ELECTRICAL CAPACITANCE TOMOGRAPHY DESIGN AND ANALYSIS FOR BUBBLE FLOW REGIME

MUHAMMAD FIRDAUS BIN ABDUL HALIM

ELECTRICAL & ELECTRONICS ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
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by

MUHAMMAD FIRDAUS BIN ABDUL HALIM

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved:

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(Ir Dr Idris bin Ismail)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Muhammad Firdaus Bin Abdul Halim

ABSTRACT

Tomography system is a process to determine the distribution of materials in some region of interest by obtaining a set of measurements using sensors that are distributed around the periphery. The process is important to monitor the characteristic of multi phase flow especially in oil and gas industry. One of the tomography methods is by using Electrical Capacitance Tomography or also known as ECT. While the hardware and image reconstruction algorithms for ECT have been published extensively, there are only few papers have been published to discuss ECT sensors and design issues. This report is briefly discuss the basic principle of designing ECT sensor include the number and length of electrodes, earthed screen, stray capacitance effect and the connection issue. Basically, ECT is divided into three parts which are capacitance measuring circuit, data acquisition system and reconstruction of image. The first phase of this project is a study on the basic concept of ECT sensor design and analysis on the available sensors in the laboratory. The analysis is done using Multi-Modal Tomography System Software (MMTC) and ITS Tomography Toolsuite. The results of the analysis are used to compare the reliability of the new fabricated sensor. All the result and analysis are shown in this report.

ACKNOWLEDGEMENT

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Thank you.

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LIST OF ABBREVIATIONS

ADC	Analog Digital Converter
CMS	Capacitance Measuring Circuit
DAC	Digital Analog Converter
DSP	Digital Signal Processing
ECT	Electrical Capacitance Tomography
FE	Finite Element

CHAPTER 1
INTRODUCTION

1.1 Background Study

A project on Electrical Capacitance Tomography (ECT) for imaging of multi-phase flow from oil wells has been conducted since mid-1980s. The basic aim of modern tomography is to determine the distribution of materials in some region of interest by obtaining a set of measurements using sensors that are distributed around the periphery.

Obtaining the image of two phase flow is a common process in oil industry. The materials could be oil or gas in a pipeline and each material are having its own permittivity which the values are normally used for further studies in ECT. By having the image of two phase flow in pipelines, it could help the industry to observe and conduct some important task such as diagnostics, monitoring, measuring and controlling industrial processes and optimization of producing wells for oil and gas industries.

1.2 Problem Statement

Process of monitoring, measuring and controlling industrial process is very important for two phase flow of oil and gas. This process can be done by developing a tomography system using electrical capacitance tomography (ECT).

ECT technology is a kind of process tomography technology and provides a new way to construct the image of the inner pipelines, reactors, vessels or other type of container s that are part of the industrial processes [1] [2].

Currently, there are two types of measurement techniques, which are destructive and non-destructive. Destructive method is not preferable because it involves separation of materials before the measurement is taken which means the data is taken is no longer up-to-date.

On top of that, non-destructive method is preferable to be used in upstream industries. There are about five types of non-destructive analyzer which are electrical, microwave, radiation scattering, density and viscosity. Though each of the non-destructive method has its own advantages, the disadvantages still cannot be avoided and the disadvantages are summarized as in Table 1. However, electrical type is chosen as this type is fast in response, inexpensive compared to other methods and safe and it includes capacitance, impedance, and conductance-based techniques.

Table 1 Non-Destructive Method (Pal, 1994)

Type	Remarks
Electrical	- Fast in response, relatively expensive, and safe
Microwave	- Insensitive to conductivity (salt content) variation
Radiation	- Pal (1994) highlights the health and safety concerns regarding its radiation source.
Density	- Emulsion density becomes independent of the composition when the density of oil and water are indifferent.
Viscosity	- Not widely-used because it is dependent on droplet size and distribution, nature, and concentration of surfactants, presence of electrolytes and etc. - Requires cautious control on the variables mentioned above.

1.3 Objectives

The objectives of this project are as below:

- To study on ECT system as an gas-in-oil analyzer.
  - In depth studies is done throughout this project for analyzing the ECT as gas-in-oil analyzer.

- To build capacitance sensors and investigate the effects of different sensor designs.
  - A few methods of capacitive sensors design are compared and the best method is chosen to design the electrical capacitance tomography. The sensor is then tested for the reliability of analyzing the two phase flow in the pipelines.

1.4 Scope of Study

In order to ensure the objective of the project is achieved, the scope of study for this project will covers the following:

- Studies on theory of ECT Sensor Design
  - There are a few criterions that are covered in designing ECT sensor such as the type of electrode, length and width, and etc.
  -

- Concept and knowledge in electromagnetic for capacitance sensor design.
  - There are a few concepts and criterion should be taken into consideration and it is the most important part in designing the sensor

- Analyzing tomography system process
  - Basic understanding of tomography system process is studied to ensure the process is fully understood

- Analyzing on a data acquisition system using ITS Tomography Toolsuite.
  - The analyzing of the data is done with the Toolsuite provided by ITS Systems.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Tomography System

Tomography system is a common technique that is used widely within oil and gas industry. The process consists of obtaining images from the inner part of pipelines, reactors, vessels or other type of containers that are part of the industrial processes [3].

There are several techniques for obtaining images, depending on the type of measurement used. Each technique works with a different kind of sensor, which is mounted around the pipe of vessel to be imaged. A sensor or vessel rotation is required in order to obtain complete information about the materials distribution.

There are two mainly type of sensors that were used in the industry which are Electrical Resistance Tomography and Electrical Capacitance Tomography. Dong *et al.* (2003) agrees that the ERT measurement prevision sometimes may be poor. Yet, there are a few advantages of ERT have been pointed out which is it can provides two or three dimensional information on two-phase flow and thus more information, phase distribution can be reconstructed at various times, and lastly it is feasible to find precise method to estimate flow parameter by statistical analysis or pattern recognition.

For Electrical Capacitance Tomography, Ismail *et al.* (2005) agrees that it has the advantages of no radiation, high rapid response, low cost, being non-intrusive and non-invasive characteristics. Besides that, measurement which is taken based on capacitance method is having high standing capacitance (stray capacitance) which results in low sensitivity of measured capacitance signal. Stay capacitance is one of the most important issues that should be emphasized in designing the sensor and will be described in the next sub-chapter.

