CHARACTERIZATION OF WAXY COOLED CRUDE OIL USING ELECTRICAL RESISTANCE TOMOGRAPHY (ERT)

By

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FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme

in Partial Fulfilment of the Requirements

for the Degree

Bachelor of Engineering (Hons)

(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Department of Electrical & Electronic Engineering
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

Approved:

____

Your Supervisor’s Name
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

May 2012

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.

____

Your Full Name

ABSTRACT

Electrical resistance tomography (ERT) is one of the most common, widely implemented and promising method in production cross-sectional image displaying the distribution of electrical conductivity for a particular multiphase flow. The method includes measurement of electrical resistance characteristics converting it to image mixtures when the continuous phase is conductive.

ERT is well suited in monitoring gas-liquid flow, whereby the liquid is in a continuous phase whereas the gas is in a disperse phase. Other type of tomography sensors which involves measurement of electrical characteristics includes electrical capacitance tomography (ECT), electromagnetic tomography (EMT) and electrical impedance tomography (EIT). The mentioned electrical tomographies are safe without any radiation hazard and low cost comparing to nuclear based methods. ERT has the advantage among others for its excellent time resolution produced from very fast measurements of electrical resistance.

Multiphase flow is of great importance in various industrial processes. As the most important characteristic of a multiphase flow, the flow regime not only characterizes the flow condition in an explicit way, but also determines the measurement model in each measuring method. The main focus for this project is to implement ERT for detection and measurement of gas void fractions in waxy cooled crude oil.

Measurement of void fraction of two-phase flows remains a challenging area. Thus, the report which consists of an introduction, problem statement, objectives, literature review and methodology is used to get a better understanding, set targets and solve the issues in hand.

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LIST OF ABBREVIATION

ERT	Electrical Resistance Tomography
ECT	Electrical Capacitance Tomography
EMT	Electromagnetic Tomography
WAT	Wax Appearance Temperature
CAPEX	Capital Expenditure
X-CT	X-ray Computed Tomography System
RTNR	Real-Time Neutron Radiography System
DAQ	Data Acquisition System

Chapter 1
INTRODUCTION

1.1 Background of Study

Nowadays, measurement of various parameters of multiphase flows becomes increasingly important in many industrial fields such as in physical, chemical and petroleum process engineering. Online measurement of multiphase flow parameters would not only help understand the variation of flow pattern but would also help improve the safety of operations as well as reliability of processes.

Multiphase flow is a complicated occurrence and is indeed difficult to understand, predict and model. The common single phase flow properties such as velocity profile, turbulence and boundary layer, are inappropriate to display the nature of such flows. The exact metering of this flow stream is dependent on the multiphase flow meter's ability to handle flow regime effects, velocity dependence, sensor dependence, emulsion effect and salinity effects.

Researchers are constantly trying to discover good visualization and accurate measurement methods. ERT is a promising method to monitor widely existing industrial conductive multiphase flows. The method does not only provide conductivity images but also provides the ability to measure flow parameters, such as void fraction of the disperse phase, monitoring flow patterns in horizontal slurry transport pipelines and interrogating the internal flow of a complex reactor [23].

The author's project covers on the detection and measurement of gas void fraction in a waxy cooled crude oil, a multiphase flow issue. Waxy cooled crude oil are usually created due to thermal shrinkage resulted by low seabed temperature or at Wax Appearance Temperature (WAT) occurring mostly during emergency or maintenance shutdown or non-operating period [17].

1.2 Problem Statement

Sepat Field is an oilfield located in block PM313, offshore Peninsular Malaysia, about 130km from Kuala Terengganu has a potential of producing 8,800 barrels of crude oil per day. The problem faced at the Sepat Field whereby production disruption due to a pipeline blockage due to waxy cooled crude oil leads to the idea for this particular project. It is important to consider the multiphase which is present in the waxy cooled crude oil. Gas voids formed in the waxy cooled crude oil may affect the compressibility of the crude oil. Using the assumption that waxy cooled crude oil behaves as an incompressible high viscous fluid, the facility such as pump designed to have superior horse power is then needed. High horse power equipment means high Capital Expenditure (CAPEX) to spend for the production process. The problem also affects the whole flow assurance process of Oil & Gas which starts from retrieving the hydrocarbon from the reservoir up to the point of sale.

Measurement of multiphase flow has become vital in the ever growing Oil & Gas industry. In determining methods of this flow measurement, realizing the flow regime is important. Determination of flow regimes in the pipeline during operation is difficult. Even in the laboratory, the flow regime may be studied by direct visual observation using a transparent piping. Descriptions of flow regimes are therefore can be considered arbitrary and depends on the observer's interpretation. The project targets a solution to this problem where process tomography is used. The method enables determination of flow measurement by utilizing flow visualization from a tomography which would result in better quality control and contribute a much more effective process development as a whole.

1.3 Objective and Scope of the project

1.3.1 *Main Objective*

The objective of this study is to measure, detect, visualize and characterize waxy cooled crude oil where image and raw data of the multiphase flow can be captured directly. Flow visualization is important in obtaining accurate flow regime. Visualization will be done using a tomography method which includes measurement of electrical resistance characteristics. The application of this tomography method, namely Electrical Resistance Tomography (ERT) is should produce a vast array of data which would later be further analyse anticipating the results to be a solution to the problem statement.

1.3.2 *Scope of Project*

ERT is the chosen tomography method to produce flow visualization by implementing the measurement of electrical resistance characteristics. Flow visualization focuses on two-dimensional imaging the multiphase gas void fraction in waxy cooled crude oil. Sensor modelling would be done using COMSOL Multiphysics and the proposed sensor is a circular 16-electrodes ERT sensor attached to a transparent pipe.

1.4 Relevancy of Project

The project is relevant to the study of Instrumentation and Control as well as Oil and Gas as it focuses on the design of resistance sensor and control unit of ERT which deals with electronic design to detect and measure gas void fractions in a waxy cooled crude oil. ERT systems are already widely used but it is the measurement of gas void fractions that can be studied further as it a common problem in the Oil and Gas industry, not only at the focused Sepat Field, thus challenging the performance of the design and control unit of the ERT system.

1.5 Feasibility of Project

The project will be conducted by collecting related materials such as journals and technical papers specifically on ERT, crude oil physical properties and gas void fractions in waxy cooled crude oil measurement. Continuous research and literature review will be done to get a better understanding towards the topic. The sensor design and fabrication will be done as soon as data and recommendation are obtain from the supervisor and reliable sources. Testing and implementation will be done at the lab using the Industrial Tomography System. The static test will be using a test rig complete with all the necessary equipment. Based on the descriptions, the author is confident that this project is feasible to be carried out within the time frame which is within two semesters.

Chapter 2
LITERATURE REVIEW

2.1 Gas Void Fraction Measurement

2.1.1 *Electrical Resistance Tomography (ERT)*

Tomography includes taking measurements around the boundary of an object, for example vessel or patient, to determine the properties or process happening inside. There are several tomography methods that involve measurement of electrical characteristics such as electrical resistance tomography (ERT), electrical capacitance tomography (ECT) and electromagnetic tomography (EMT). In this paper, ERT is implemented where it involves the measurement of fluid resistance [12].

