OIL-IN-WATER ANALYZER USING ELECTRICAL CAPACITANCE TOMOGRAPHY

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OIL-IN-WATER ANALYZER USING ELECTRICAL CAPACITANCE TOMOGRAPHY (ECT)

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
June 2009

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.

LYE SUET YENG

ABSTRACT

Electrical Capacitance Tomography (ECT) is a non-intrusive measurement technique. It visualizes the phase distribution in closed pipes or vessels by measuring the variations in the dielectric properties of materials in within. Dielectric constant (ε_r) measured is the main concern in determining the type of material. The objective of this project is to develop ECT sensors and evaluate performance of different sensor designs. Capacitance sensors are designed and simulated using COMSOL software. COMSOL simulation gives a visualization of the potential distribution within the measuring area. Four types of sensor designs – with radial screen, without radial screen, internal electrodes and external electrodes sensors are simulated. Next, two types of sensors are fabricated – sensor with internal and external electrodes. The capacitance sensors are calibrated and experimented with various oil-in-water distributions. Data is obtained through the ITS M3000 multi-modal data acquisition unit and computer with M3000 software. Simulation results show that sensor with radial screen and sensor with internal electrodes perform better. Meanwhile, experimental results show both internal and external electrodes sensor designs are capable in visualizing static and dynamic oil-in-water distribution. As a conclusion, designed sensors are able to provide visualization of oil-in-water. Approximate visualization is achieved but image reconstructed do not show the exact oil-in-water distribution.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Tomography imaging of an object is widely used in different industries, especially in medical and engineering field. In engineering field, tomography technique is well-known for its non-invasive and non-intrusive characteristic. It is ideal for monitoring, measuring and controlling industrial process without interrupting the flow.

Electrical Capacitance Tomography (ECT) is one of the measuring techniques derived from the tomography imaging. According to Flores *et al.* (2005), physical arrangement of a basic ECT system consists of three major parts: capacitance sensor, data acquisition unit and a control computer (see Figure 1).

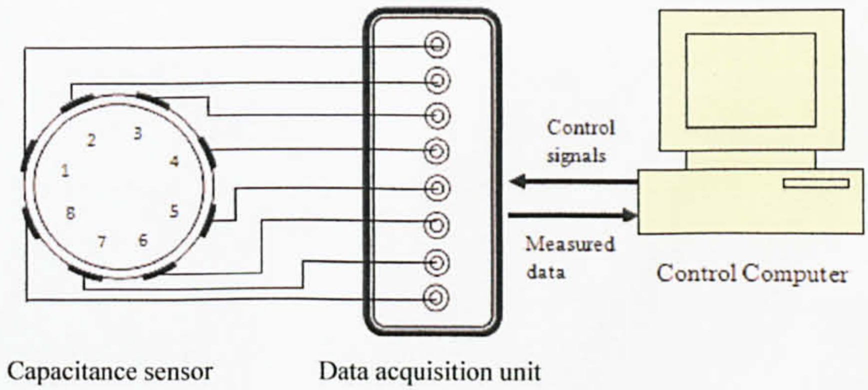


Figure 1: Basic tomography system

The capacitance sensor measures the permittivity of the materials inside the enclosed pipe or vessel. Number of electrodes is different according to the application. Every capacitance sensors are connected to the data acquisition unit through a high-speed serial links. Meanwhile, high speed USB link cable connects the data acquisition unit to the control computer. Data from the unit is then sent to a control computer for data storage, processing and display (ITS, 2004).

There are increasing demands from the industry for accurate and instantaneous data of multiphase flow, especially in the petroleum industry. Hwili and Yang (2007) pointed out that the crude oil extracted from undersea contains a certain amount of water. Due to the high cost of transporting the oil to seashore for separation process, it is better to separate oil from water at the platform. Limited space available on the platform demands a dynamic oil-in-water visualization system. This system contributes to a more effective process planning.

Oil and water are different in their dielectric properties, especially the permittivity value. The relative permittivity value for water (high permittivity) is around 80 while the relative permittivity is 2.1 for petroleum oil (low permittivity) (Ulaby, 2005). ECT technique is suitable for to two different liquids with huge difference in permittivity. In this project, ECT is used for oil (low permittivity) and water (high permittivity) distribution measurement.

1.2 **Problem Statement**

In the petroleum industries, pipelines and vessels are used to transport materials. In most conditions, it involves multi-phase flow (Hasan & Azzopardi, 2007). Measurement and on-line visualization of oil and water distribution is important to provide an actual data on the productivity. Currently, there are two types of measurement techniques, namely destructive and non-destructive techniques. Destructive techniques are not favorable because it involves separation of materials before the measurement is taken. In this case, the data obtained is no longer up-to-date. In fact, the multi-phase flow data is usually used for the separation process planning.

In general, direct in-line analyzer with non-destructive technique is preferable in upstream. Table 1 summarizes the types of non-destructive analyzer. Though being insensitive to conductivity variation, microwave techniques are applicable to both oil-in-water and water-in-oil condition (Pal, 1994). Electrical techniques include capacitance, impedance and conductance-based techniques. The advantages of these techniques are fast in response, inexpensive compared to other methods and safe.

Radiation related techniques are considered reliable. However, Pal (1994) highlights the health and safety concerns regarding its radiation source. As for density techniques, he also points out the problem which emulsion density becomes independent of the composition when the density of oil and water are indifferent. Meanwhile, viscosity techniques are not widely-used because it is dependent on droplet size and distribution, nature and concentration of surfactants, presence of electrolytes and etc. This method requires cautious control on the variables mentioned above.

Table 1: Non-destructive analyzer

No	Name	Remarks
1	Electrical	Fast in response, relatively inexpensive, safe
2	Microwave	Insensitive to conductivity (salt content) variation
3	Radiation scattering	Safety concerns of its radiation source
4	Density	Independent of composition when then density of oil and water are same
5	Viscosity	Dependent on droplet size and distribution, nature and concentration of surfactants, presence of electrolytes.

1.3 Objectives

The following objectives are expected to achieve through project:

- To study on ECT system as an oil-in-water analyzer.
- To build capacitance sensors and investigate the effects of different sensor designs.
- Sharpen the skill of trouble shooting and gain knowledge.

1.4 Scope of Study

Throughout this project, knowledge and theory learned is much involved. The scope of study includes:

- Background and theory of ECT system.
- Overall operation of ECT system.
- Measurement algorithm of ECT.
- Concept and knowledge in electromagnetic for capacitance sensor design.

CHAPTER 2
LITERATURE REVIEW

2.1 Electrical Tomography

There are a numbers of non-destructive measurement techniques using the electrical methods. Oil and water in a mixture exhibit vast difference in their electrical properties. By measuring their electrical properties such as capacitance and conductance, the mixture distribution can be calculated.

2.1.1 *Electrical Impedance Tomography (EIT)*

EIT is another measurement technique used to obtain the concentration distribution. Electric currents are injected through the electrodes and the resulting currents are taken as raw data. It is a relatively simple and inexpensive technique (Wang, Yin, & Holliday, 2002). However, Wang *et al.* (2002) also mentioned that EIT would not be giving accurate data for stratified flow or an intermittent flow in a horizontal channel or large bubble formation and foams. This happens when some of the electrodes lose contact with the conductive fluid.

2.1.2 *Electrical Resistance Tomography (ERT)*

Dong *et al.* (2003) agrees that ERT measurement precision sometimes may be poor. However, he also pointed out some strengths of ERT compared to other technique.

1. ERT can provide two or three dimensional information on two-phase flow and thus more information.
2. Phase distribution can be reconstructed at various times.
3. Feasible to find precise method to estimate flow parameter by statistical analysis or pattern recognition.

2.1.3 *Electrical Capacitance Tomography (ECT)*

ECT has the advantages of no radiation, rapid response, low cost, being non-intrusive and non-invasive characteristic (Ismail *et al.*, 2005). Pal (1994) stated capacitance measurement has issue of high standing capacitance (stray capacitance) which results in low sensitivity of measured capacitance signal. In many situations, the stray capacitance can be much larger than the capacitance of the fluid being monitored. It is important consider the stray capacitance and minimize it in order to improve the sensitivity and accuracy of measurement. Furthermore, this method is generally restricted to oil external mixture. Table 2 reviewed on the advantages and disadvantages of EIT, ERT and ECT measurement techniques.

Table 2: Characteristics of EIT, ERT and ECT

	Advantages	Disadvantages
EIT	Simple and inexpensive	Inaccurate for stratified flow or intermittent flow in a horizontal channel / large bubble formation and foams
ERT	Provide 2D and 3D flow, phase distribution can be reconstructed,	Low measurement precision but it is feasible to find precise method
ECT	No radiation, rapid response, low cost, non-intrusive and non-invasive	Issue of stray capacitance and limited to measure oil mixture

2.2 Capacitance and Permittivity

A capacitor is formed when any two conducting bodies (regardless of the shapes and sizes) separated by an insulating (dielectric) medium (Ulaby, 2005). When a voltage source is supplied to the conductors, charge of equal and opposite polarity is transferred to the conductors' surface as shown in Figure 2. To ensure a conductor as an equipotential body, excess charge distributes on the surface to maintain a zero electric field everywhere within the conductor. Thus, the electric potential is the same at every point in the conductor.