In addition, ECT system has been using widely for industrial multiphase process visualization, suitable for electrically insulating materials and it consists of multiple equal-spaced electrodes. The capacitance data acquisition system measures the capacitance between all possible combination pairs of the 8 or 12 electrodes, converts the measured capacitance into a digital signal, and sends the data to the image reconstruction computer.

The measured capacitance is depending on the dielectric constant value (electrical permittivity) of the different phases or components of the mixture and the way they are distributed inside the pipeline or vessel [3]. Basically, permittivity is an electrical property that will be different for each type of phases and the permittivity of the mixture is a measure of the fractions of the different components which referred to the dielectric constant value [6] as mention in the previous paragraph.

The measurement and reading is depending on the number and the size of electrodes. A high electrode number results in high resolution for the images, but because electrodes are smaller, measurement sensitivity will lower compared to a sensor with few electrodes [3].

The schematic block diagram of an ECT system with its main components is shown in Figure 1.

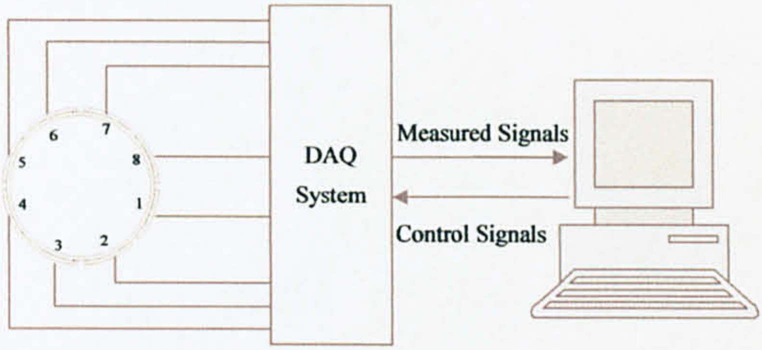


Figure 1 ECT Schematic Block Diagram

Based on Figure 1, ECT is divided into three parts which are sensors with capacitance measuring circuit, data acquisition unit and lastly is a control computer. The connection between the sensors and capacitance measuring circuit to the data acquisition is using coaxial wire as it is cheaper and having a high data rate transfer. This project is mainly focusing on the designing of the ECT sensors and analyzing the data based on the new ECT sensors.

2.2 Electrical Capacitance Tomography Working Principle

ECT sensor in Figure 1 is taken as an example. There are 8 electrodes where the first step is electrode number one will be used as excitation electrode while remaining electrodes are used for detection, obtaining 7 capacitance measurements. Next step is electrode 2 with be used as excitation electrode while the remaining is used for detection. This process will only finish when electrode 7 is used for excitation and electrode 8 for detection.

Generally, there will be about 28 independent capacitance measurement for 8 electrodes where the number of independent capacitance measurement governed by the equation below:

$$ICM = \frac{N(N-1)}{2}, where\ N\ is\ the\ number\ of\ electrodes$$

Table 2 gives some figures of number independent capacitance measurement corresponding to the number of electrodes being used, 6, 8, 12 and 16.

Table 2 Relationship between number of electrodes and number of independent capacitance measurement

Number of electrodes	Number of independent capacitance measurement
6	15
8	28
12	66
16	120

2.3 Electrical Capacitance Tomography Sensor Design

The most important part of this project is the designing of the sensor for ECT. Based on Xie *et al* (1992) the structure of a primary sensor will no doubt influence the performance of a capacitance measurement system.

Typical ECT sensors must be having a high level of mechanical stability in order to ensure the value of the inter-electrode capacitance is not changed due to the small movement. The sensors must be designed according to the requirements that meet with the oil and gas industries necessary which are as below [4]:

a. Compatibility with primary sensors with up to 12 electrodes
b. High measurement resolution
c. Low noise level
d. Low baseline drift
e. Wide dynamic range of measurement
f. Fast data capture rate
g. Fully software-controlled circuit setting

Different materials can be used to make measurement electrodes, solid brass plates (Huang *et al.* 1989) or copper adhesive tape (Xie *et al.* 1989). As for this project, copper adhesive tape is used as it is cheap, and easy to get.

2.3.1 Sensor with External and Internal Electrodes

There are two method of constructing ECT sensor; either external or internal. External method is considered as non-invasive because it has no direct contact with the measurement area while internal method is invasive. The advantages and disadvantages of both of these methods are summarized in table below:

Table 3 Advantages and Disadvantages of External and Internal Electrodes [15]

	Advantages	Disadvantages
External	- Small standing capacitance, no contact to process - Simple - Low cost - Easy to construct - No contact to process	- Has pipe wall capacitive effect
Internal	- High sensitivity - Small standing capacitance - No pipe wall capacitive effect	- Electrostatic pick up - Contact to process - Difficult to prevent leakage - Difficult to construct

2.3.2 Number of electrodes

The number of electrodes determines the sensitivity and image capture rates. The radial resolution can be improved by increasing the number of electrodes. In an ECT system, due to the overlapping capacitance, therefore the value of capacitance will be the same.

W.Q. Yang (2010) in her paper mentioned that small number of electrodes will be having three expected benefits which are:

a. A smaller number of data acquisition channels are required, which can simplify the hardware significantly if all channels are operated in parallel.

b. A faster data acquisition rate is expected because the number of capacitance measurements is reduced.

c. The length of electrodes may be reduced due to the increased cover angle of the electrodes, resulting in increased inter-electrode capacitance.

However from Table 2, as the number of electrodes is small, the number of independent capacitance measurement is also small, thus expecting less quality of image. But, having a large number of electrodes would also result in the following problems [13]:

a. Complicated and expensive hardware
b. Smaller capacitance to be measured
c. Larger eigenvalues of the sensitivity matrix causing difficulties in solving the inverse problem for image reconstruction and
d. A slower data acquisition rate because of more measurement to be taken.

