrodes 3-16 are used for detection, obtaining 14 capacitance measurements. This process continues until electrode 15 is used for excitation and electrode 16 for detection, which obtains only one capacitance measurement. In this case, there will be 120 independent capacitance measurements. In general, the number of independent capacitance measurements is represented by $N(N-1)/2$, where N is the number of electrodes [9].

The signal conditioning system will measure the capacitance produced by the electrode pairs when a 500 kHz sine wave voltage with the voltage sources (4 $V_{p\text{-}p}$ and 24 $V_{p\text{-}p}$) sequentially is injected to one of the electrode pair. With a 500 kHz excitation signal, the circuit has good linearity and stability [15]. The controlling unit will be used to select which electrode to be injected with the sine-wave. In the receiving circuits, the signals will be conditioned through several stages, including the AC based capacitance measuring circuit, amplifier circuit, AC to DC converter circuit and filter circuit.

7. Results and discussion

In this work, the distributed flows of water (ε of 80) and oil (ε of 3.1) phases were passed through a pipe. A liquid/liquid flow facility that consists of a test section at the laboratory of the Faculty of Electrical Engineering, Universiti Teknologi Malaysia, was reconfigured for the present work. The flow rig was composed of

Table 1
Reconstructed image of horizontal oil–water flow concentration.

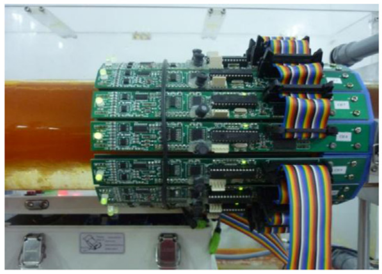
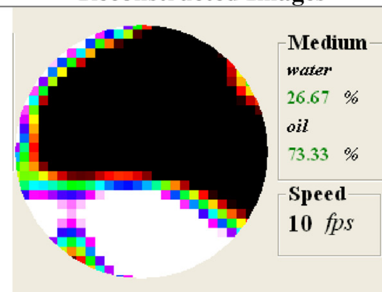
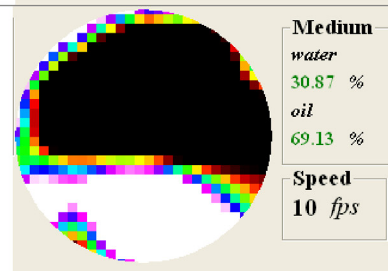
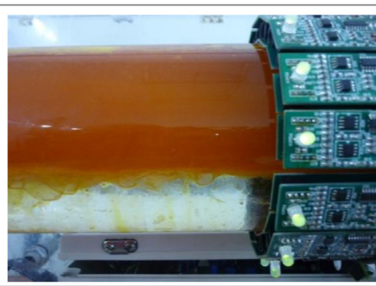
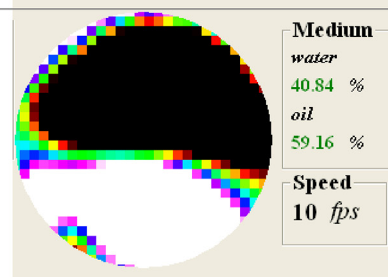
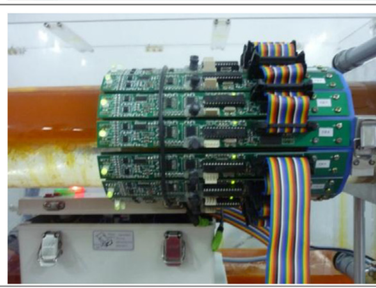
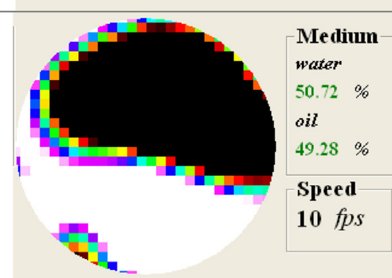
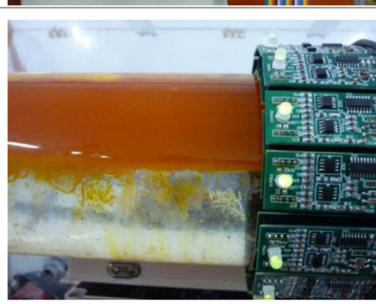
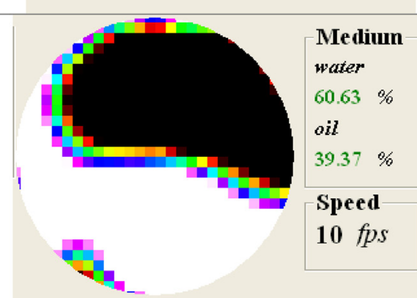
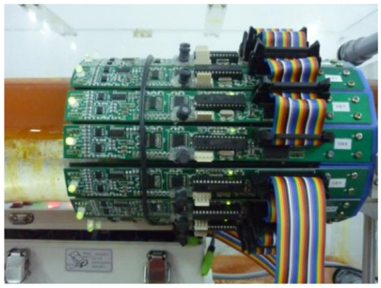
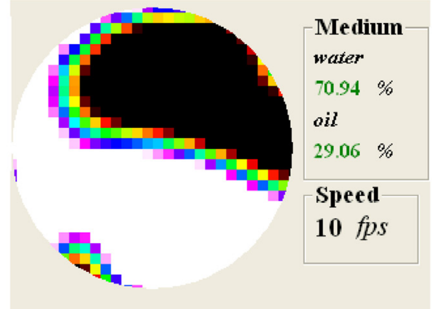
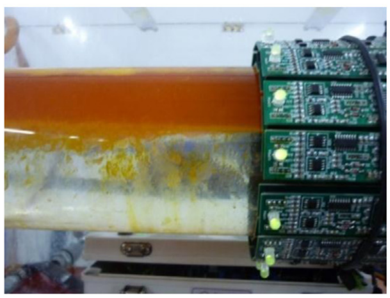
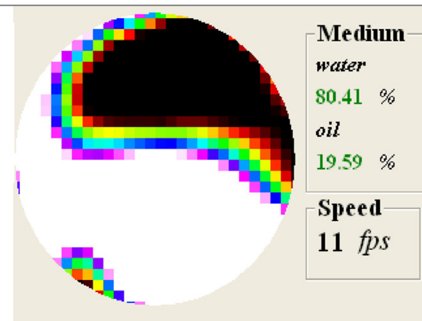
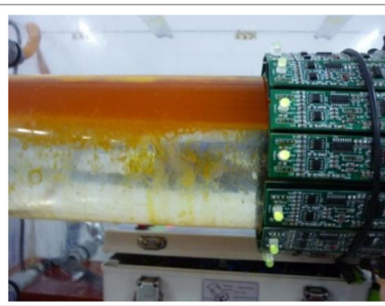
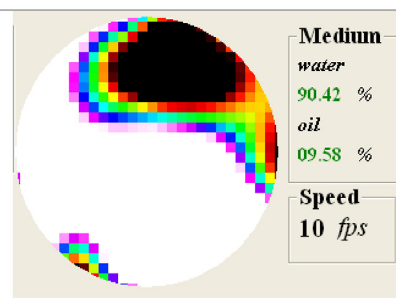
Test Section	Reconstructed Images
	