An ERT system produces a cross-sectional image showing the distribution of electrical conductivity of the contents of a process vessel or pipeline from measurements taking at the boundary of the vessel [14]. Basically, the operating principle of ERT is that the systems will inject a current between a pair of electrodes and the resultant voltage difference between remaining electrodes pairs will be measured according to a predefined measurements protocol [6]. Based on the resistance data, the material distribution can be obtained using sensitivity maps or physical models of the sensor arrangement.

In an ERT system, the electrodes are directly in contact with the material inside the vessel. Different models are used to describe an ERT system based on the needed complexity level [21]. Therefore, a phenomenon called contact impedance between the electrode and the process material may be necessary to account for in the equations. The equation used for sensitivity region in the ERT case is given as follow;

$$\nabla\sigma(r)\cdot\nabla\varphi(r) = 0 \qquad (1)$$

Where,

$\sigma = \text{conductivity}$

$\varphi = \text{electrical potential}$

The measurement principle can also be presented in a theoretical derivation of the optimum excitation field distribution where current injection and voltages on the electrode form the electrical field in homogenous conductive media. The current density obeys the continuity laws inside the space;

$$\nabla \cdot J = 0 \qquad (2)$$

Where,

$J =$ current density

As the media has a constant conductivity, σ, so electrical field and current density has a simple relation;

$$J = \sigma \cdot E \qquad (3)$$

Where,

$J =$ current density

$E =$ electrical field

Therefore the electrical field is;

$$\begin{aligned} \nabla \cdot E &= 0 \\ \nabla \times E &= 0 \end{aligned} \qquad (4)$$

The equation above satisfies as the electrical field is mainly set up by the voltages on the electrodes at low frequency. Thus;

$$\nabla \times J = 0 \qquad (5)$$

The structure of a typical ERT system is composed of three main parts; sensors, data acquisition system and image reconstruction system/host computer [7].

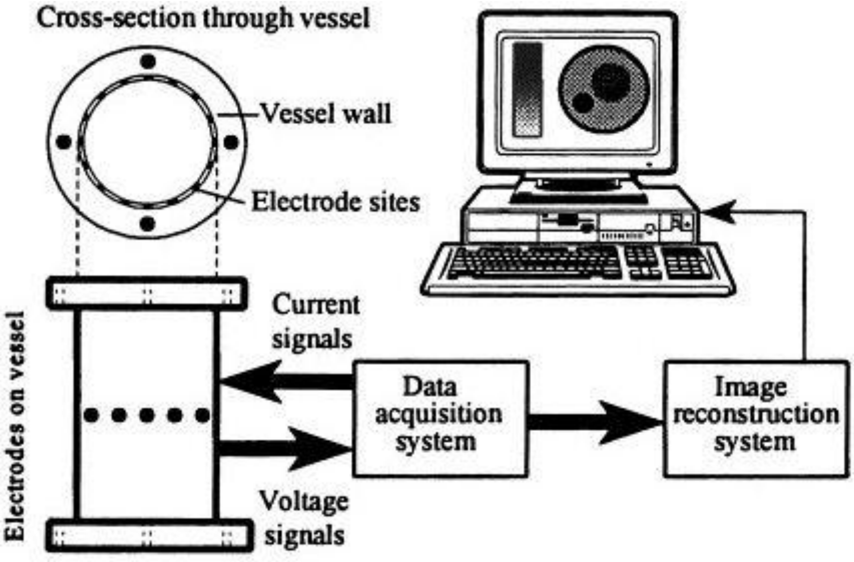

Figure 1: Structure of a typical ERT system

2.1.2 *ERT and ECT Comparison*

Basically, ERT and Electrical Capacitance Tomography (ECT) have been developed separately as non-intrusive and/or non-invasive imaging methods in the past. The author chose to directly state the differences between ERT and ECT because these two methods are the most common and widely used tomography compared to other tomography methods. ERT is used to visualise conductivity distributions and measure conductive components whereas ECT is used to visualise permittivity distributions and measure dielectric components. Both methods indeed have their own advantages and disadvantages.

Generally, in phase-flow, ERT has an advantage over other method in terms of providing two or three dimensional information on multiphase flow and it is able to construct phase distribution various times [11]. It should also be noted that ERT measurement precision may sometimes be poor. ERT and ECT are further explained in the table below.

Table 1: ERT and ECT Direct Comparison

Criteria	ERT	ECT
Image	Visualize conductivity distributions	Visualize permittivity distributions
Function	Measure the conductive component such as water acids bases and ionic solutions	Measure the dielectric component such as oil, air or sand
Advantage	Provide 2D and 3D flow, phase distribution can be constructed	Non-intrusive at the same time non-invasive
Disadvantage	Low measurement precision but it is feasible to find precise method	Issue of stray capacitance

2.1.3 *Nuclear*

Advanced radiation method is generally considered as another non-intrusive measurement alternative to obtain information for gas void fractions in a multiphase flow. The two of the most recently developed advanced radiation method are X-ray Computed Tomography system (X-CT) and Real-Time Neutron Radiography system (RTNR). These methods use ionizing radiation, measuring attenuation of a radiation beam in a flow channel leads to detection and measurement of void fraction, the percentage of flow channel volume that is not occupied by liquid [19].

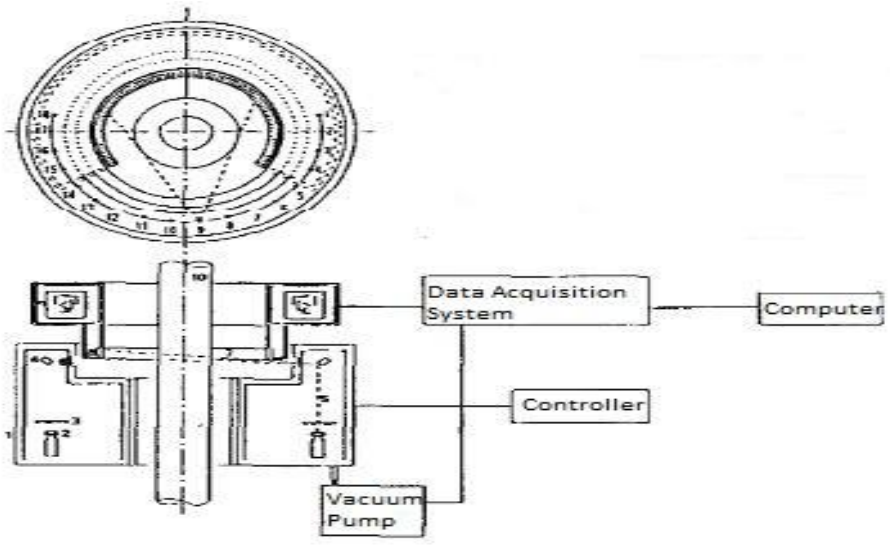

Figure 2: Typical X-ray Computed Tomography (X-CT) system

Other than measuring the void fraction, X-CT and RTNR are also able to characterized flow regime by two methods. The first is to reconstruct the cross-section image data in a binary format where one colour represents void fraction whereas the other represents the liquid phase [19]. The second method determines the history of the cross-sectional averaged void fraction.

The disadvantage of using these advanced radiation methods is the necessary shielding, which becomes expensive with increasing radiation energy. The temporal resolution gamma-sources with standard radiation intensities are too low to monitor all rapid changes in void fraction.

2.1.4 *Differential Pressure*

The present gas void fraction measurement using the differential pressure method invention relates to multiphase flow in pipelines, in particular, to flow regime analysis of a multiphase mixture of materials through a pipeline.