2.3.3 Length of Electrodes

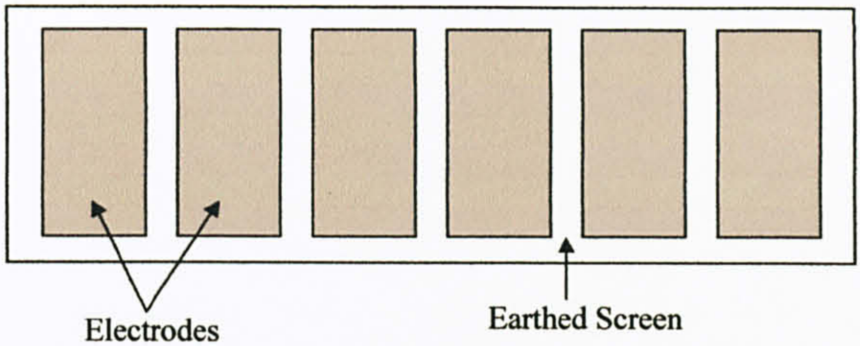
The length of the electrode should also be considered in designing ECT sensor. As the capacitances are proportional to the surface area of the electrodes; the measurement electrodes must have a finite length L_t [12]. Thus, the total length of an electrode for sensor design should normally be at least equal to the diameter of the inner vessel or pipe wall. A larger value of L_t will further increase the sensitivity of the sensor.

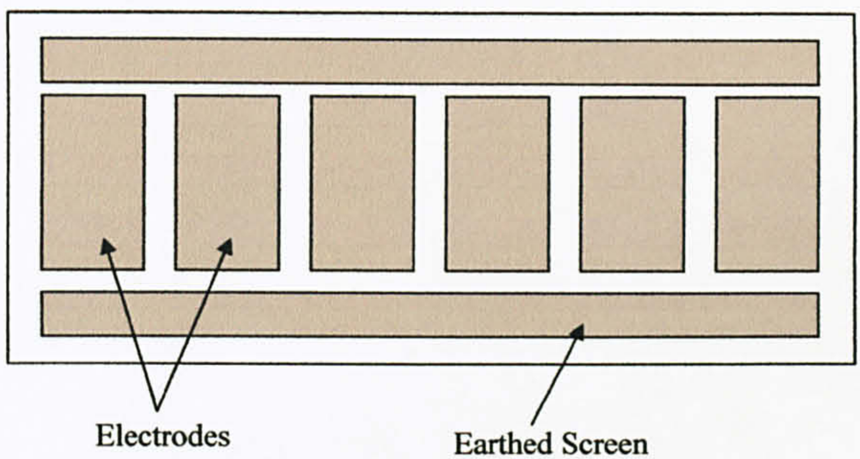
Theoretically, the length of electrode will be reduced if the diameter of ECT sensor is small. A typical ECT sensor is between approximately 2.5 cm to 10 cm and for a 2.5 cm diameter is suggested to have 10 cm length of 12 electrodes but 6.7 cm length for 8 electrodes.

2.3.4 Earthed Screen

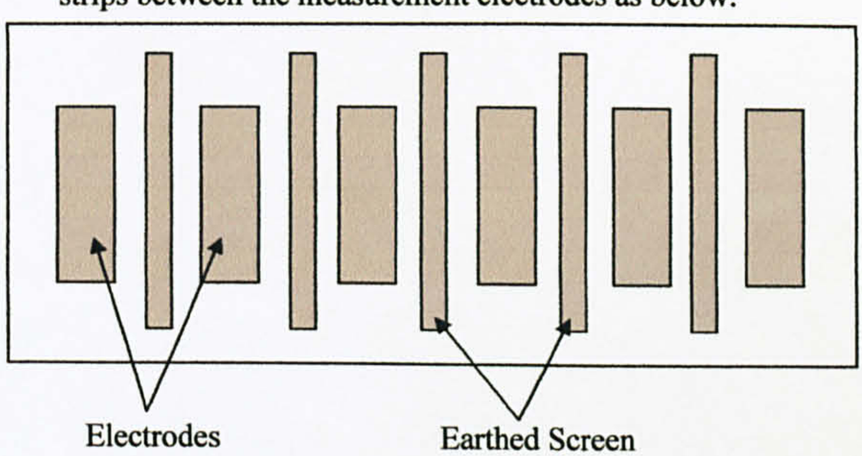
In obtaining a good images or results, the stray capacitance issue should also be emphasized in designing the ECT sensor. To prevent the stray capacitance effect, earthed screens are used and there are many ways of locating the earthed screens and it is summarized as below:

Table 4 Earthed screen design for ECT Sensor

<table>
<tr>
<td>a.</td>
<td>


- This method has been proposed by Marc Macmillen (2006)
</td>
</tr>
<tr>
<td>b.</td>
<td>


- This method has been proposed by W.Q. Yang (2010)
- Mechanical construction issue would also cause a problem in placing the earthed screen. A simplified version is to place earthed strips between the measurement electrodes as below:



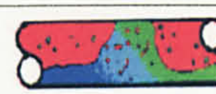
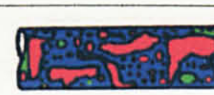
</td>
</tr>
</table>

For some application, earthed screen is not used because the signal would leak to ground through the earthed screen thus giving a negative effect on capacitance measurement.

2.4 Flow Regime Analysis

The image that is obtained from the test basically is used to determine the type of flow regime for two phase flow. The flow structures are classified in flow regimes, whose precise characteristics depend on a number of parameters [14]. The types of flow regimes are summarized in table below:

Table 5 Flow Regime Classification [14]

No	Flow Regime Classification	Types of Flow	Figure
1	Dispersed	Bubble	
		Mist	
2	Intermittent Flow	Slug	
		Churn	
3	Separated Flow	Stratified	
		Wavy	
		Annular	

There are three main mechanism involved in forming the different flow regimes which are transient effects, geometry/terrain effects and hydrodynamic effects. However, there are also some activities that would cause the forming of different flow regimes which are:

a. Transient occurs as a result of changes in system boundary conditions. This is not to be confused with the local unsteadiness associated with intermittent flow. Opening and closing of valves are examples of operations that cause transient conditions.

b. Geometry and terrain effects occur as a result of changes in pipeline geometry or inclination. Such effects can be particularly important in and downstream of sea-lines and some flow regimes generated in this way can prevail for several kilometers. Severe riser slugging is an example of this effect.

c. In the absence of transient and geometry/terrain effects, the steady flow regime is entirely determined by flow rates, fluid properties, pipe diameter and inclination. Such flow regimes are seen in horizontal straight pipes and are referred to as "hydrodynamic" flow regimes. These are typical flow regimes encountered at a wellhead location.