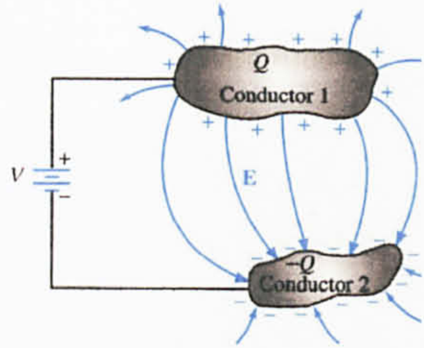


Figure 2: Voltage source connected to electrodes

Capacitance can be defined as the magnitude of charges on both electrodes (Q) divided by the potential difference between the electrodes (V). Capacitance is also defined as a function of distance between two electrodes (d), area of the plate (A) and the constant of the dielectric ($\mathcal{E}_r$) and free space ($\mathcal{E}_0$).

$$C = Q/V \tag{1}$$

$$C = (\mathcal{E}_r \mathcal{E}_0 A)/d \tag{2}$$

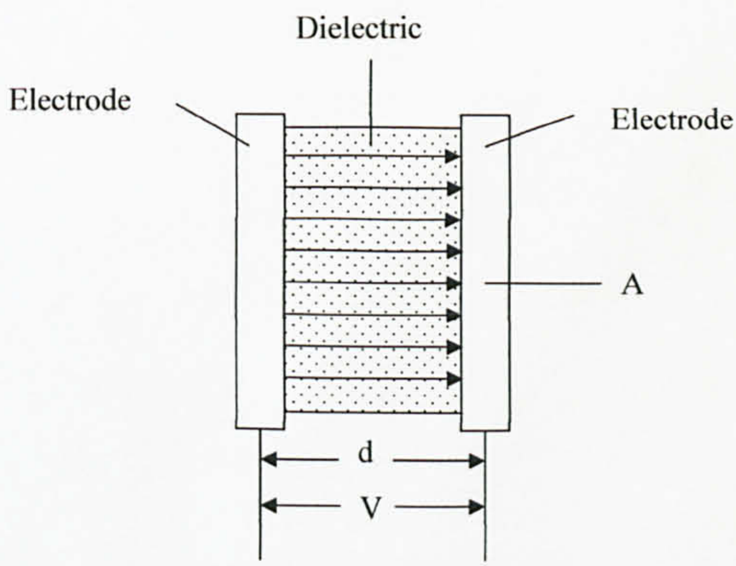


Figure 3: Electric charge and voltage of capacitor

Any insulator placed between the plates will cause the capacitance increase by a particular factor. The factor by which the capacitance is increased is the relative permittivity of the material between plates. Permittivity is defined as the material's ability to "permit" an electric field.

The concept of ECT is based on capacitance and permittivity of the medium within the vessel / pipe. Since the permittivity of each measured element is a constant, the measured element can be identified by knowing the capacitance / voltage between the electrodes.

2.3 ECT Sensor

Figure 4 is based on a common case of electrodes placed around the outer wall of the pipe. The function of different parts of the sensor is as listed below (Hasan & Azzopardi, 2007):

- Screen – Prevent interferences between the sensor's applied signal and any devices present near the capacitance sensor.
- Electrode – Initiate the charge and detect capacitance between two electrodes.
- Projected guard – Reduce stray capacitance between back surfaces of adjacent electrodes.

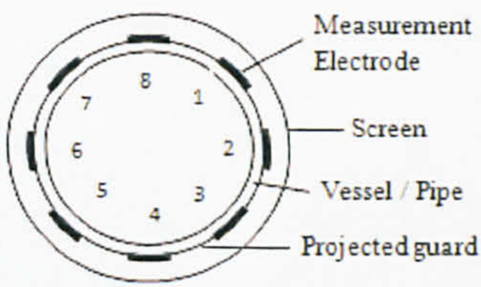


Figure 4: Cross section of a sensor

While other shapes of ECT sensor have been used, most ECT sensors are in circular shape. Usually, the diameter of an ECT sensor is between 2.5cm and 10cm (Yang, 2006). Figure 5 shows the choices of sensor design discussed by (Pal, 1994).

(I) A pair of parallel metallic plates placed inside the pipe or mounted on the outside (non-conductive) pipe wall.

(II) A pair of concave metallic plates placed inside the pipe or mounted on the outside (non-conductive) pipe wall.

(III) A series of concave metallic plates placed staggered spirally around the outside (non-conductive) pipe wall.

(IV) A pair of continuous metallic helices mounted on the outside (non-conductive) pipe wall.

(V) Three pairs of continuous metallic helices mounted on the outside (non-conductive) pipe wall and connected alternatively in parallel.

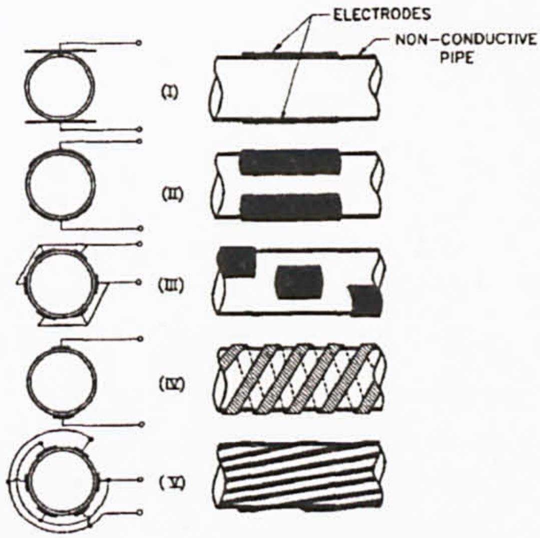


Figure 5 Electrode sensors

There are four main issues to consider when designing a sensor – number of electrodes, length of electrodes, external or internal electrodes and earthed screen.

2.3.1 *Number of Electrodes*

There are trade-offs when considering the number of electrodes used. Commonly, 8 and 12 electrodes are used for ECT sensors. For higher image resolution, people consider the optimum number of electrodes because the increase of electrode generates more number of independent measurements. However, there are a few benefits of using less number of electrodes. Firstly, hardware design can be simplified by reducing the number of data acquisition channel, coaxial cables and SMB plugs. Next, there will be less data acquisition and processing time because the number of independent measurement is reduced (Yang, 2006).

Figure 6 Width of electrodes

The length of electrodes can also be reduced by having less number of electrodes. As we reduce the number of electrode, each independent width of electrode can be increased as well. The inter-electrode capacitance is proportional to the area of electrode. To maintain the inter-electrode capacitance, we can increase the width meanwhile reducing the length. The relevancy of electrode length with sensor performance is discussed at the following part.

2.3.2 *Length of Electrodes*

Shorter electrode is more sensitive to the dynamic flow. However, by reducing the length, the inter-electrode capacitance is reduced as well. It is important to make sure that the smallest capacitance is able to be measured by the capacitance measuring circuit. It is impossible to reduce the length to the μm or mm value, considering that currently the smallest capacitance can be measured is 0.8aF (Yang, 2006). Typically, length of measurement electrodes is around twice the diameter of the sensor. In this case, the fringe effect at the two axial ends can be ignored and the inter-electrode capacitance is independent of the diameter of the sensor.

2.3.3 *External or Internal Electrodes*

There are two types of sensor design – invasive and non-invasive. External electrodes are considered non-invasive because it has no direct contact with the measurement area. Internal electrodes are invasive. Non-invasive sensors are subject to coating wax, dirt and etc while invasive sensors have higher sensitivity. Thinner wall gives the better sensor performance because the wall capacitance is effectively in series with the internal capacitance (Yang, 2006).

Niu *et al.* (2004) discussed the followings shortcoming of sensor with external electrodes:

i) Introduce pipe wall parasitical capacitance which is difficult to immune.

ii) Increase the distance between every electrode pair and the capacitance become smaller.

iii) Sensitivity map of neighbor electrodes sometimes gives negative values.

iv) Image reconstruction is more difficult because of the permittivity of pipe wall (ε_{pw}) existing.

2.3.4 *Earthed Screen*

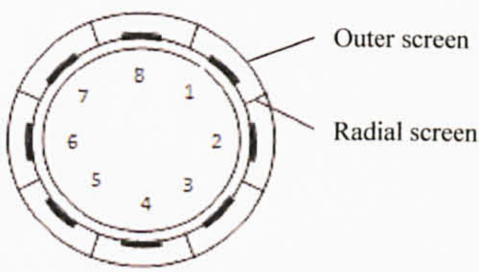


Figure 7: Sensor with radial earthed screen

Beside the outer screen, there are axial end screens and radial screens. Axial end screens are placed at the both ends of measurement electrodes to reduce external noise. However, Yang (2006) pointed out the earthed axial screens have a negative effect on capacitance measurement because the electrical field is dragged to the earthed axial end screens. Earthed radial screen is the grounded electrodes placed in between the measurement electrodes to more effectively eliminate the stray capacitance between back surfaces of adjacent electrodes (Ismail *et al.*, 2005). The stray capacitance affecting adjacent electrodes is significantly reduced.

2.3.5 *COMSOL simulation*

Fuchs (2007) had done a simulation-based analysis using commercial FEM software COMSOL Multiphysics. The software is used to calculate the sensitivity of the ECT system. Besides, Flores (2005) and Hwili (2007) also designed the electrical capacitance verified by simulation using COMSOL. Hwili concluded the following based on simulations using COMSOL:

- Sensitivity is higher if the distance to electrode decrease.
- Segmented electrodes are able to calibrate each other and to give a more accurate data.
- Capacitance decrease with the decreasing of electrode size.