	
	
	
	

Table 1 (*continued*)

liquid storage tanks and pumps, and the liquids were returned to storage tanks beyond the test section (pipeline). The flow rig was designed such that the different combinations of two phases can be investigated. Fig. 10 shows the horizontal water/oil flow rig for the current research.

7.1. *Dispersions flows of oil–water*

In the first part of the experiment, the concentration of oil and water mix was verified. The stationary level of water was varied from low to high or from 20% to 90% of the pipe diameter. A single-plane ECT was applied for the concentration analysis, as shown in Fig. 11.

The resulting images based on the LBP algorithm when the reconstruction program was operated in real-time (10 frame per second [fps] in average) are shown in Table 1 where the white color represents the concentration of water, black represents oil and the colorful pixels indicates a varying permittivity that represent the layer of water/oil emulsion in the flow regimes. The two liquids tended to stratify when they were given time to stabilize. The obtained water/oil flow patterns and phase distribution in a pipe cross section were in line with the findings of previous studies, indicating that the system is capable of visualizing the reconstructed image of horizontal water/oil flow concentration.

7.2. *Repeatability of image concentration measurement for ECT system*

The repeatability of the image concentration measurement for the two-phase flow measurement experiments on liquid–gas flow was evaluated using the Gage R&R method, is a measurement systems analysis technique that uses an analysis of variance (ANOVA) random effects model to assess a measurement system. This statistical software is used to evaluate repeatability of image concentration measurement for ECT System. In the current study, 10 parts of different percentages of liquid levels in the pipe setting with four time repeatability measurement were conducted. Forty runs in randomized measurement order were made through the experimental layout using the Mini-Tab statistical software.

The one-way ANOVA analysis in Fig. 12 shows that the variations due to part significantly refer to the p-value of 0.000. Looking at %VarComp, the variation due to the differences between parts contributes to 99.3% of the overall variation, which is much larger than the Total Gage R&R at 0.7%. The percentage contribution of variance component (%Contribution) under the Gage R&R shows that 0.7% of the variations were caused by repeatability or the measuring equipment. The variation due to measuring equipment was small at below 30%, indicating that the ECT gage is capable and considered acceptable.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
Concentration	9	28389.2	3154.36	564.595	0.000
Repeatability	30	167.6	5.59		
Total	39	28556.9			

Alpha to remove interaction term = 0.25

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	5.587	0.70
Repeatability	5.587	0.70
Part-To-Part	787.193	99.30
Total Variation	792.780	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	2.3637	14.182	8.39
Repeatability	2.3637	14.182	8.39
Part-To-Part	28.0570	168.342	99.65
Total Variation	28.1564	168.938	100.00

Fig. 12. ANOVA and Gage R&R.