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

This project will be done based on the flow chart as following:

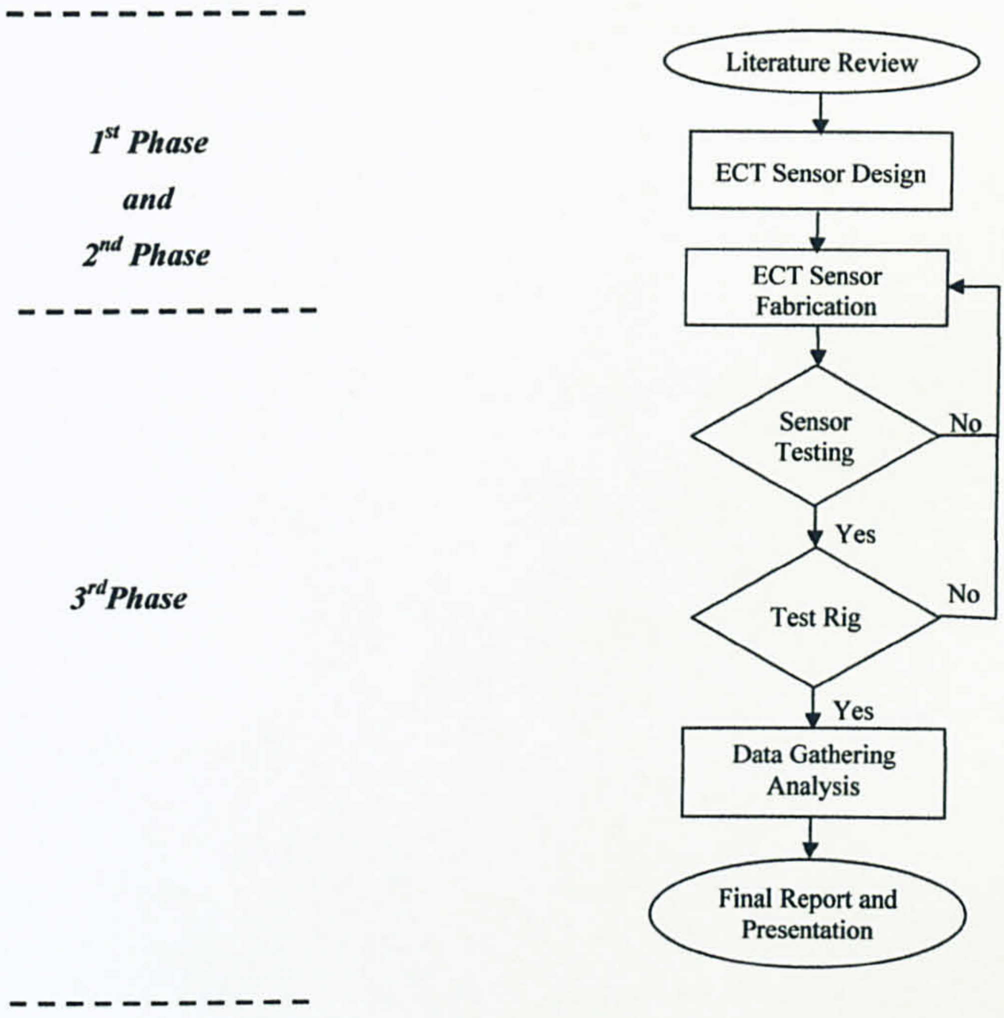


Figure 2 Flowchart of the project

This project comprises of three phases which described as following:

- First Phase – this phase is a section of data gathering for the conceptual and theory of electrical capacitance tomography as well as design procedure.

- Second Phase – this phase is a section where the sensor is fabricated according to the design procedure method studied in first phase.

- Third Phase – this phase is a section where the test is going to be done on the sensor design and also test rigs will be conducted where the first test is to test the reliability of the sensor and the second test is to collect all the data needed for measurement and reconstruction of the image.

3.2 Tools and Equipments

The tools and equipments required for this project are:

- Electrical Capacitance Tomography (ECT)
- ECT Sensor
- Gas Compressor
- Water Pump
- Industrial Tomography System (ITS) Tomography Tool Suite

3.3 Sensor Fabrication

The second phase of this project is fabrication of the sensors. As discussed in chapter 2.3, copper electrodes were used for the sensor fabrication. The electrodes are fabricated at the outer of the pipe and follow the design as below:

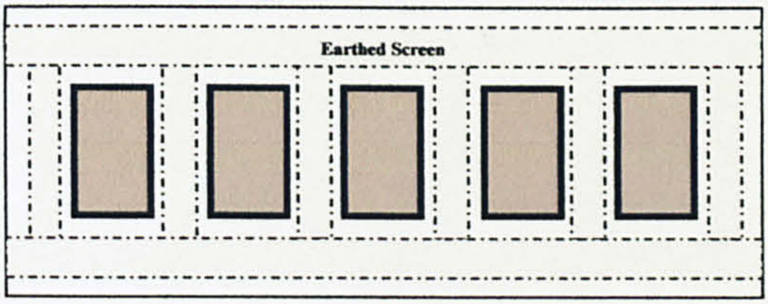


Figure 3 Sensor Design

The sensor details are as following:

Table 6 Specification Details of ECT Sensor

ECT Sensors	Specification
Number of Electrodes	12
Diameter of Pipe	8.5 cm
Circumference @ Perimeter	28.5 cm
Electrode Length	10 cm
Electrode Width	1.5 cm
Space between each electrode	8 mm

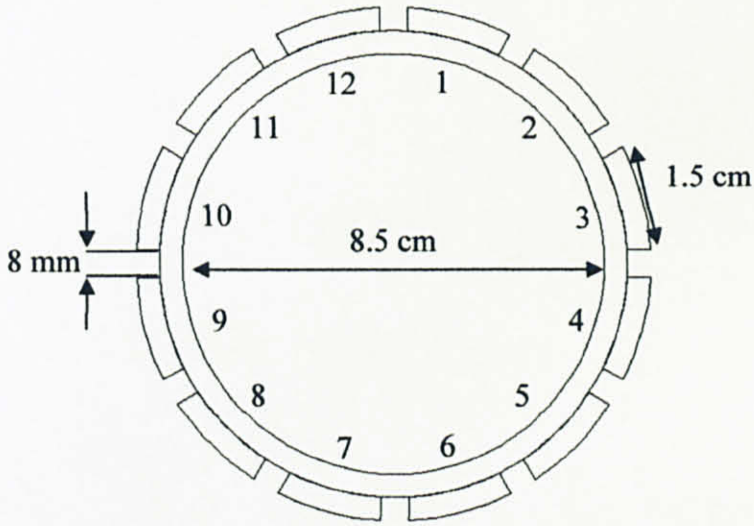


Figure 4 ECT Sensor with External Electrode

The electrodes are connected using coaxial cable RG-174 to transfer the measured capacitance from the electrode to the data acquisition unit. RG-174 coaxial cable is used as it has a high data rate transfer. Besides that, it also has a capability of eliminating the stray capacitance by connecting the "screen" cable to the earthed screen.