2.4 **Measurement**

The cross section to be images is surrounded by a set of capacitance electrodes and the electrical capacitances between all combinations of the electrodes within each set are measured (http://www.tomography.com). Materials of the cross section inside the pipe enclosed by sensor have varies permittivity. The measured data is then sent to data acquisition unit.

There are various types of measurement strategies. A commonly used method is normal adjacent. Voltage is applied through an electrode and the permittivity between the initialized electrode and other electrodes are measure. For example, when the first electrode is initialized, the voltage between first and second electrode is measured. This 1-2 voltage measurement continued with 1-3, 1-4 … 1-8 voltage measurements. After completing 2-3, 2-4, 2-5 … until 7-8 voltage measurement, it is considered one set of data.

These steps are repeated by initializing the other electrodes. For N number of electrodes, there are N (N-1)/2 measurements taken. Referring to Figure 8, a 12-electrode sensor has 66 independent measurements.

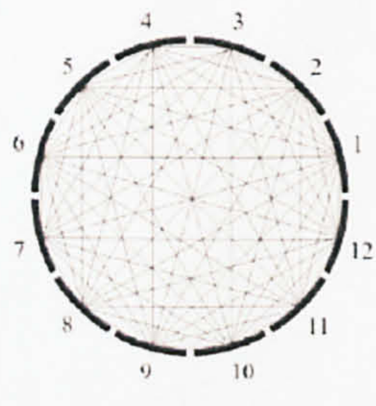


Figure 8: 66 measurements for 12-electrode sensor

2.5 **Oil-in-Water Flow**

Multiphase flow study is important in the later part of this project when the sensor is used to measure the flowing fluids. Commonly seen flow patterns are as followed (Angeli & Hewitt, 2000):

i. Stratified : Low density material is on top of the high density material.

ii. Annular : One phase forms the annular in the middle part of the pipe.

iii. Three-Layer : There are obvious oil and water layer at the top and the bottom. The third layer appears in between the oil and water, where drops of each phase appear within the other phase.

iv. Bubble : Low fraction material forms bubbles in the high fraction material.

v. Mixed : One phase is dispersed almost uniformly into the other and occupies a whole pipe cross section

CHAPTER 3
METHODOLOGY / PROJECT WORK

3.1 Research Methodology

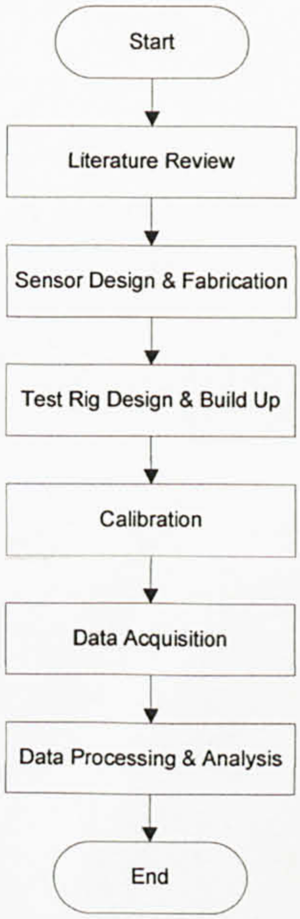


Figure 9: Research methodology

The research methodology for the final year project is meant to be conducted in two semesters. In the first semester, literature reviewed and design for sensor and test rig are done. The modeling of sensor is conducted in both semesters. For the rest, it is carried out in the second semester.

3.2 Project Activities

Gantt chart and key milestones is attached in Appendix A of this report. The main stages in this project include literature review (Chapter 2), sensor design and modeling, test rig design and build-up, data acquisition, data processing & analysis will be discussed in Chapter 4. In the first semester of final year project, oil-in-water mixture is experimented using ECT equipments in the laboratory. Steps of calibration, data acquisition, processing and analysis can proceed without going through the sensor fabrication.

3.2.1 *COMSOL simulation*

The sensor is designed using COMSOL software. In COMSOL, the capacitance sensor is defined as an electrostatic problem. According to Flores (2005), the three-dimension model of sensor is possible to represent by a two-dimension model. During this step, the number of sensors used, sensor placement, shape and other details are determined. Simulation run by COMSOL gives visualization on the voltage distribution within the measurement area when the electrode is initialized.

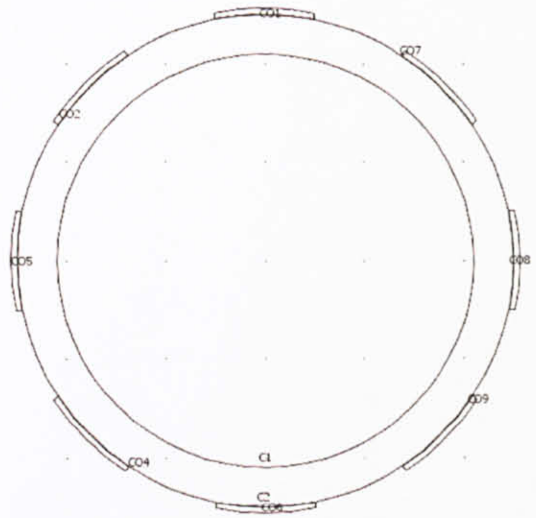
Geometry drawing is created using graphical user interface (GUI) of the software. It is based on 8-electrodes sensor where each electrode occupied 30° of the pipe wall. Three major parts in this design flow are (1) geometry drawing (shown in Figure 10a); (2) boundary conditions assignment; (3) defines the subdomain conditions.

For boundary condition assignment, three types of boundary conditions are defined. Figure 10b shows the arrangement of each boundary condition when the first electrode is initialized. Grounded boundary (blue), initialized boundary (green) and continuity boundary (red) are using the equation 3, 4 and 5 respectively.

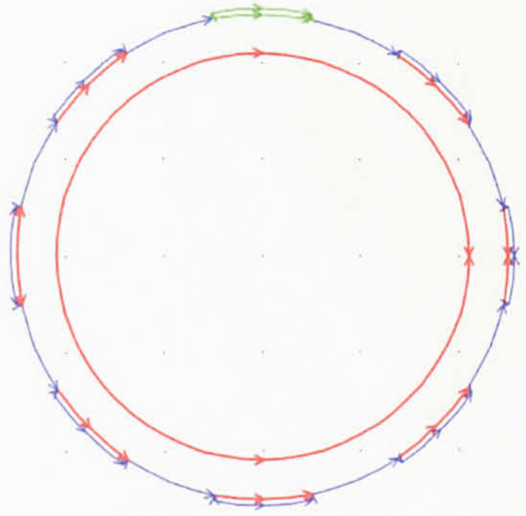
$$V = 0 \tag{3}$$

$$V = V_0 = 2V \tag{4}$$

$$n.(D_1 - D_2) = 0 \tag{5}$$



(a) Geometry drawing



(b) Boundary settings

Figure 10: Geometry drawing and boundary settings

Equation 6 is used for the electrostatics model in defining the subdomain condition. Relative permittivity of copper electrodes and pipe is defined as 1 and 2.9 respectively. The measuring area is set to permittivity 1 for air-filled pipe.

$$-\nabla.\varepsilon_0\varepsilon_r\nabla V = \rho \tag{6}$$

The electric potential $\emptyset$ within the sensor is calculated by solving the following second order partial differential equation 7 (Flores *et al.*, 2005) where $\emptyset(x,y)$ is the potential distribution in two dimensions and $\varepsilon(x,y)$ is the relative permittivity distribution in two dimensions.

$$\nabla.[\varepsilon(x,y)\nabla\emptyset(x,y)] = 0 \tag{7}$$

By solving equation 7, the potential distribution $\varepsilon(x,y)$ is obtained within the sensor. A way to calculate $\varepsilon(x,y)$ is using finite element method (FEM) as shown in Figure 11. This method gives an approximation to the potential $\emptyset$ in the sensor at a finite set of points. The finite set points are determined by corresponding nodes of triangular mesh. After the potential distribution is obtained, the electric charge Q_j on each detector electrode is calculated by using Gauss Law (Flores *et al.*, 2005).

$$Q_j = \oint(\varepsilon(x,y)\nabla\emptyset(x,y).n)ds \tag{8}$$

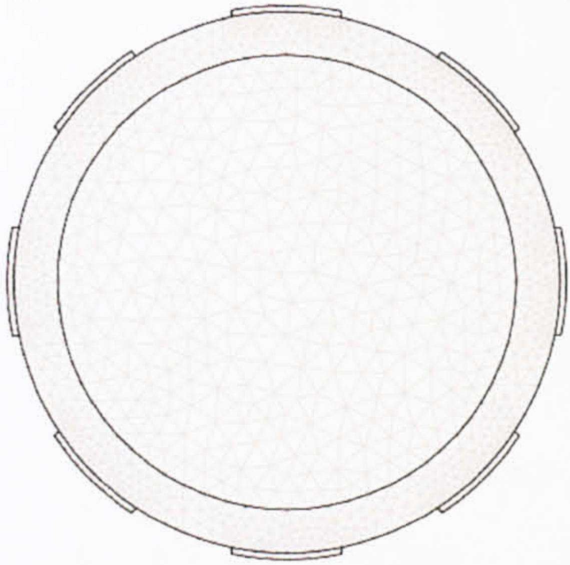
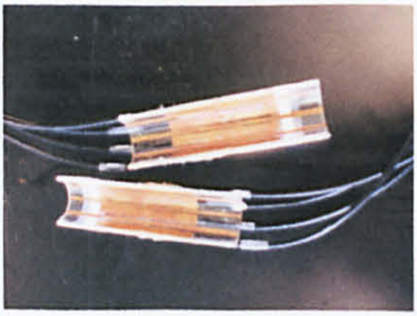


Figure 11: Finite element method

3.2.2 *Sensor Fabrication*

The design step is followed by its fabrication. During the fabrication, precise measurements are taken so that the parts and pieces can be assembled as planned. The specifications are confirmed to make sure the functionality matches the purpose.