Brine and carbon dioxide gas are commonly present in oil pipelines. The oil, water and gas mixture creates a highly corrosive environment for typical carbon steel pipelines [10]. To compound the problem, as oil wells are often at remote locations, the corrosive mixture must be transported long distances before it can be separated. During this transport, the multiphase mixture travel through numerous changes of inclination, affecting the flow pattern and flow characteristics of the multiphase pipeline so as to further compound the pipeline corrosion problem.

The consequences of a major oil line break are undesirable, it is important to quantify the level of corrosiveness of a particular multiphase flow under varying conditions so effective corrosion control can be achieved [16].

Flow regime characterization and detection and measurement of gas void fraction in a pipeline may be identified by using the differential pressure method. The steps as mentioned by Jepson, Wilkens and Maley are as follows:

I. Identifying an analysis pipe section containing a multiphase fluid flow
II. Measuring a first differential pressure at first pair of pressure measuring points positioned along the analysis pipe section
III. Measuring a second differential pressure at second pair of pressure measuring points positioned along the analysis pipe section
IV. Identifying a primary drop in the first differential pressure and secondary drop in the second differential pressure
V. Measuring a time delay between initiation of the primary pressure drop and initiation of the secondary drop
VI. Determining as a function of the time delay whether the primary pressure drop corresponds to a predetermined multiphase flow anomaly moving through the pipe analysis section

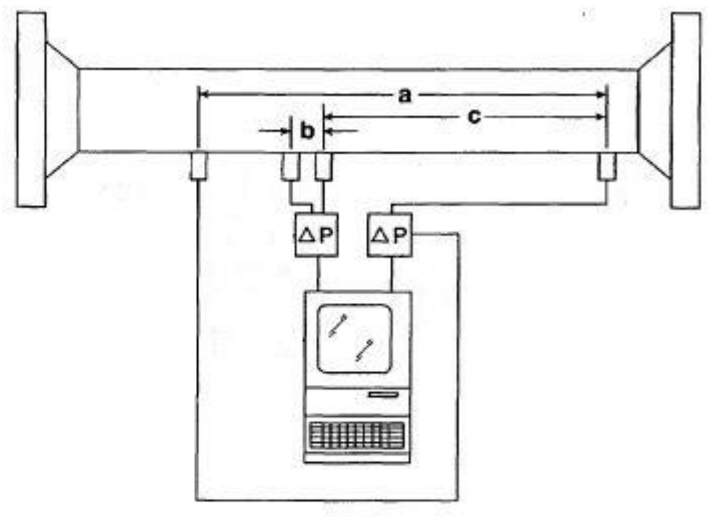

Figure 3: Differential Pressure Gas Void Fraction Measurement Method Structure

The disadvantage of this method is the poor accuracy of results it produces. For a number of years, much flow-related research and development time and money has been invested by companies to develop smarter and more accurate pressure transmitters. Unfortunately, there has not been any significant progress in developing more accurate primary elements [15].

2.2 Multiphase Flow

2.2.1 *Flow Regimes*

Multiphase flow is a flow that consists of two or more phases which are not chemically related but flowing simultaneously in a closed conduit. Multiphase flow structures are classified in flow regimes. Flow regimes is the physical geometry exhibited by a multiphase flow in a conduit which will vary depending on operating conditions, fluid characteristics, flow rates and the orientation and geometry of the pipe through which the fluids flow. The transition between different flow regimes may be a gradual process [6].

Generally, flow regimes can be grouped into dispersed flow, separated flow, intermittent flow or a combination of these. Dispersed flow is characterized by a uniform phase distribution in both the radial and axial directions whereas; separated flow is characterized by a non-continuous phase distribution in the radial direction and continuous phase distribution in the axial direction [1]. On the other hand, intermittent flow is characterized by being non-continuous in the axial direction and therefore exhibits locally unsteady behavior [2]. In this experiment, multiphase flow is used and the figure below shows the cross-section of typical flow profiles for liquid-gas flow.

Main mechanisms involved in forming the different flow regimes include transient effects, geometry/terrain effects or hydrodynamic effects. Transient effects occur as a result of changes in system boundary conditions [3]. Example of operation that involves this effect are opening and closing of valves and changes in pressure and temperature. On the other hand, geometry or terrain effect those take place as a result of changes in pipeline geometry or inclination (vertical, horizontal etc.). Steady state flow regime which is entirely determined by flow rates, fluid properties, density, viscosity, pipe diameter and inclination is called hydrodynamic effects and it can be seen in horizontal straight pipes. These flow regimes are typically encountered at a wellhead location.

The figure below shows the flow regime map where it provides general illustrations of most flow regimes for vertical flow and indicates where the various flow regimes occur. Physical parameters like density of gas and liquid, viscosity, surface tension, etc. affect the flow regime is the diameter of the flow line. If the liquid and gas flow rates are kept constant and the flow line size is decreased from 4" to 3", both the superficial gas and liquid velocities will increase by a factor 16/9. Hence, in the multiphase flow map, this point will move up and right along diagonal to a new position. This could cause a change in flow regime. This shows how flow regime transitions are dependent on superficial gas and liquid velocities in a multiphase flow.