The fabricated ECT sensor is shown in figure below:

Figure 5 Fabricated ECT Sensor

Figure 6 Coaxial Cable – RG 174U

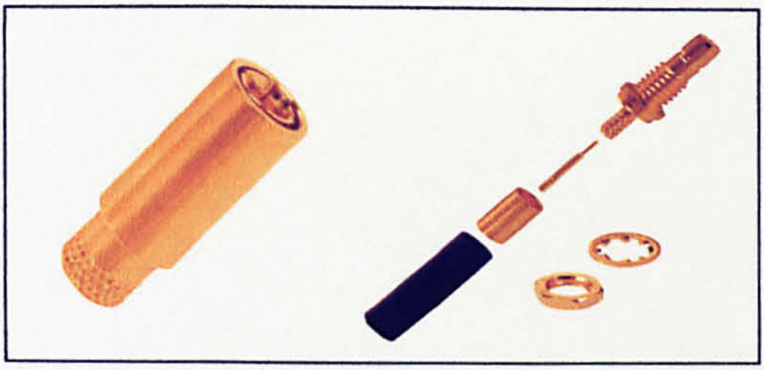


Figure 7 SMB Connector

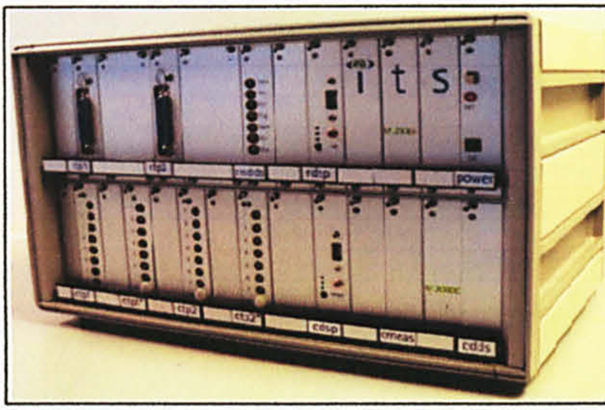


Figure 8 Data Acquisition Unit – Industrial Tomography System m3000

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 ECT Calibration Results

Calibration is very important to ensure the ECT sensor is capturing the images correctly. There are two steps of calibration which are Low and High. Basically, low calibration is determined by the lowest permittivity while high calibration is determined by the highest permittivity of phases.

The calibration process is first tested with the existing sensor in laboratory. This sensor was designed by Industrial Tomography System Ltd and all results and analysis is using two software, which are MMTC and ITS Tomography Toolsuite.

The calibration results will be used for comparing with the result of fabricated sensors by the author. Basically, a good result will be having the following characteristics:

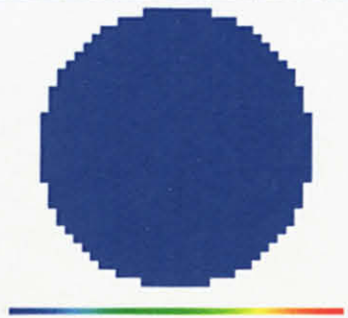
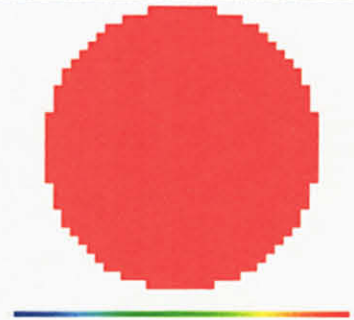
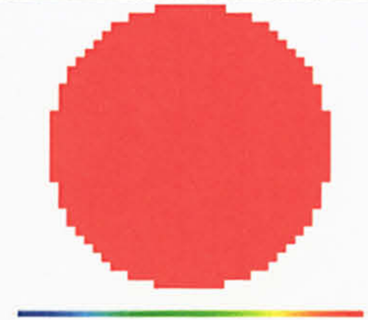
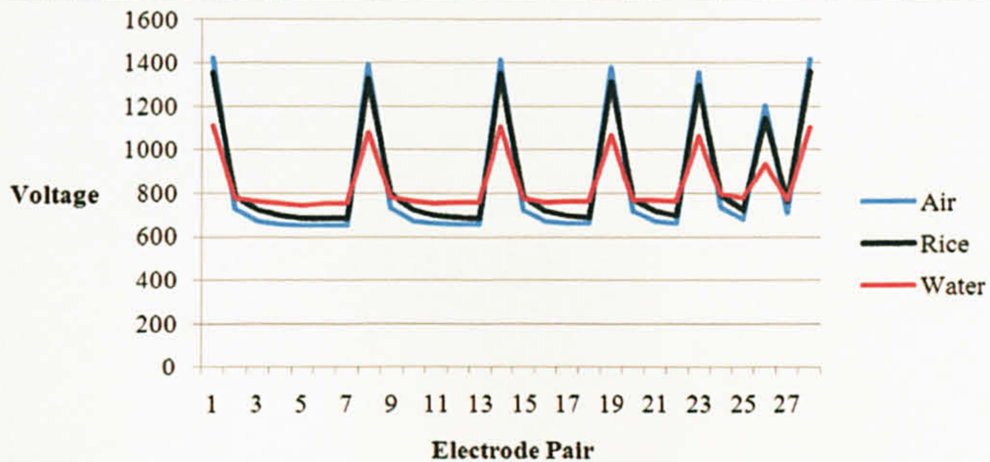
a. Symmetrical graph results
b. Clear low and high calibration image

The tomogram is based on the normalized value as below:

0  1

The calibration results of existing ECT sensor are shown in table below:

Table 7 Calibration Results

Types	Calibration result with *air* (ε=1)	Calibration result with *water* (ε=80)	Calibration result with *rice* (ε=5)
Graph Result			
Explanation	- Calibration with air is used for *Low Calibration*	- Calibration with water and rice is used for *High Calibration* as both of the elements are having higher permittivity compared to *air*	
Reference Voltage graph			