Copper electrodes are placed at the inner wall of the pipe to increase the accuracy of measurements by neglecting the effect of wall thickness. The acrylic pipe is cut into half (see Figure 12a) and the reassemble back to enable the copper foil stick at the inner wall. Another sensor has the electrodes at the outer pipe wall.



(a) Acrylic cut into half

(b) Electrodes reside at the inner wall

Figure 12: Internal-electrodes sensor fabrication

Data cable RG-174 is the coaxial cable used to transfer capacitance data from the electrode to the data acquisition unit. Figure 13 shows the components of the cable. The use of coaxial cable is able to reduce the stray capacitance around the vessel and along the cable itself.

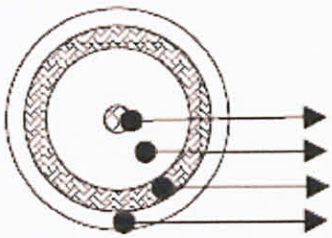
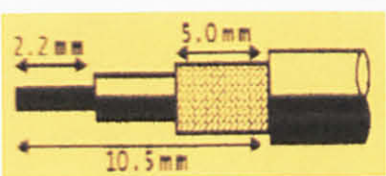


Figure 13: Components of RG-174 cable

The conductor of the data is soldered to the electrode of sensor by drilling a hole through the acrylic pipe. Meanwhile, the other end of the coaxial cable is connected to SMB straight female crimp plug according to the specification shown in Figure 14a.



(a) Connection specification

(b) RG-174 connected to SMB

Figure 14: RG174 cable and SMB plug connection

3.2.3 *Test Rig Design & Set up*

The purpose of building a test rig is to examine the sensor performance in measuring a dynamic oil-in-water flow. Referring to Figure 15 and 16, the fabricated sensor is placed before the mixture tank. Sensor electrodes are connected to the data acquisition unit. The pumps are immersed into oil and water respectively. It is connected to different flow meters to measure its flow. A valve is located after each flow meter to control the liquid flow.

However, flow meter used to measure the oil flow is removed when the experiments are carried out. This is mainly due to two issues. Firstly, the conventional flow meter is applicable for water-flow measurement only. Using it to measure the oil flow causes inaccuracy. Secondly, the oil pump is not powerful enough to pump up the oil when the flow meter is installed. During the designing stage, the difference of water and oil viscosity is overlooked. The oil used for this experiment is having viscosity of 2.19mm²/s compared to water viscosity of 0.001mm²/s. It needs a much larger power pump for oil.

When the flow meter is installed, the friction is further increased; thus the pump is not strong enough to pump up the oil. This problem did not occur before the flow meter installation. To overcome this problem, the flow meter was replaced by a pipe of same height. The oil-flow was measure manually.

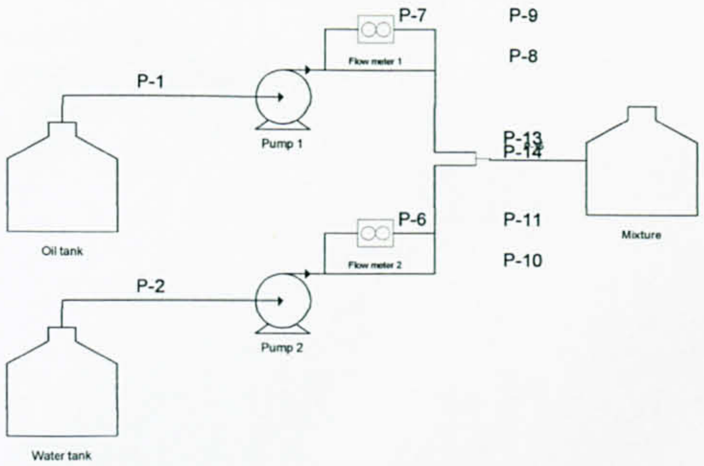


Figure 15: Test rig design

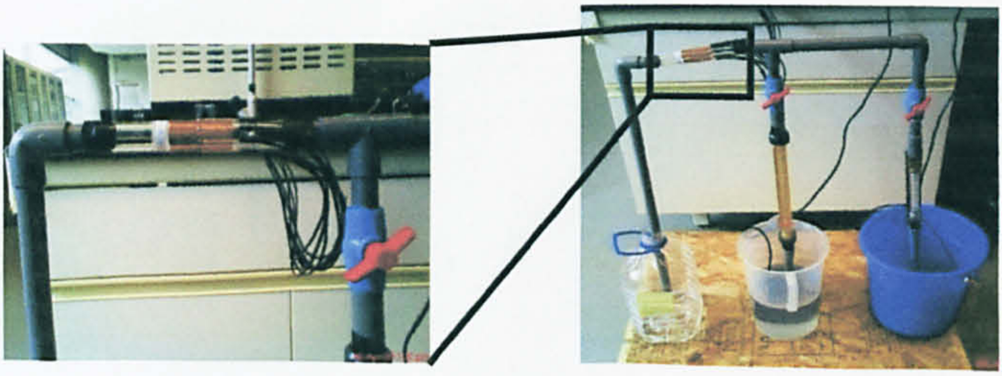


Figure 16: Experiment Setup

3.2.4 *ECT Equipments*

Calibration, data acquisition and processing are done using the ECT equipments in laboratory. With the data acquired from the experiment, built-in software processed the data in to graphs and images. Raw and processed data are then analyzed.

Figure 17 shows the ECT equipment facility available in the laboratory. The ECT equipments are consists of three major parts: data acquisition unit (left), capacitance sensor (middle) and data processing unit (right).

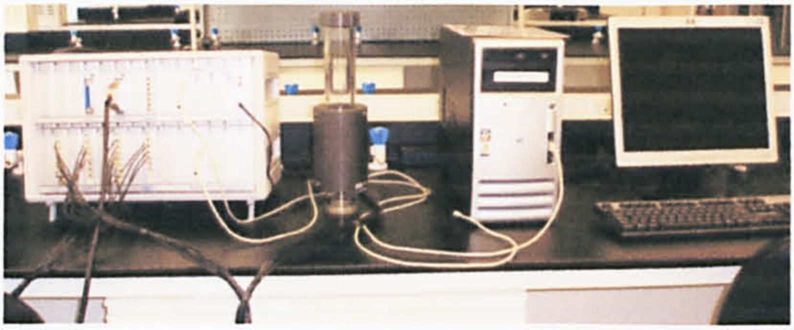


Figure 17: ECT equipments

A pre-defined flow (see Figure 18) of Ect-onep-1 is used. This flow analyze on one plane; 12 electrodes per plane. Its functions include online measurement, display and save. The settings in each step are as followed:

Protocol	: Number of electrodes, current inject base, voltage inject base and array size.
Calibration	: Low / High calibration, measurement.
Acquisition	: Pipe width, min and max permittivity, number to average and time interval.
Others	: Location of save the data.

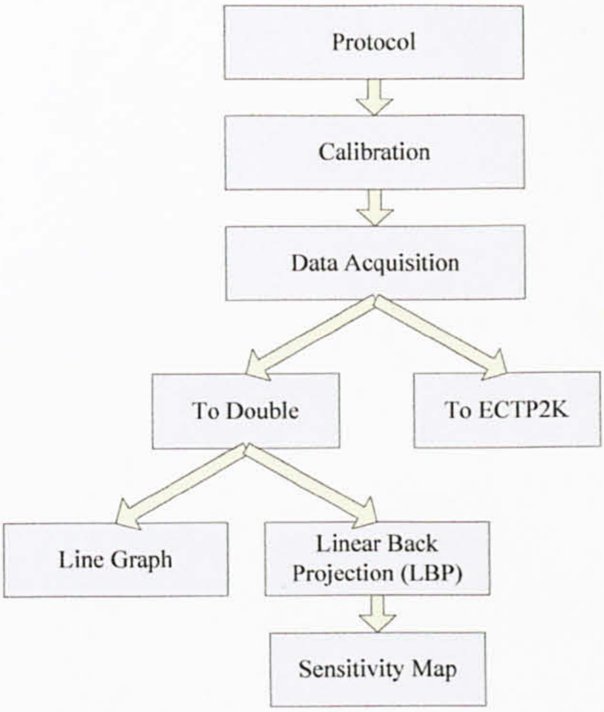


Figure 18: Pre-defined flow

3.3 Tools Required

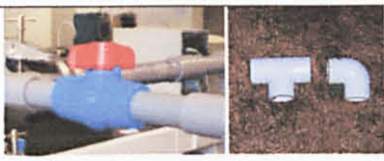
Software required in assisting in the design and simulation is COMSOL. The commercial finite element method software COMSOL Multiphysics version 3.3 was used to generate voltage distribution image of design sensors. For sensor fabrication, tools listed in Table 3 are used. Equipments required for building up the test rig is shown in Table 4.

Table 3: Tools for sensor fabrication

No.	Tools	Description
1.	 Data cable (Appendix B)	50Ω RG174U coaxial cable used for radio frequency.
2.	 Plug (Appendix C)	SMB 50 Ω straight female crimp plug with connectors in clamp and crimp termination options. Reliable and quick connect system.