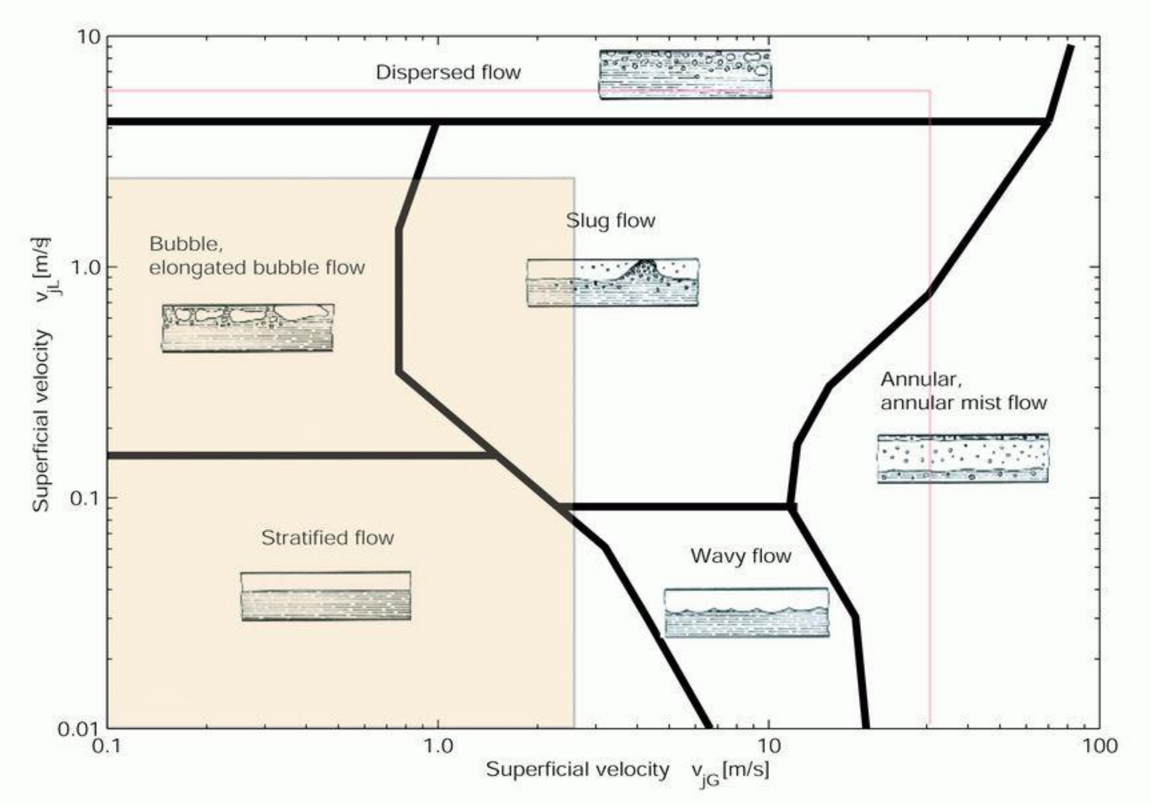

Figure 4: Flow Regime Map

2.2.2 *Superficial Velocities*

The term superficial velocity is often used on the axes of flow regime maps. For example, the superficial gas velocity ($V_{s,gas}$) is the gas velocity as if the gas was flowing in the pipe without liquids, in other words the total gas throughput (q_{gas} in m^3/s at the operating temperature and pressure) divided by total cross sectional area of the pipe (A). The expression is given in Eqn. (1). For the superficial liquid velocity the same can be derived and the simple expression is given in Eqn. (2)

$$V_{s,gas} = \frac{Q_{gas}}{A} \qquad (1)$$

$$V_{s,liquid} = \frac{Q_{liquid}}{A} \qquad (2)$$

Where,

$V_{s,gas}$ = Superficial gas velocity (m/s)

$V_{s,liquid}$ = Superficial liquid velocity (m/s)

Q_{gas} = Gas volume flow rate (m^3/s)

Q_{liquid} = Liquid volume flow rate (m^3/s)

A = Cross sectional area of pipe (m^2)

The sum of the $v_{s,gas}$ and $v_{s,liquid}$ is the multiphase mixture velocity and the expression is given below

$$V_{m=} V_{s,gas} + V_{s,liquid} \qquad (3)$$

Where,

$V_{m\,=}$ Multiphase mixture velocity (m/s)

$V_{s,gas}$ = Superficial gas velocity $\left(\frac{m}{s}\right)$

$V_{s,liquid}$ = Superficial liquid velocity (m/s)

The latter is a derived velocity and only has a meaningful value if the multiphase flow is homogenous.

In multiphase flow, the superficial gas velocity will increase and will change between phase; bubble – slug – churn and annular. The increase of the liquid viscosity clearly increases the gas void formation. Gas holdup values decrease when increasing the liquid viscosity (M. Wang, 2000). For a particular superficial gas velocity, the multiphase flow is annular for all superficial liquid velocities [6].

2.3 Waxy Cooled Crude Oil

Thermal shrinkage definition for this study point of view is the cooling process that the crude oil undergoes. In the real situation thermal shrinkage happens to the crude oil in the pipeline naturally as the temperature of the seabed is low depending on the geographical different and the thermal shrinkage happens during the plant shutdown period therefore, the crude oil remains in the pipeline for a certain period of time.

Based on the study, the petroleum crude contains paraffin (C_nH_{2n+2}) and if the carbon atoms contained are more than eighteen the petroleum crude is then known as waxy crude oil (C.W Sum, 2011). During the thermal shrinkage or cooling process of this crude oil, wax or gelled crude will start to form at the Wax Appearance Temperature (WAT) and the wax starts to deposit at the pipeline forming a solid layert hat decrease the available flow area [1].

A study on the thermal shrinkage entitled “Novel Approaches to Waxy Crude Restart: Part 1: Thermal shrinkage of waxy crude oil and the impact for pipeline restart” had come out with a result which proven that there were gas voids produced by cooling process of the crude oil in the flow line (Phillips, David A., 2010). The gas voids appearance may affect the compressibility of the gelled crude since there are spaces for the gelled crude to move after some amount of pressure applied.This assumption was also confirmed by Margarone which stated that gelled crude behaves as an incompressible high viscous fluid.

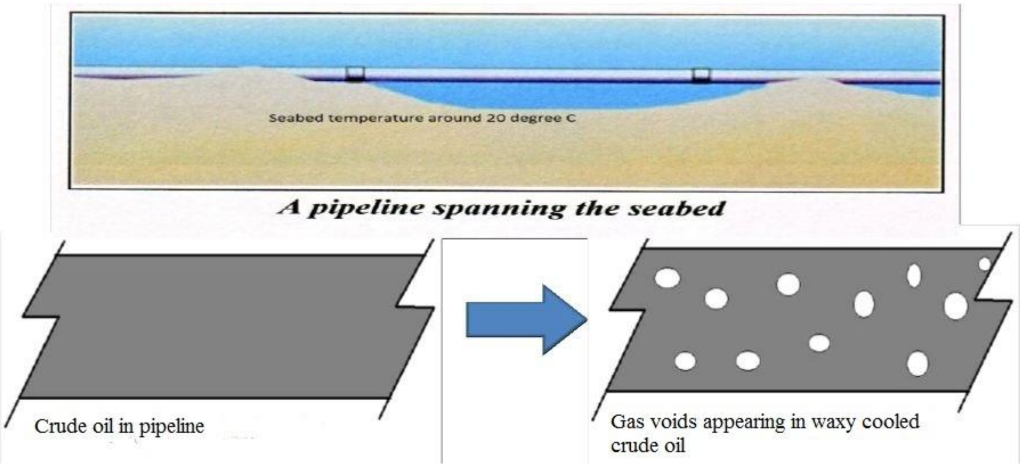

Figure 5: Appearance of Gas Voids in Waxy Cooled Crude Oil

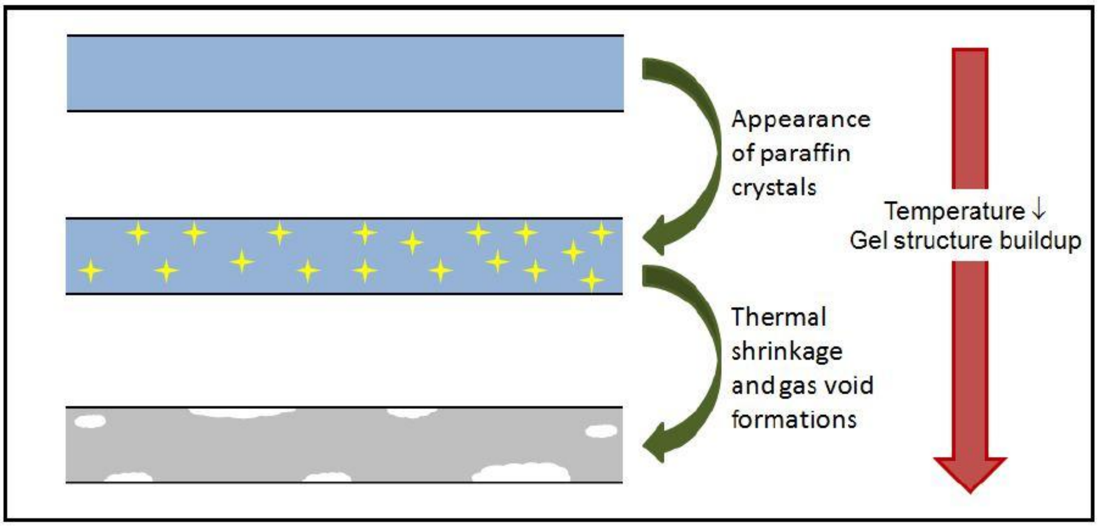

Figure 6: Wax Formation Stage

2.4 Yield Stress for Waxy Crude

Yield stress is simply defined as the minimum stress required in order to produce a shear flow. The material was thought to be in a solid state when the applied stress was less than the yield stress. In other words, the yield stress was thought to be a transition between the elastic solid and viscous liquid behavior [18].