4.2 Fabricated Sensor Result

The fabricated ECT sensor was undergoing a testing process with MMTC and ITC Tomography Toolsuite. The purpose of this test is to check whether the sensor is working properly or not, thus calibration 0 is used as the key factor for this testing. However, the results are really dissatisfying and it is discussed as following:

i. First Trial

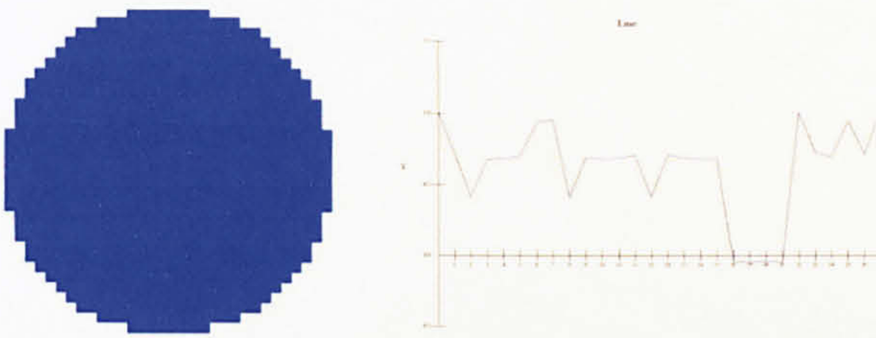


Figure 9 First trial result – tomogram and reference voltage graph

The tomogram result is showing perfect image, however the reference voltage graph is showing bad results which indicates that the sensor was having problem in acquiring the data.

ii. Second Trial

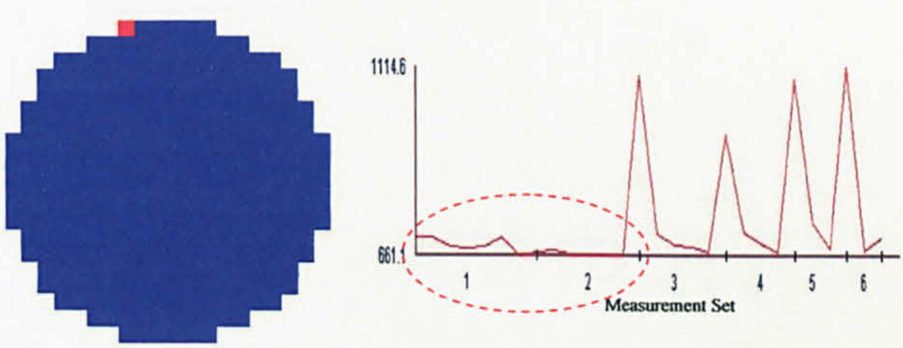


Figure 10 Second trial result – tomogram and reference voltage graph

The result in second trial is showing an improvement; however there were still problems with measurement set 1 and 2. This result might caused by the connection of the cable with SMB connector.

iii. Third Trial

In this trial, coaxial cable and SMB connectors are replaced with the new connection. And the result is recorded as below:

- Low Calibration
- High Calibration

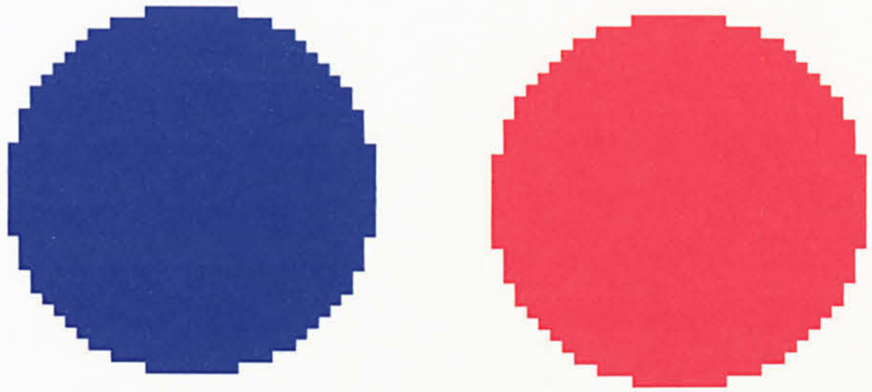


Figure 11 Third trial – tomogram images with low and high calibration

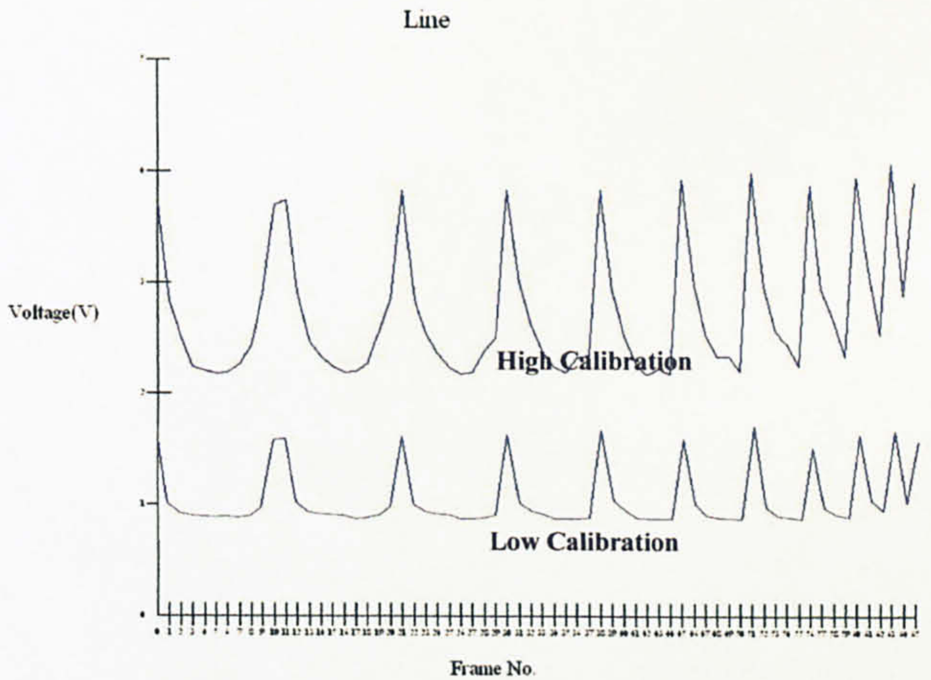


Figure 12 Results of reference voltage graph for high and low calibration

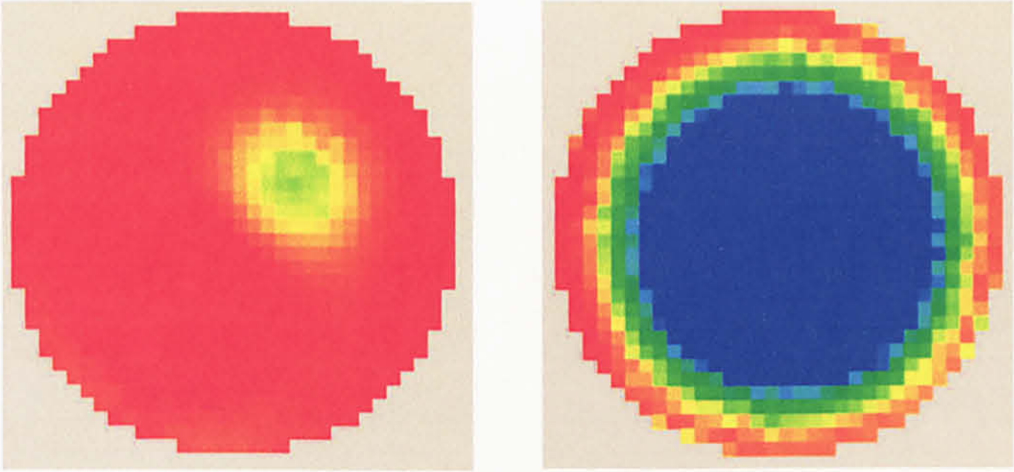
Since the ECT sensor is working well in third trial, the test is then continued with performing another three tests and recorded as following:

i. Conductivity Test

This test is conducted to observe the conductivity effect cause by the element that flowing through the pipe. Details of the test as below:

Low Calibration	: Empty (Air)
High Calibration	: Oil
Tester	: Empty PVC and Metal Rod

The results of testing are shown as following:



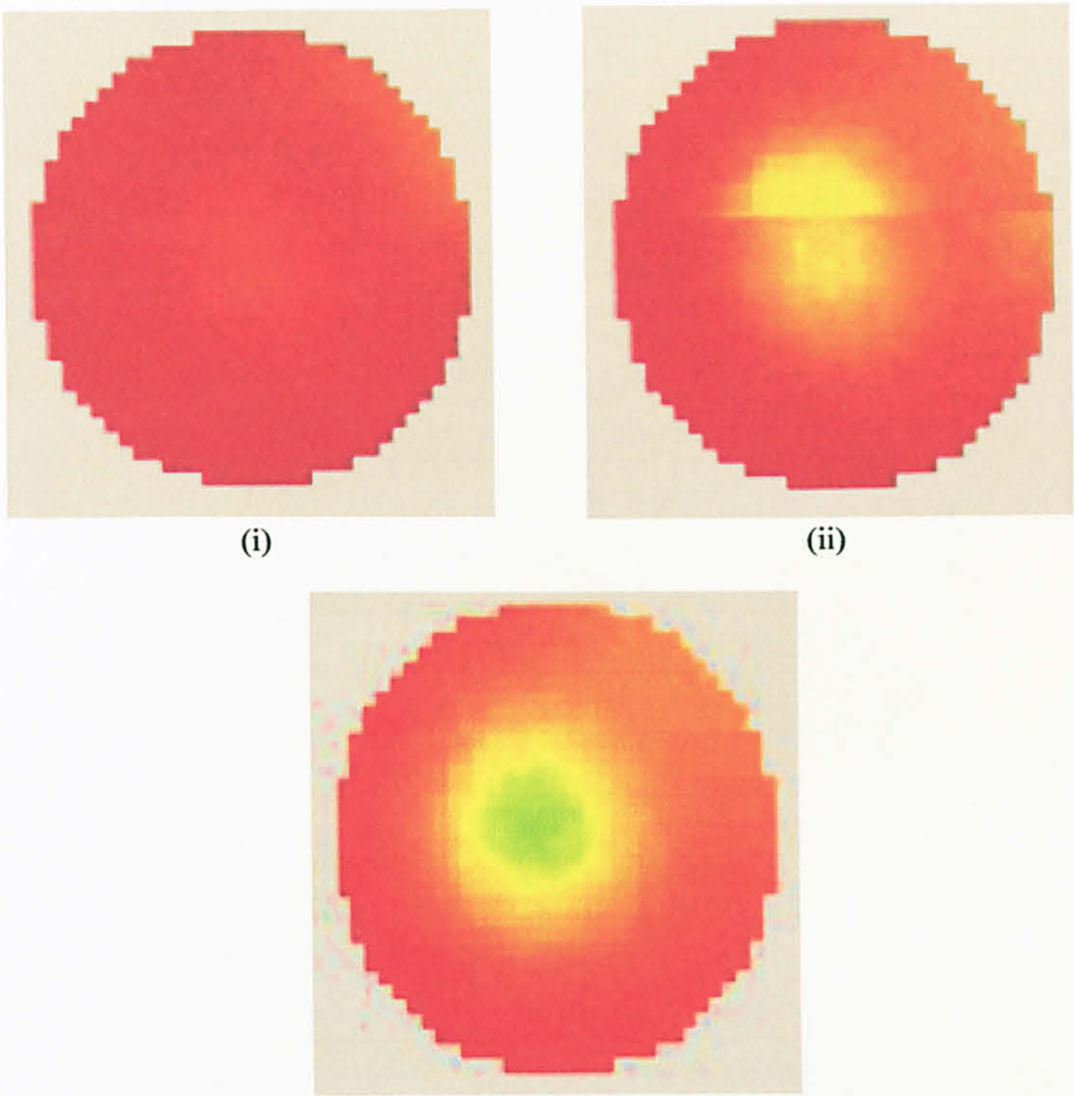
(i) (ii)

Figure 13 Tomogram of (i) PVC Rod and (ii) Metal Rod in Oil

From figure above, the conductivity effect can be clearly seen from the tomogram. The metal rod as conductive element was giving totally different tomogram if compared to the PVC rod. As known, ECT sensor is the most suitable for non-conductive element. Thus, if any of the conductive elements are flowing through the pipe, it will influence the type of tomogram itself.

ii. Online Measurement with Gas-in-Water

This test is conducted to observe the flowing of gas in water. The result is recorder as following:



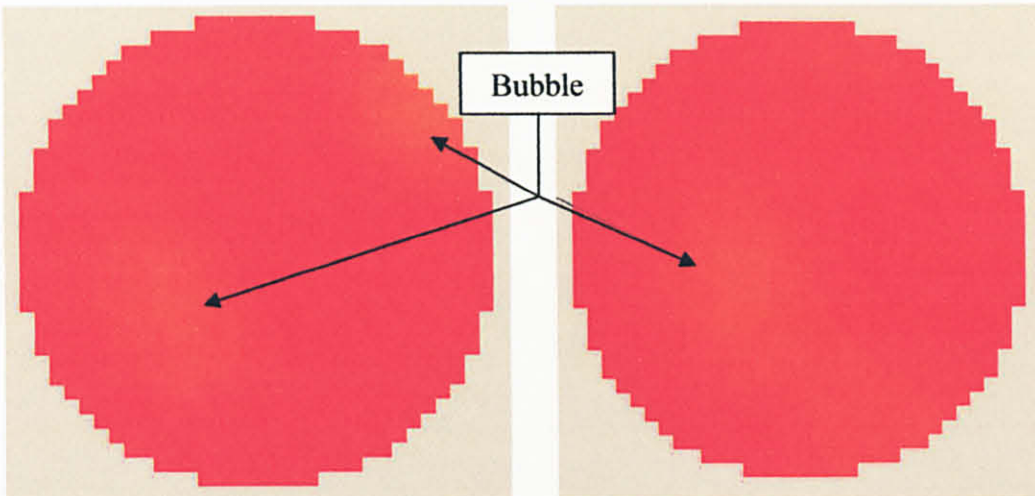
(i) (ii) (iii)

Figure 14 Tomogram with Gas-in-Water, (i) No bubble, (ii) Little bubble (iii) More bubble

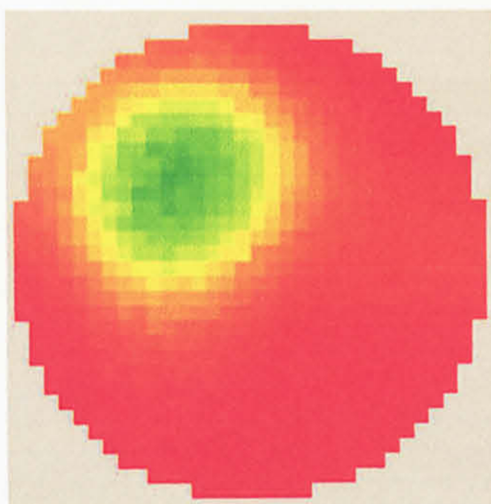
From figure above, it is observed that increasing the percentage of bubble would increase the size of bubble image in tomogram. Besides that, the author found that the value of measured capacitance with this test is in between 0 to 4.9pF. Typically, the value of measured capacitance is 0 to 1pF which means the sensor is having high sensitivity in measuring the capacitance between electrodes. However, this data is very limited as ECT sensor is best for non-conductive element but water is not.

iii. Online Measurement with Gas-in-Oil

This test is conducted to observe the correlation between gas in oil. The results are recorded as below:



(i) (ii)



(iii)

Figure 15 Tomogram with Gas-in-Oil, (i) Low bubble, (ii) More bubble (iii) Bubble near with the sensor

Since the bubble produces is not in high pressure, the result cannot be seen clearly from the test. However, better images could be seen if higher pressure of gas is supplied to the pipe. In Figure 15(iii) shows that as source of gas is brought nearer with the sensor, the size of bubble could be seen clearly through the tomogram.

4.3 Problem Solving

Based on author's observation, there are three matters should be emphasized in designing the ECT sensor as following:

- SMB Connector
- Coaxial Cable Connection
- Mechanical Construction

The connection of the coaxial cable and SMB connector is very important. It gives poor result if the connection is bad. This can be proven based on the comparison between second trial and third trial whereby when coaxial cable and SMB connectors are replaced, the result is better.

This problem can be encountered if extra precautions are taken during the fabrication process such as ensure the connectivity between the cable and electrodes are tight, also ensure that there is no connectivity between the earthed screen with the electrode because as discussed in previous chapter, the electrical field can be dragged to the earthed axial and screens.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The ECT sensor is designed generally used to determine the type of regime flow in oil and gas industries. However, in order to design a good sensor, there many aspects that should be taken into consideration. From this report, the author managed to observe the effect of a few aspects in designing the sensor and it is summarized as following:

i. 8 or 12 electrodes is the most simplest sensor to construct in Industrial Tomography.

ii. The length and width of the sensor should be measured according to the diameter of the pipeline.

iii. The connection of SMB connector, coaxial cable with the sensor should be taking care safely as any bad connection would affect the result of the reconstruction image.

iv. Earthed screen is the best method to reduce the noise and most importantly enable to limit the stray capacitance effect onto the results.

5.2 Recommendations

The results obtained are not sufficient enough to determine the reliability of sensor. Even though the sensor has been tested by using water and hydrocarbon oil, the results is still very limited due to the bubble produces by the "aquarium oxygen generator". For the next experiment, it is suggested to use high pressure of bubble in order to see better results of tomograms. Besides that, the author would like to suggest for the future researched to conduct test rig for Dynamic test as well as to develop a new data acquisition by using either LabVIEW or MatLAB.

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APPENDICES

APPENDIX A

DATASHEET COAXIAL CABLE RG-174

RG174AU

50 Ohm Coaxial Cables

PRO-POWER
Quality Cables

Features:

- Solid polyethylene insulated 7/34 AWG copper covered steel conductors
- Braid screened.
- Black PVC sheathed overall to MIL-C17.
- Use with SMB, SMC and MCX connectors.

Specification:

Nominal outside diameter	: 2.8mm.
Capacitance	: 101pF/m.
Maximum voltage (core to screen)	: 6kV dc.
(screen to sheath outer)	: 2.8kV dc.
Maximum RF working voltage	: 2.1kV peak.
Nominal attenuation (100m)	: 6.23dB at 400mHz.

Specification Table

Conductor Type*	CCS
Conductor Number / Dimensions	7/0.16
Insulation	Polyethylene
Insulation Diameter	1.52
Screen Braid**	TC
Screen Diameter	1.95
Sheath	PVC
Sheath Diameter	2.8
Weight (Kg/1000m)	13
Capacitance (pF/m)	100
Impedance (Ω)	50
Attenuation dB per 100 meters at	
400MHz	57.5
Velocity Ratio	0.666

Dimensions : Millimetres (Unless Specified)

Key

*CCS - Copper Covered Steel
**TC - Tinned Copper

Part Number

Colour	Reel Length (m)	Part Number
Black	50	RG174/AU 50M
	100	RG174/AU 100M
	500	RG174/AU 500M

PRO-POWER
Quality Cables