3.	 Crimping tool	To crimp plug onto RG174U data cable.
4.	 Acrylic pipe	Transparent acrylic pipe to allow flow observation. Diameter of 1 inch is same as the diameter of test rig PVC pipe.
5.	 Soldering gun and lead	To solder one termination of data cable onto copper foil and another termination to plug.
6.	 Copper foil (Appendix D)	AT526 35μ Copper Foil Shielding Tape coated with an electrically conductive acrylic adhesive supplied on a removable silicone liner.
7.	 Silicone sealant	To seal the connections of acrylic pipe.

Table 4: Tools for test rig setup

No.	Tools	Description
1.	 PVC pipe	Diameter of 1 inch to fit the acrylic pipe. Light, economical, available, and easy to cut and connect.
2.	 PVC valve and connectors	PVC ball valve of 1 inch. Connectors needed are 1 inch T-connector, L-connector and straight connector.
4	 Flow meter	CT Platon vertical water flow meter with measurement range from 0.2 liter/min to 40 liter/min.
5	 Exxsol D80 (APPENDIX E)	Kerosene with density of 0.769kg/dm^3 and viscosity of 2.19mm^2/s.
3	 Pump (Appendix F)	At-104 pump with maximum pump rate of 1800 liter/hour.

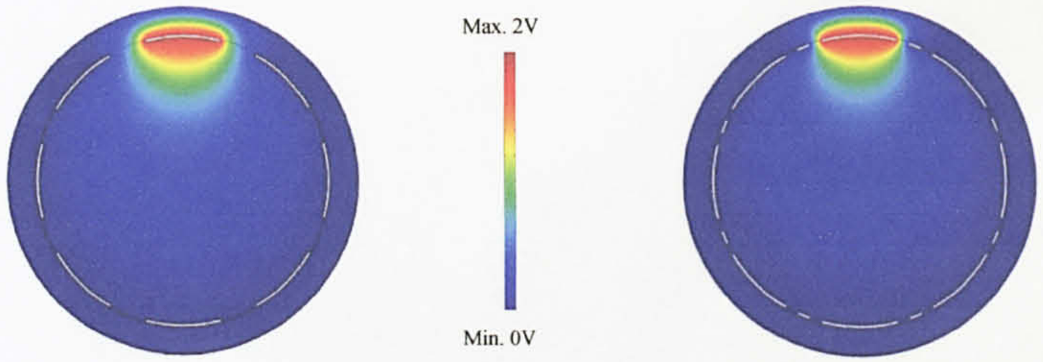
Exxsol D80 is used as oil component in the oil-in-water experimental set up discussed by Azlina (2006) and Angeli (1999). Both papers discussed the oil-in-water flow pattern in defined velocity, water fraction and types of pipe. However, due to delayed transportation of this material, it is not used in experiments carried out. As a substitution, palm oil is used as the oil component instead of Exxsol D80.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Sensor Design

COMSOL uses finite element method (FEM) to calculate the potential distribution. When one electrode is initialized, voltage is not evenly distributed to the measurement area. The nearer distance to the initialized electrode will have higher voltage distribution.

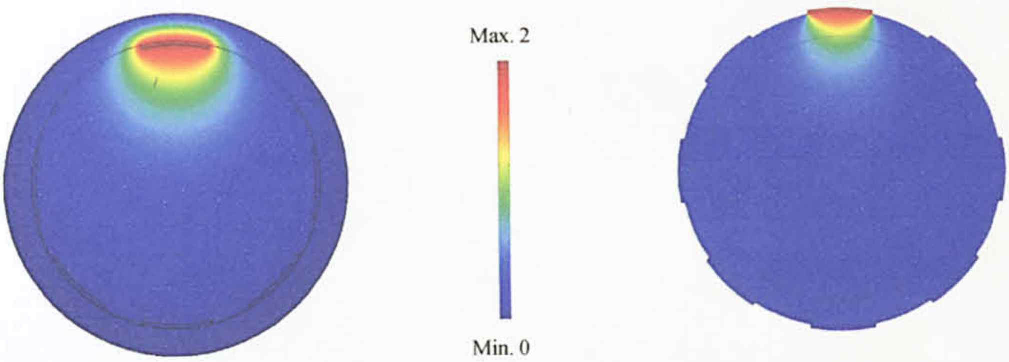
Two types of sensors are simulated using COMSOL – with radial screen and without radial screen. It is observed that sensor with radial screen is less likely to be affected. Earthed radial screen protect other measurement electrodes from interferences of unwanted electromagnetic fields.



(a) with radial screen **(b) without radial screen**

Figure 19: Sensor with and without radial screen

The voltage distributions of both internal and external electrodes are shown in the following figures. For the sensor with mounted electrodes at the inner wall, the media in the pipe can be measured directly. Meanwhile, the pipe wall's thickness has negative impact on the measurement. The capacitance characteristic of pipe wall is measured as part of the oil-in-water flow, which results in lower accuracy. Thus, whenever possible, the electrodes should be mounted at the inner pipe / vessel wall.



(a) with internal electrode **(b) with external electrode**

Figure 20: Sensor with internal and external electrodes

4.2 Measurement

The measurement was taken through the capacitance sensors and data acquisition unit. Figure 25 shows an example of the measurement taken and arranged by ITS Toolsuite. As discussed, 8-electrode sensor generates 28 independent measurement data. The data is used to generate the line graph and sensitivity map. As an alternative, the raw voltage and capacitance can be exported out to further manipulate the data.

Voltage Measurement Points

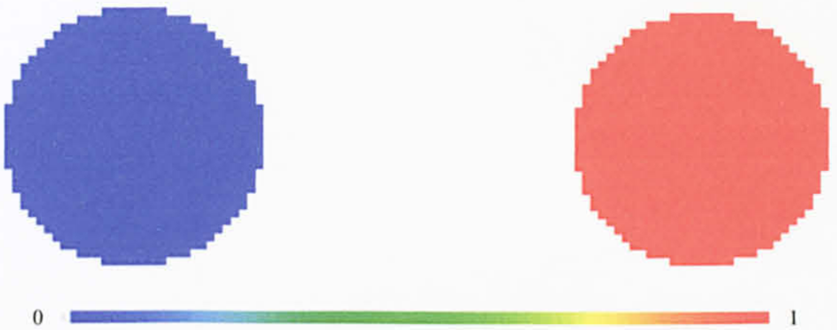
	02	03	04	05	06	07	08
01	1.076e+003	7.632e+002	7.537e+002	7.487e+002	7.371e+002	7.444e+002	7.480e+002
02		1.040e+003	7.687e+002	7.571e+002	7.435e+002	7.502e+002	7.524e+002
03			1.072e+003	7.652e+002	7.481e+002	7.535e+002	7.548e+002
04				1.035e+003	7.566e+002	7.589e+002	7.589e+002
05					1.041e+003	7.830e+002	7.737e+002
06						9.049e+002	7.560e+002
07							1.060e+003
08							

Figure 21: Data measurement set

4.3 Calibration

Calibration is done using the ITS Tomography Toolsuite in laboratory. Oil is set as low calibration while water is set as high calibration. During low calibration, whole pipe is filled with oil for measurement. During high calibration, whole pipe is filled with water for measurement. In the following graphs, X-axis indicates the number of voltage measurement taken and Y-axis indicates the voltage value.

Comparing both line graphs, low calibration shows slightly higher voltage value. This is expected because water (high calibration) has permittivity of 80 while oil (low calibration) has permittivity of around 3.