Yielding of waxy crude oil occurs by an initial elastic response, followed by viscoelastic creep and a final fracture. A model with an elastic limit yield stress, a static yield stress and a dynamic yield stress was introduced to describe the yielding process. The three yield stresses were determined by means of different methods. The effect of the time scale in different measurements on the three yield stresses was studied [18].

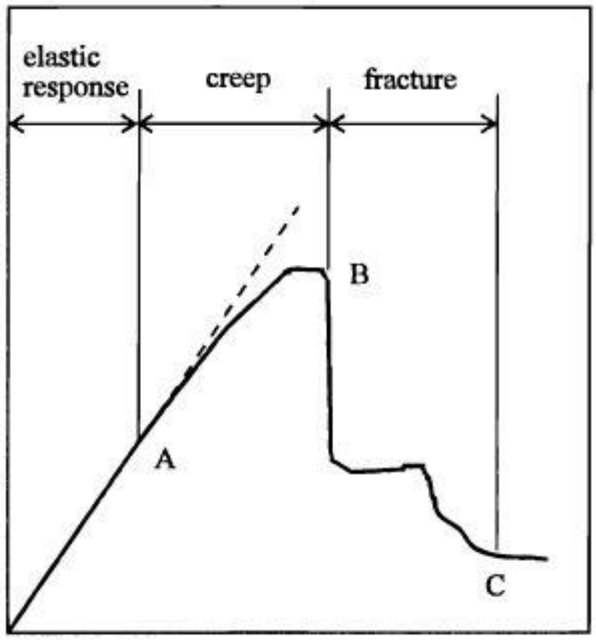

Figure 7: Yielding of Waxy Crude Oil Phases

However, no standard test for determining the yielding quantity of waxy crude oils has been adopted by the petroleum industry because of the poor repeatability in any given instrument and the poor reproducibility between different tests [17]. One of the reason for the poor repeatability and poor reproducibility is that the yield values, along with all other rheological properties of waxy crude oils, strongly depend not only on what the sample is experiencing, i.e., temperature and shear rate, but also on what the sample experienced, i.e., thermal and shear history. Even small variation in any of the test conditions or history can cause a marked difference in the measurements results. Another important reason for poor repeatability is that there are various confusing definitions of the yield stress due to a lack of understanding of the complicated yielding process [20].

Chapter 3
METHODOLOGY

3.1 Research Methodology

Continuous research and literature review will be done until the end of the project duration, expected to be within two semesters, to get a better understanding towards the project topic as well as for overall system improvements.

The whole process of the project can be divided into two parts; designing and assembling the ERT sensor and performing the static test. These phases are given a duration of one semester each and different modification and trial & error are conducted respectively.

Designing the ERT sensor is a very tough task. Research has to be done to fully understand on the ways to construct the sensor. Assembling the sensor is also not a very easy task. Parts of the highest quality are needed to make sure the Data Acquisition System is able to detect the sensor and also for the sensor to properly measure the material in the vessel. This is usually tested during the calibration session. A more detailed explanation is done in part 3.6 and 4.1.

During the static test phase, ERT sensor and test rig design and assembly are done. The test rig design period is expected to take longer than the sensor design period simply because of the thorough planning, tests properties and parameters that has to be taken into consideration. The static test will be carried out once the sensor has been assembled. The static test manipulated variable is the temperature to see the waxy cooled crude oil's reaction towards it while analyzing the data regarding measurement of the multiphase flow and characterizing the flow regime using the ERT sensor. If the result is not satisfactory, troubleshooting to be done and the experiment will be carried out again.

Once the overall result is acceptable, the final report will be prepared. The final report consists of introduction, literature review, methodology, result and discussion and conclusion and recommendation.

3.2 Flow Chart

The following flow chart explains the methodology in executing the project:

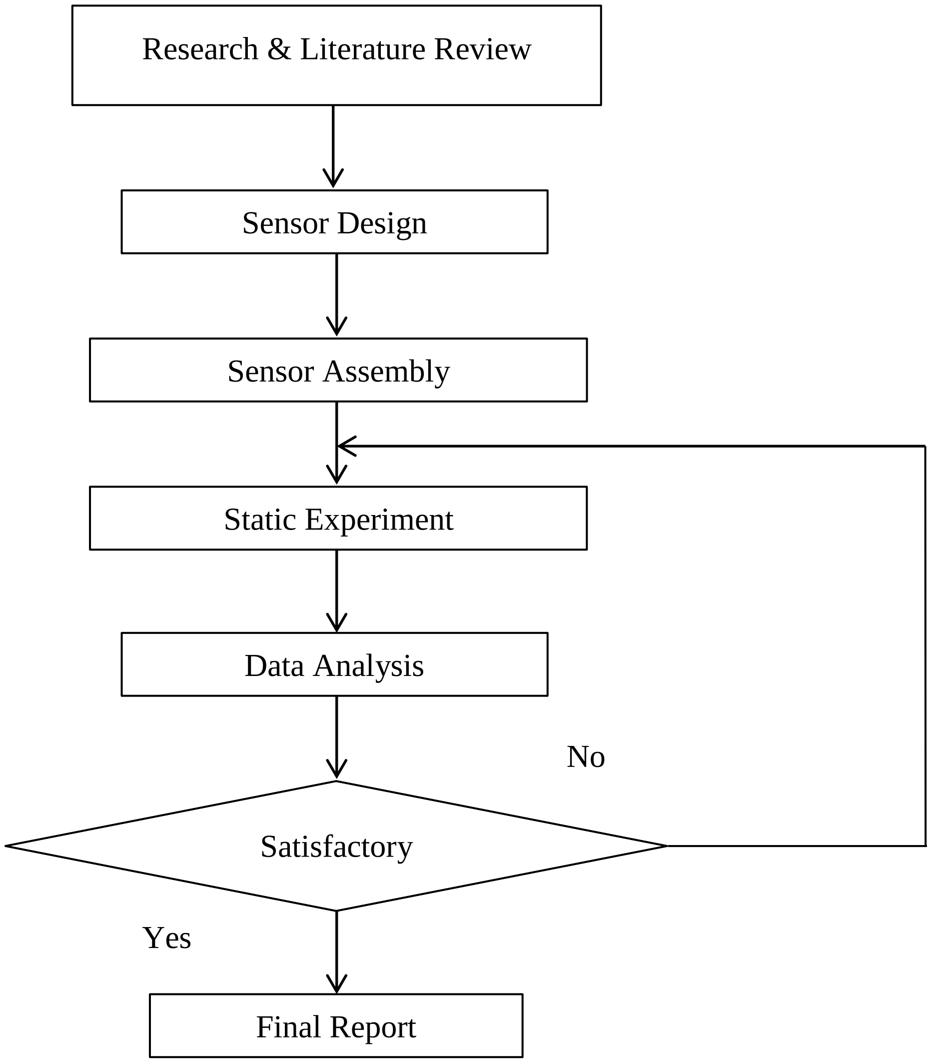

Figure 8: Methodology Flow Chart

3.3 Key Milestones

The key milestones of the project are presented in the table as shown below.