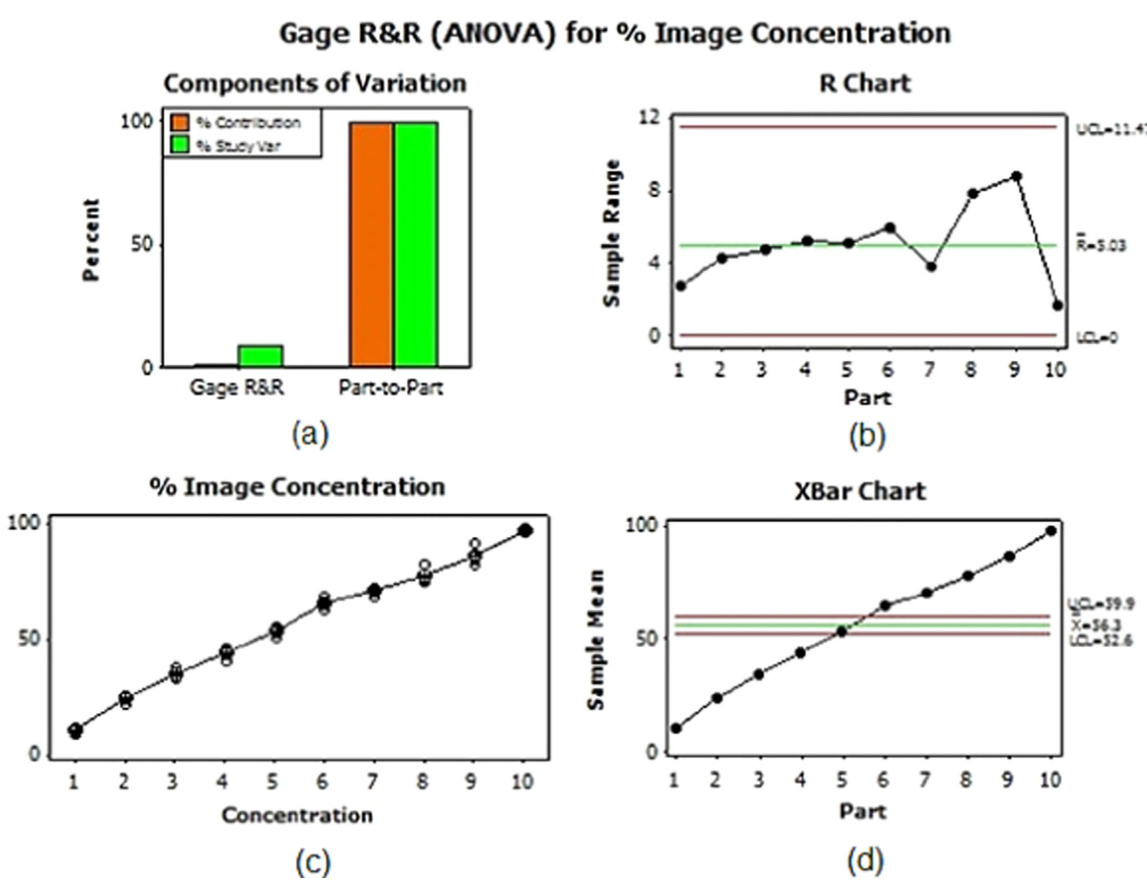


Fig. 13. (a)–(d) Gage R&R For ECT image concentration measurement.

The same observation can be made in the graph in Fig. 13. The Components of Variation bar graph in Fig. 13(a) shows that the part-to-part variation was the largest component of both the total process variation (variance of the dataset) and study variation (using the sum of the Gage R&R and part variation). This finding is consistent and shows a good measurement system. Fig. 13

(b) shows that the R chart is in control (almost all data points were inside the control limits), indicating that ECT provides consistency in the measurement system. The next chart on percentage of image concentration in Fig. 13(c) shows the individual readings of each part that consisted of large variation around the average of each part. These results indicate that each concentration profile still differs from one another, however the measurement taken from the readings were very close to the mean measurement from the ECT device. The Xbar in Fig. 13(d) shows the average of each percentage of image concentration measurement for each 'part.' The area between the two control limits in this case represents the ECT measurement and shows that most of the points should fall outside the limits on the graph, indicating that the ECT measurement system can detect part-to-part differences.

8. Conclusions

This paper investigates the experimental capability of using a segmented ECT sensor with 16 portable electrodes using two different excitation potentials technique. The reconstructed images obtained from this experiment show that the developed system is able to be applied and utilized to visualize the water/oil multiphase flow. The repeatability analysis of the concentration measurement showed that the system provided consistency in the concentration measurement and indicate its ability to be used as flow imaging instrument. The visualization results were able to deliver information regarding the flow regime, and concentration distribution in two-phase measurement system incorporated with a liquid flow measuring device.

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