(a) Low calibration image **(b) High calibration image**

Figure 22: Low and high calibration images

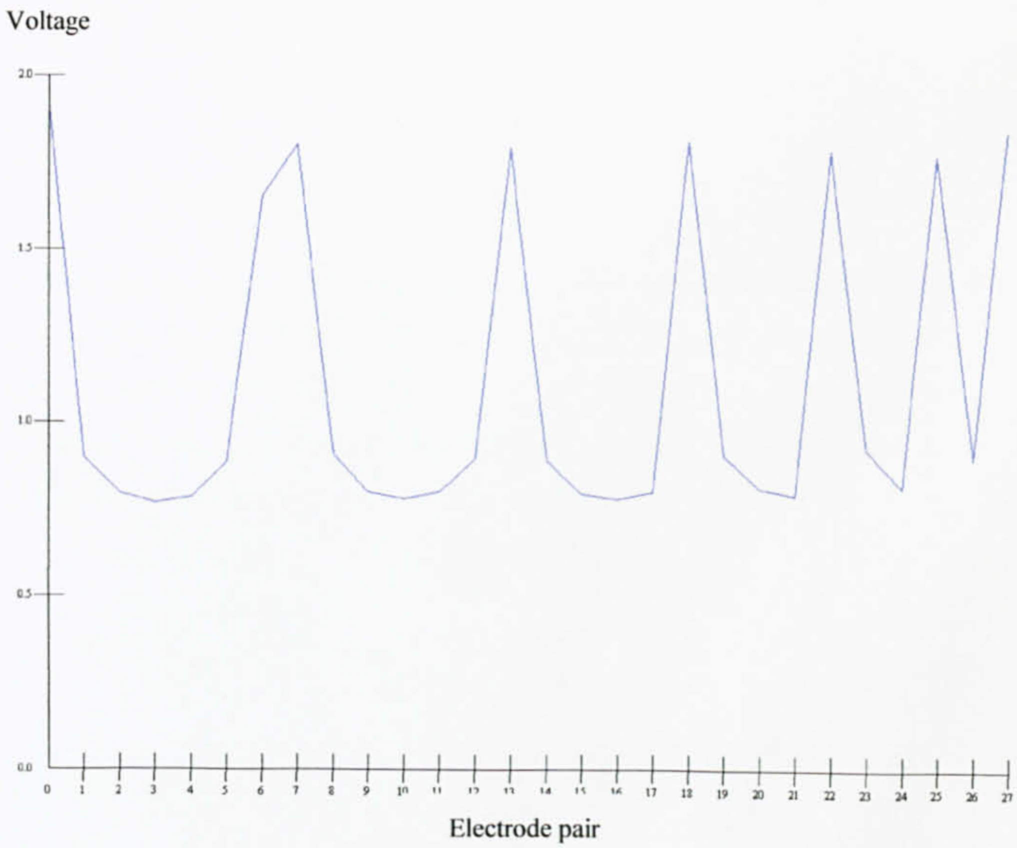


Figure 23: Low calibration line graph

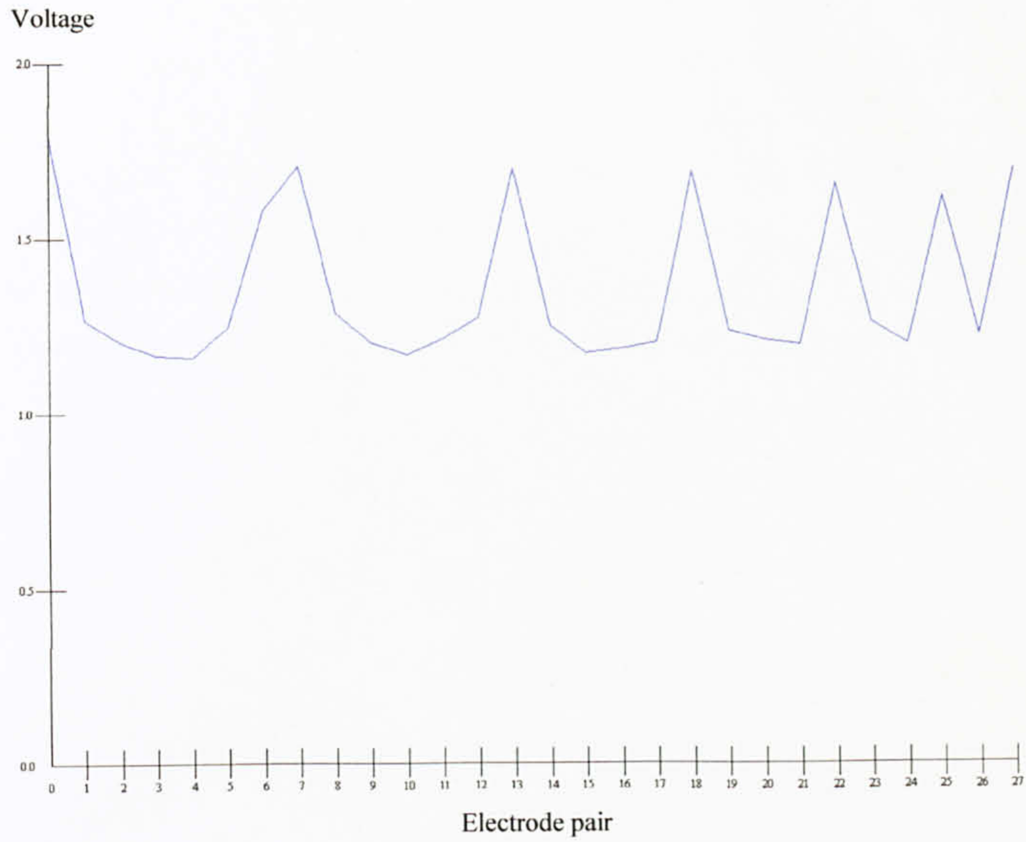


Figure 24: High calibration line graph

4.4 Static and Dynamic Experiments

In this project, two types of sensors are fabricated – internal electrodes and external electrodes sensors. For each fabricated sensor, its static and dynamic performances are experimented. ITS M3000 sensor is part of the ITS Tomography System. It is also experimented with static and dynamic oil-in-water distribution. The specifications of ITS M3000 sensor used in the experiments are:

- 12 electrodes
- External electrodes
- Pipe diameter of 4"

4.4.1 *Static Tests*

In the static test, the pipes were placed horizontally during the measurements. 25% and 50% oil-in-water distribution were experimented. Due to high viscosity of oil, some oil stuck at the bottom part of the pipe instead of floating to the top of the water. There is no clear stratified distribution of oil and water. This issue is less noticeable for ITS M3000 sensor. It is due to its larger pipe diameter. The layer of oil stuck at the pipe wall is relatively small when the pipe diameter is larger. Comparing to the 25% oil-in-water, 50% oil-in-water distribution is expected having more oil (blue) area shown in the image. Though, there are errors in displaying the actual oil-in-water measurement. Only a rough oil-in-water distribution images are obtained.

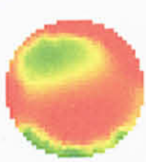
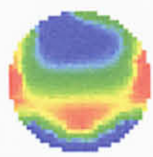
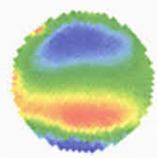
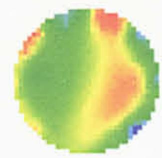
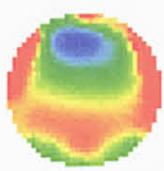
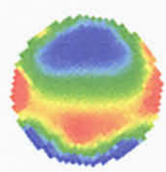
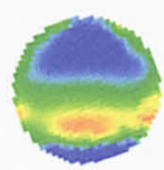
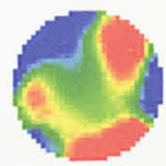
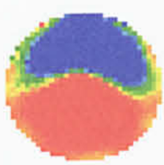
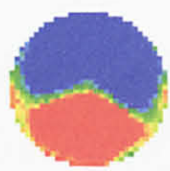
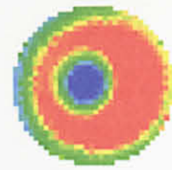
	Static		**Dynamic**	**Stirred Mixture**
	25% oil-in-water	**50% oil-in-water**	**20% oil-in-water**	
Internal electrodes				
External electrodes				
ITS M3000 sensor			**N/A**	

Figure 25: Static and dynamic test

4.4.2 *Dynamic Tests*

The test rig mentioned in previous chapter was used for dynamic tests. Same condition as the static test, a layer of oil stuck at the bottom part of pipe due to high viscosity. The air trapped in the pipe during the experiment contributes error to the measurement taken. The permittivity of air is 1 (low). Thus, area occupied by the air gives reading of low permittivity, which is almost same as the oil. In the post processing image generated, the area occupied by air is displayed as blue, which is supposed to indicate oil distribution. Dynamic test for ITS M3000 is unavailable because there is no opening at other end of pipe. Due to time constraint, only 20% oil-in-water distribution was experimented. Further experiments on other percentage of oil-in-water distribution are recommended.

4.4.3 *Stirred Mixture*

When the mixture is stirred, ITS M3000 sensor provides an image of oil and water roughly formed a circle without mixing up. This effect cannot be observed for the internal and external electrodes sensors. This is because the diameter of ITS M3000 is larger than the others. It creates enough space for oil and water movement. Considering the result from external electrodes, oil and water tends to hold back to its initial position when it is stirred. When the stirring force exceeded a limit, a mixture of oil and water is created. This is indicated by green area shown in the result column of stirred mixture of internal electrode.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The sensor is designed by represent it with two-dimensional model. Simulation of the sensor using COMSOL software enables to know the voltage distribution of measurement area. According to simulation results, sensor with radial screen and internal electrodes provides better measurement data.

ITS M3000 Multi-Modal Tomography System in laboratory is used to conduct the calibration, data acquisition, data processing and data analyzing. Symmetry line graph showed good calibration is obtained. Oil-in-water mixture in measuring pipe is visualized by developing sensitivity map from the raw data obtained. Tool errors such as loose cable connectivity, electrodes do not charge / discharge properly reduce the accuracy of data obtained.

Three types of sensors are experimented – ITS M3000 sensor, fabricated internal and external sensors. These sensors were tests with static 25% and 50% oil-in-water distribution, 20% oil-in-water dynamic flow and stirred mixture. Different results of ITS M3000 and fabricated sensors are mainly due to different sensor diameter. Differences caused by electrodes placement (internal/external) and number of electrode is hard to identify. In general, the results do not show the exact distribution of oil-in-water, only a rough estimation is obtained.

5.2 Recommendation

For dynamic test, different experiments on vary percentage of oil-in-water distribution are recommended. This project can further investigate the impact of different number of electrodes, length and width of electrodes, effect of different types of earthed screed and etc. When studying on a certain effect, other specifications should be remained constant.

In this project, the study is focused on the sensor part. In an ECT system, there are another two main parts – data acquisition unit (DAQ) and data processing software. This project can be further carried out by studying and implementing DAQ and data processing parts.

Two types of capacitance measuring circuits are widely used in DAQ – the charge/discharge circuit and AC-based circuit. Both circuits are different in the aspects of circuit design, signal-to-noise ratio (SNR), cost, complication and etc. Study on each circuit's suitability of various implementations and circuit build-up can increase the overall understanding of the system.

There are two approaches to reconstruct the image from raw data obtained – single-step calculation and iterative processing. An example of single-step calculation is linear back projection (LBP) is the most popular reconstruction method for electrical tomography. This method is also used by the ITS M3000 System itself to generate the sensitivity maps. LBP is an important part of ECT to study on.