Table 2: Key Milestones

		FYP 1														FYP 2													
	Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Completion on the study of ERT, gas void fraction in multiphase flow and waxy cooled crude oil properties						*																						
2	Completion on developing the model. Static experiment using assembled ERT sensor and data analysis												*																
3	Completion on the test rig design and assembly. Static experiment with varying temperature is done using the merged test rig and ERT sensor.																				*								
4	Completion on the overall data analysis																										*		
5	Research completion																												*

3.4 Gantt Chart

In order to effectively monitor the progress of this project, a Gantt chart consists of one year duration had been constructed.

Table 3: Gantt Chart

NO	DESCRIPTION	FYP 1														FYP 2														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Literature study and review 1. Study of Electrical Resistance Tomography 2.Study about gas void fraction in multiphase flow and flow regime characterization 3. Study about waxy cooled crude oil properties	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
2	Submit extended proposal						■																							
3	Development of ERT sensor and static experiment							■	■	■	■	■	■	■																
4	Viva: proposal defence									■																				
5	Submit draft report FYP 1													■																
6	Submit final report FYP 1														■															
7	Design and develop test rig															■	■	■	■	■	■									
8	Carry out test and experiment of the developed test rig and sensor																		■	■	■									
9	Collect data result and analysis the data																			■	■	■								
10	Collect and analyse the experiment result																						■	■	■	■				
11	Data analysis																							■	■	■	■			
12	Submit draft report FYP 2																											■		
13	Submit final report FYP 2																												■	
14	Viva																													■

3.5 Electrical Resistance Tomography (ERT) Measurement

ERT Sensor comprises measurement of fluid resistance whereby the fluid flowing in the measurement area is categorized as an electrical conductor [8]. The proposed measurement process is simplified in the flow chart as shown in the figure below.

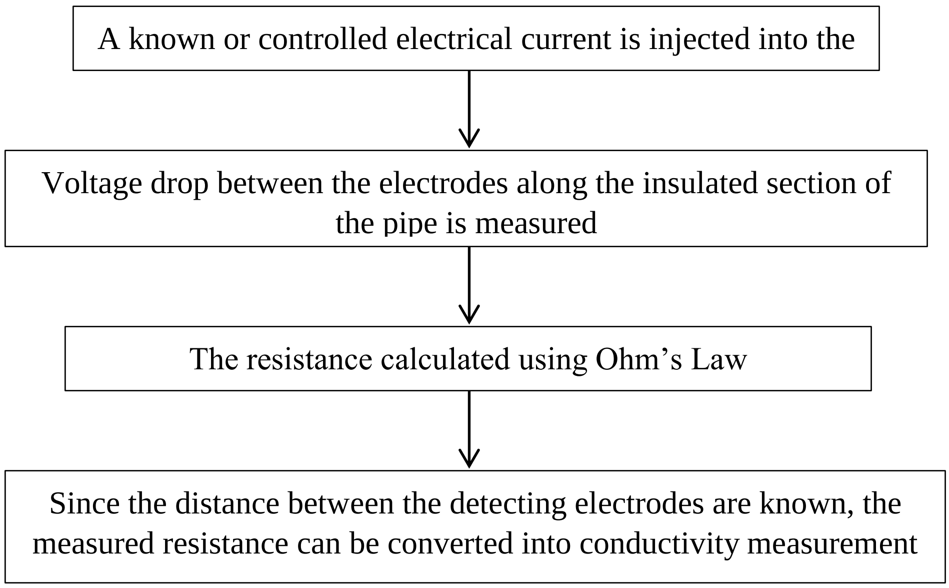

Figure 9: ERT Measurement Flow Chart

3.6 Electrical Resistance Tomography (ERT) Sensor Design

Factors and its descriptions needed to be taken in consideration for a particular ERT sensor design are as listed below:

i. Material for the electrodes
   - Material should be more conductive than the fluids being imaged to prevent problems due to contact impedance

ii. Number of electrodes
   - Typical ERT sensor implements 8, 16 or 32 electrodes. The more electrodes would provide a better image reconstruction [22]. Though, feasibility studies must be done and available resources has to be considered.

iii. Length of electrodes
   - The length depends on the number of electrodes implemented. The more electrodes mean shorter length. The general parameter should be within 0.5-1.0 cm.

iv. Electrodes arrangement
   - Electrodes are arranged and drilled uniformly around circumference of column. They must make electrical contact with the fluid within the process volume.

v. Normal electrical conductivity properties
   - ERT sensor detection and measurement process is based on conductivity. The basic properties of Ohm's Law, V=IR are essential for this project.

vi. Image reconstruction
   - Edge of the sensor is connected to the Data Acquisition System (DAQ) using 9-core control cable terminated with a D-connector. The process is explained further in part 3.7.

3.7 Image Reconstruction

From the data acquisition, the data that will be processed using appropriate image reconstruction algorithm. Assume acceptable results, the reconstructed image should give information on the cross-sectional electrical conductivity distribution within the measurement plane. For this particular project, this means the measurement of gas void fraction in waxy cooled crude oil. The result would show the percentage of which gas void fraction inhabits a certain amount of waxy cooled crude oil [9]. The targeted image reconstruction flow for this project is as shown in the figure below.