REFERENCES

Angeli, P., & Hewitt, G. (2000). Flow structure in horizontal oil-water flow. *International Journal of Multiphase Flow 26* , 1117-1140.

Dong, F., Jiang, Z., Qiao, X., & Xu, L. (2003). Application of electrical resistance tomography to two-phase pipe flow parameters measurement. *Flow Measurement and Instrumentation 14* , 183-192.

ECT. (2004, November 23). *Electrical Capacitance Tomography*. Retrieved August 13, 2008, from Process Tomography Ltd.: http://www.tomography.com/pdf%5Cecttechov.pdf

Flores, Norberto; Gamio, J Carlos; Ortiz-Aleman, Carlos; Damian, Enrique. (2005). Sensor Modeling for an Electrical Capacitance Tomography System Applied to Oil Industry. *COMSOL Multiphysics User's Conference*. Boston.

Fuchs, A., & Zangl, H. (2007). Simulation-Based Analysis of the Spatial Sensitivity Function of an Electrical Capacitance Tomography System. *COMSOL Users Conference* . Grenoble.

Hasan, N. M., & Azzopardi, B. J. (2007). Imaging stratifying liquid-liquid flow by capacitance tomography. *Flow Measurement and Instrumentation 18* , 241-246.

Herman, G., & Kuba, A. (1999). *Discrete Tomography Foundation*. Boston: Birkhauser.

Hussain, S. A., Xu, X. Y., & Hewitt, G. F. (2008). Water Local Volume Fraction on Oil in Water Dispersion. *Journal of Applied Fluid Mechanics 1(2)* , 57-63.

Hwili, A., & Yang, W. (2007). Multi-modality multi-interface level sensor with segmented capacitance and inductance sensing elements. *Sensor Review 27(3)* , 217-223.

Ijaz, U. (2007). Concentration distribution estimation of fluid through electrical impedance tomography based on interacting multiple model scheme. *Flow Measurement and Instrumentation 18(1)* , 47-56.

Ismail, I., Gamio, J., Bukhari, S., & Yang, W. (2005). Tomography for multi-phase flow measurement in the oil industry. *Flow Measurement and Instrumentation 16* , 145-155.

ITS. (2004). ITS M3000 Multi-Modal Tomography System User's Manual. Industrial Tomography Systems.

ITS. (2006). ITS Tomography Toolsuite User's Manual. Industrial Tomography Systems.

Jeanmuere, L. F., Dyakowski, T., Zimmerman, W. B., & Clark, W. (2002). Direct flow-pattern indentification using electrical capacitance tomography. *Experimental Thermal and Fluid Science 26* , 763-773.

Kjell, K., & Saba, M. (2007). Comparison of different measurement protocols in electrical capacitance tomography using simulation. *IEEE Transaction on Instrumentation and Measurement 56* , 2119-2130.

Niu, G., Jia, Z., & Wang, J. (2004). Design and Simulation of a Novel Capacitance Sensor for Tomography Systems. *The 4th International Symposium on Measurement Techniques for Multiphase Flows.* Hangzhou.

Pal, R. (1994). Techniques for measuring the composition (oil and water content) od emulsions - a state of the art review. *Colloids and Surfaces A: Physiochemical and Engineering Aspects, 84* , 141-193.

Plaskowski, A. (1995). *Imaging Industrial Flows.* NY: Taylor & Francis Group.

Qiu, C., Hoyle, B., & Podd, F. (2007). Enginnering and application of a dual-modality process tomography system. *Flow Measurement and Instrumentation 18* , 247-254.

Ramm, A. (1998). *Inverse Problems, Tomography, and Image Processing* . NY: Plenum Press.

Siti Aslina, H., Siti Mazlina, M., & Wan Hassan, M. (2006). In-situ phase fraction for oil and water occupied in pipe channel. *International Journal of Engineering and Technology 3(2)* , 248-256.

Ulaby, F. (2005). *Electromagnectics for Engineers.* NJ: Pearson Education Inc.

Wang, M., Yin, W., & Holliday, N. (2002). A highly adaptive electrical impedance sensing system for flow measurement. *Measurement Science Technology 13* , 1884-1889.

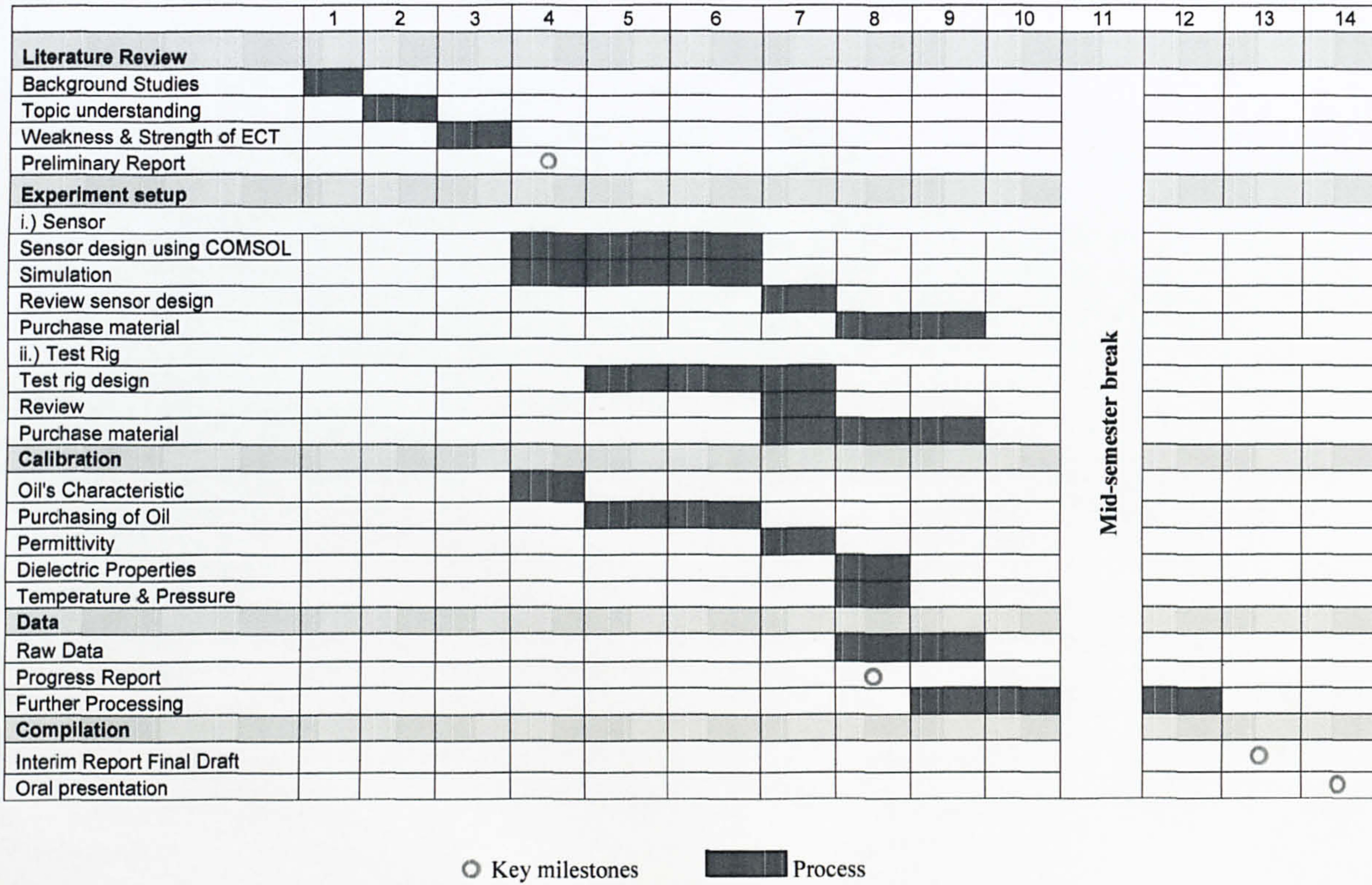
Yang, W. (2006, October 22-25). Key issues in designing capacitance tomography sensors. *IEEE Sensors 2006* , 497-505.

Yang, W. (1997). Modelling of capacitance tomography sensors. *IEE Proceedings 144(5)* , 203 - 208.