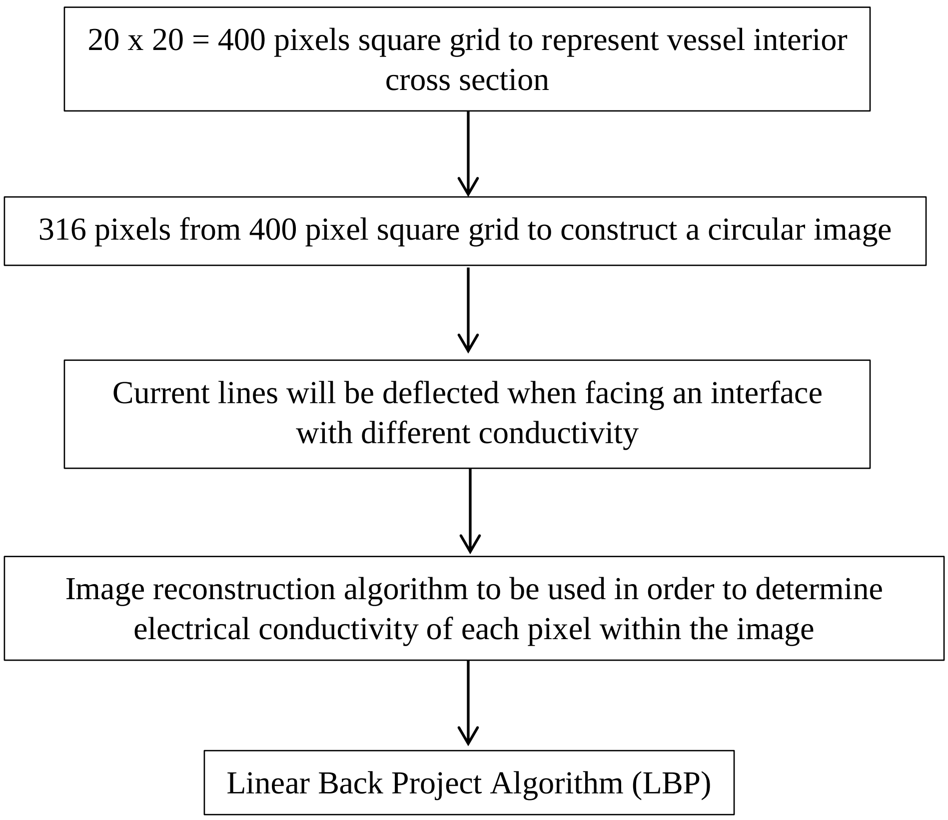

Figure 10: Proposed Image Reconstruction Flow Chart

3.8 Linear Back Projection Algorithm (LBP)

There are many image reconstruction algorithms relevant for tomography system but the author has decided to use the LBP algorithm mainly because it is simple and computationally fast [4-5]. The flow chart shown in the figure below explains concisely on the planned course of image reconstruction using the LBP.

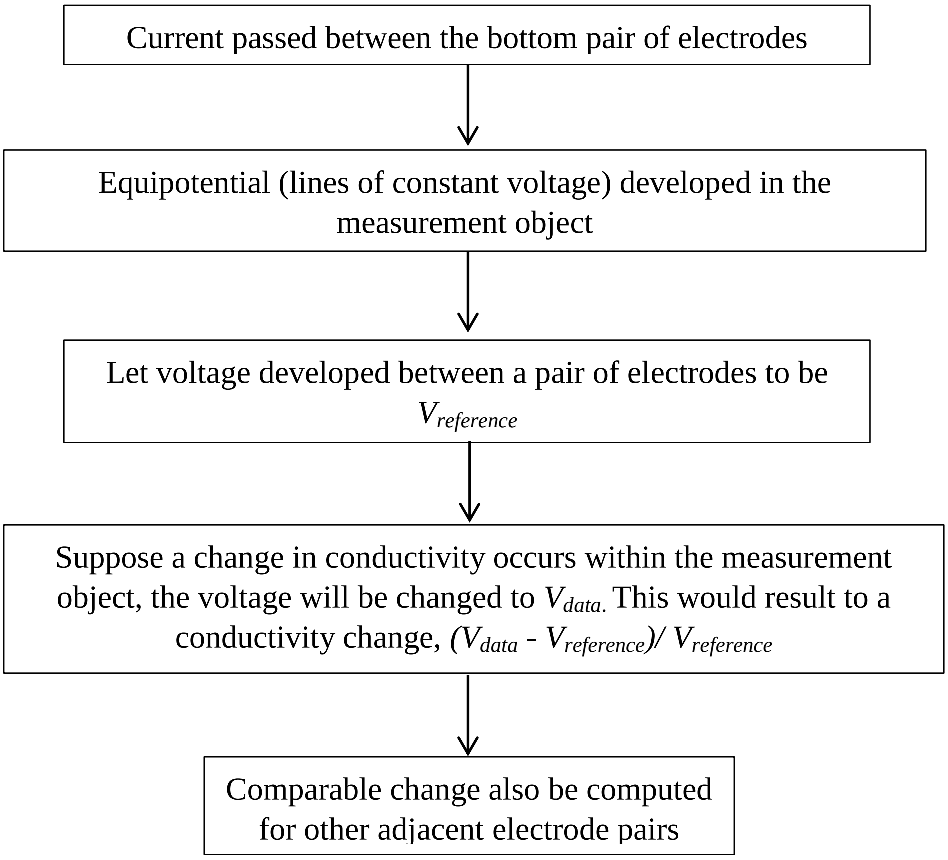

Figure 11: LBP Process Flow Chart

3.9 Static Test

The static test is the most crucial part of this experiment. With reference to the project's objective, this is the part whereby the author will measure, detect, visualize and characterize waxy cooled crude oil with varying temperature.

For the static experiment, the assembled ERT Sensor with proper shielding enclosing waxy cooled crude oil is then placed in a container filled with water. The temperature is then varied from 10°C to 50°C thus affecting the properties and characteristics of the waxy cooled crude oil in the sensor. Data for Raw Resistance (Ω) was collected for every 5°C change of temperature.

Analysis was done towards the collected data to check whether it meets the targeted values before it is finalized in this report.

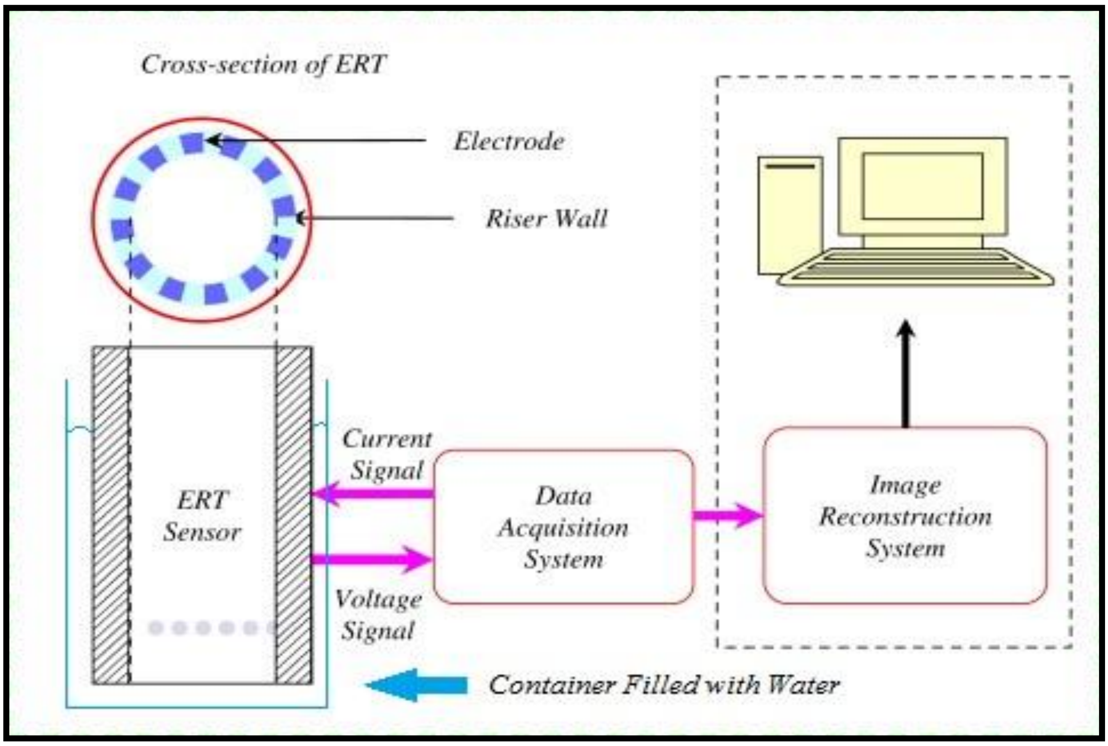

Figure 12: Static Test Setup

Chapter 4
RESULTS AND DISCUSSION

4.1 Sensor Design

For the first phase of this project, an initial or prototype model of 16-electrodes ERT sensor is designed and constructed. PVC is selected to be the main column. The material used for the electrodes should be more conductive than the material being imaged to prevent problems due to contact impedance, for this particular project aluminium plate is being used. The electrodes are then arranged uniformly around the circumference of the column. It should also be noted that the electrodes must make electrical contact with the material within the process volume. This shows that ERT is an invasive yet nonintrusive method.