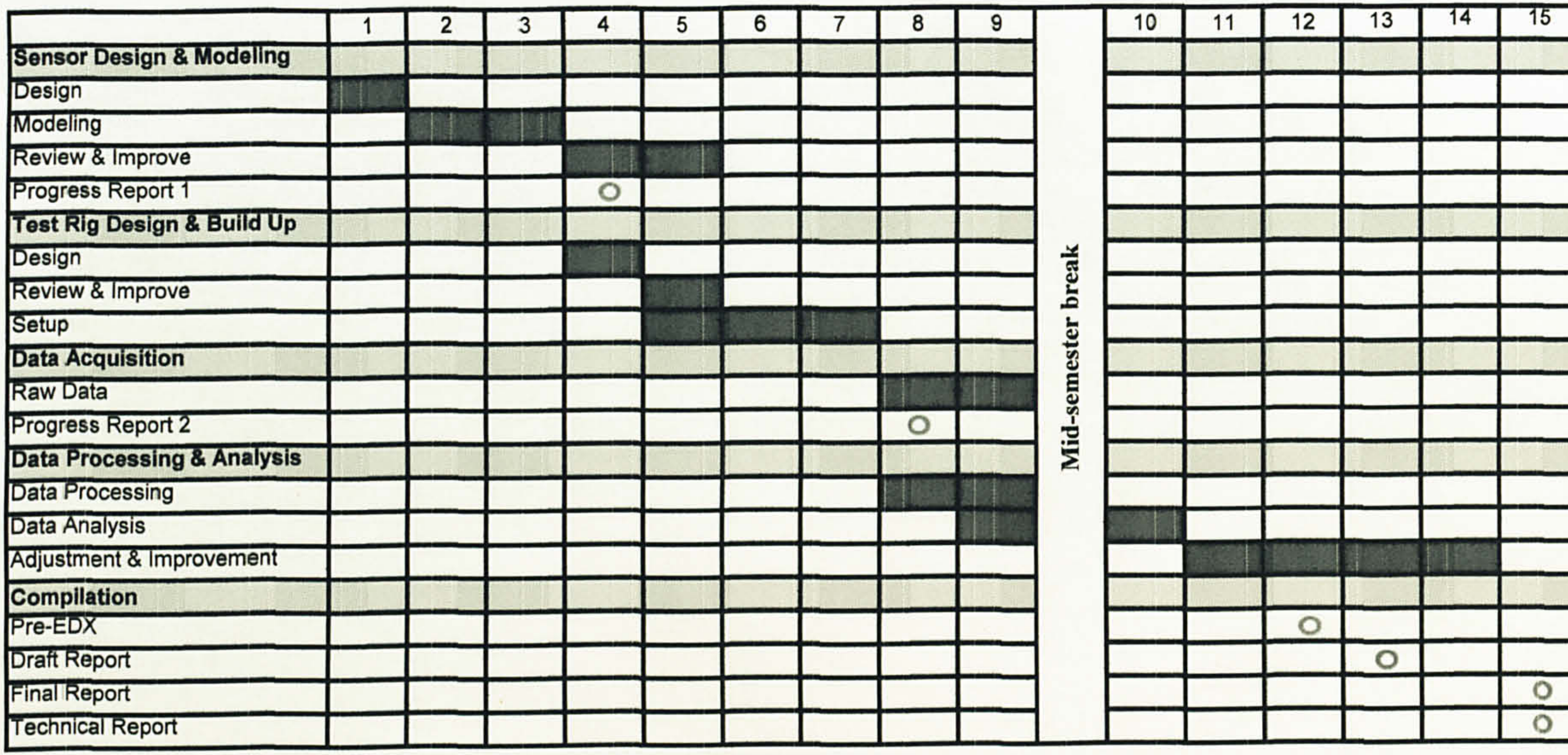
APPENDICES

APPENDIX A

GANTT CHART & KEY MILESTONES (FYP I)



APPENDIX A
GANTT CHART & KEY MILESTONES (FYP II)



APPENDIX B

DATA CABLE

	TECHNICAL DATA SHEET	code	MRG1740
		version	2
		date	2005-11-09
	R.F. CABLE 50 OHM RG 174 U CCS	page	1/2

APPLICATION
Coaxial cable used for Radio-frequency, designed according MIL-C-17F/119F

CONSTRUCTION

1) Conductor	7x0.16 mm copper clad steel wire
Diameter	0.5 mm
2) Dielectric	Solid PE
Diameter	1.50 mm ± 0.10 mm
3) Screen	braid
Material	0.1 mm tinned copper wire
Diameter	1.97 mm ± 0.11 mm
4) Sheath	PVC
Diameter	2.80 mm ± 0.10 mm
Color	black

REQUIREMENTS AND TEST METHODS
Test methods generally in accordance with MIL-C-17F/119F

1) Conductor		
Elongation at break	≥ 1%	
3) Screen		
Coverage	86 %	
Electrical characteristics		
Mean characteristic impedance	50 ± 2 Ohm	
DC resistance inner conductor	≤ 317 Ohm/km	
Capacitance at 1 kHz	100 ± 3 pF/m	
Velocity ratio	0.66 ± 0.02	
Insulation resistance	> 10^4 MOhm.km	
Voltage test of dielectric	3 kV dc	
Corona	≥ 1.5 kV ac	
Return loss at..	100 – 400 MHz	≥ 22.5 dB
	400 – 900 MHz	≥ 19.2 dB
Electrical characteristics (cont..)		
Power rating at..	100 MHz	≤ 50 W
	1000 MHz	≤ 16.5 W
Nominal attenuation at..	400 MHz	80 dB/100m
	1000 MHz	148 dB/100m
Maximum attenuation	10% higher	

MARKING
Text Inkjet printing

POPE VENLO HOLLAND RG 174 U MIL-C-17F

PACKAGING

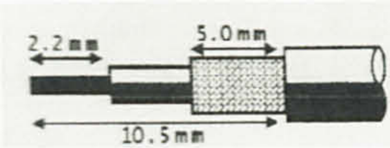
Code 46968 0025 040	One way reel E 250/100/160 Length 500 m ± 5% Max. 10 % of the length to be delivered contains a shorter length with a minimum of 250 m. Each reel or coil contains one length of cable

Code 46968 0025 153	Ring 200 m ± 5% Max. 10 % of the length to be delivered contains a shorter length with a minimum of 50 m.

Weight	
Total cable	11.50 g/m
Copper	4.82 g/m

APPENDIX C

STRAIGHT FEMALE CRIMP PLUG



Attributes

Attribute Type	Attribute Value
Gender	Jack
Mounting	cable
Orientation	Straight
Impedance Ω	50
Contact Plating	Gold
Contact Material	beryllium copper
Contact Termination Method	Solder
Cable Type	RG174A/U

Range Overview

SMB 50Ω Connectors in clamp and crimp termination options.
Reliable and quick connect/ disconnect system

Technical specification	
Working Voltage	250V max.
Proof Voltage	750V rms max.
Insulation Resistance	$>5 \times 10^9 \Omega$
Temperature Range	-65°C to +165°C

APPENDIX D

COPPER FOIL SHIELDING TAPE

Technical Data

Issue 2 / July 2006

AT526 35 Micron Copper Foil Shielding Tape

General description

35 micron copper foil coated with an electrically conductive acrylic adhesive supplied on a removable silicone liner.

- Conductive acrylic adhesive
- Good high and low temperature resistance
- Can be easily soldered
- Easy unwind

Specification

- Tested in accordance with ASTM D-1000 latest issue, BS EN 60454 - Part 2 test methods (Formerly VDE 0340, BS 3924.)
- Tested and meets military spcification MIL - T - 47012
- Construction is tested in-house and conforms to the Flame retardant requirement part only of UL510

Technical Details

Technical details	BS value	ASTM value
Typical values		
Foil thickness:	0.035mm	1.4 mil
Adhesive thickness:	0.025mm	1.0 mil
Total thickness:	0.060mm	2.4 mil
Adhesion to steel:	4.5 N/cm	41 oz/inch
Tensile strength:	40 N/cm	23 lbs/inch
Temperature Resistance:	-20°C to +155°C	Up to +311°F
Recommended curing cycle:	1 hour at 150°C or	
	2 hours at 130°C	
Electrical resistance through		
Adhesive*:	0.003 ohms	
RoHS compliant	Yes	
Storage Temperature	+12°C to +25°C	

*Tested according to MIL STD 202F method 307 across surface area of 1 sq. inch.

NOTE

Except where indicated otherwise, the figures stated are average values and should not be regarded as MAXIMUM or MINIMUM values for specification purposes. The Company reserves the right to improve products and any change in specification will result in a re-issue of the relevant 'Technical Data Sheet'. Customers should satisfy themselves that the tape is suitable for their requirements whether after such modifications or otherwise. Please check that you have the latest issue of the 'Technical Data Sheet'. All slitting and length tolerances are to British Standards. Before use the customer is advised to consult the Health & Safety Data Sheet produced by the company for this product, which is available on request.

STORAGE

Tapes stored below the minimum recommended temperature will require warming up to that level before use. Up to 24 hours may be required for this to take place.

APPENDIX E

EXXSOL D80

Effective date: Mar 1, 2002

Exxsol™ D80

Dearomatized Aliphatic Hydrocarbon

Product Properties

Property	Units	Typical values	Test method
Distillation range	°C		ASTM D 86
IBP		208	
DP		243	
Flash point	°C	82	ASTM D 93
Density @ 15 °C	kg/dm^3	0.798	ASTM D 4052
Viscosity @ 25 °C	mm^2/s	2.19	ASTM D 445
Evaporation rate (n-BuAc=100)	-	2	EMC-AP-F01
KB value	-	29	ASTM D 1133
Aniline point	°C	77	ASTM D 611
Aromatic content	wt%	0.3	AM-S 140.31
Colour (Saybolt)	-	+ 30	ASTM D 156
Bromine index	mg/100g	40	ASTM D 2710
Surface tension @ 25 °C	mN/m	26.3	EC-M-F02 (Wilhelmy Plate)
Refractive index @ 20 °C	-	1.440	ASTM D 1218

Notes

- **Values indicated describe typical physical properties and do not constitute specification limits.**
- **This product typically contains less than 2 ppm sulphur.**

APPENDIX F

LIQUID PUMP

POWER CONSUMPTION(W)	18.0
FLOW RATE	1100L/H(319G/H)
HMAX(M)	1.8
OUTLET CONNECTION	13/20*44,16/20*44,19/20*44
FLOW CONTROL(L/H)	0-1100L/H(319G/H)
HZ	50-60HZ
INPUT VOLTAGE(V)	12/100/110/120/220-240
DIMNSIONS L*W*H(MM)	93*58*77