Table 4: Tools Description and Amount for Sensor Design

Tools	Description	Amount
Industrial Tomography System (ITS)	Interface module for calibration, data acquisition, processing and analyzing.	1
Aluminum Plate	Electrode fabrication. Should be more conductive than process material. Uniformly arranged around circumference of column	16
Data Cable and Connector	Connection for each electrodes to ITS	16
Pipe Column	Chosen column, body material and sensor holder. PVC.	1
Soldering Iron and lead	Merging of data cable terminal and copper tape.	1

Figure 13: Prototype Model of the 16 Electrodes ERT Sensor

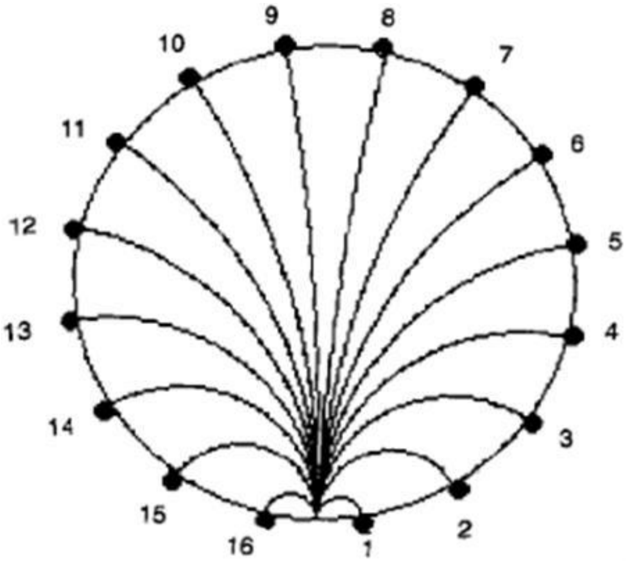

Figure 14: Expected Equipotential Lines for 16 Electrodes ERT Sensor

A better suited dimension will be used to design another ERT sensor for the next part of the project which is to run the Static test to characterize waxy cooled crude oil.

4.2 Sensor Calibration Results

<u>Low Calibration</u>

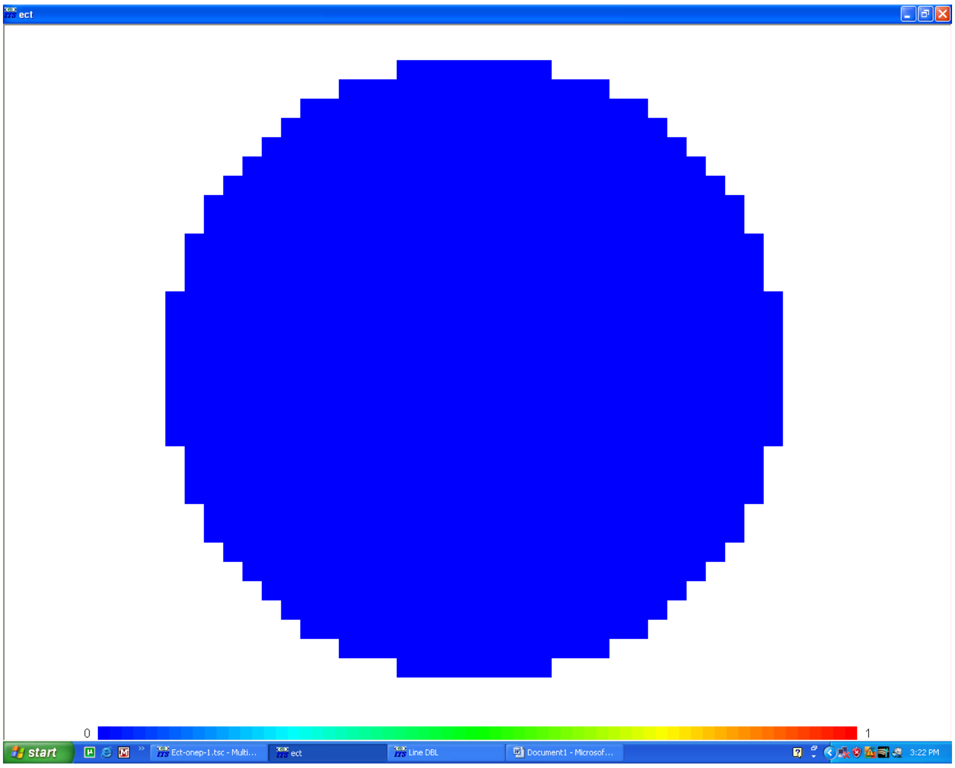

Figure 15: Resulting Low Calibration Tomogram

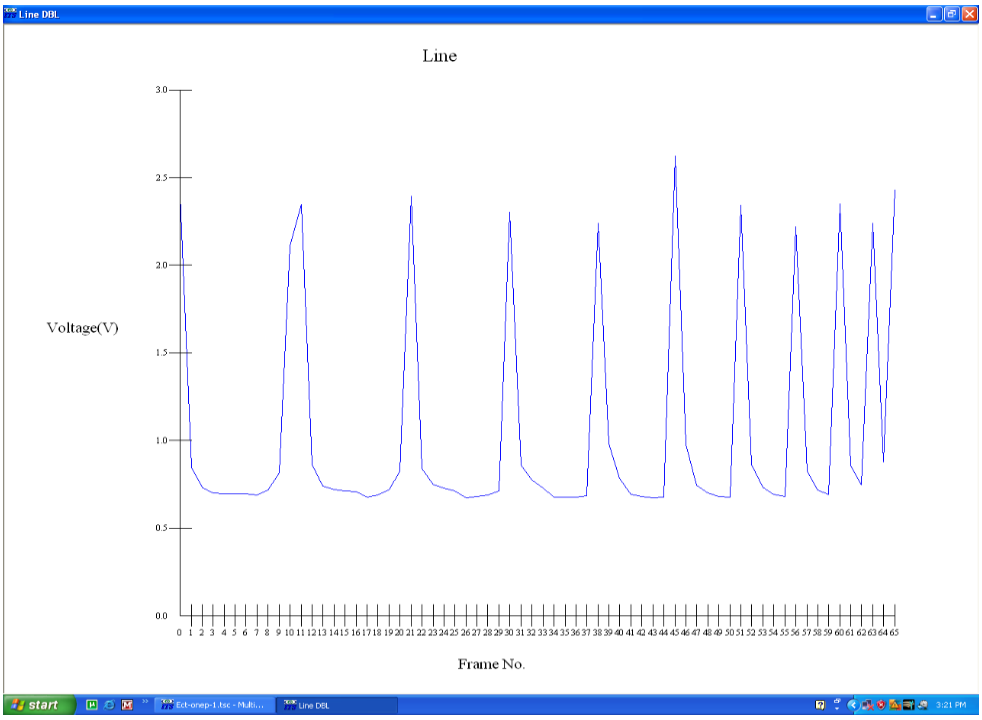

Figure 16: Resulting Low Calibration Voltage Measurement

High Calibration

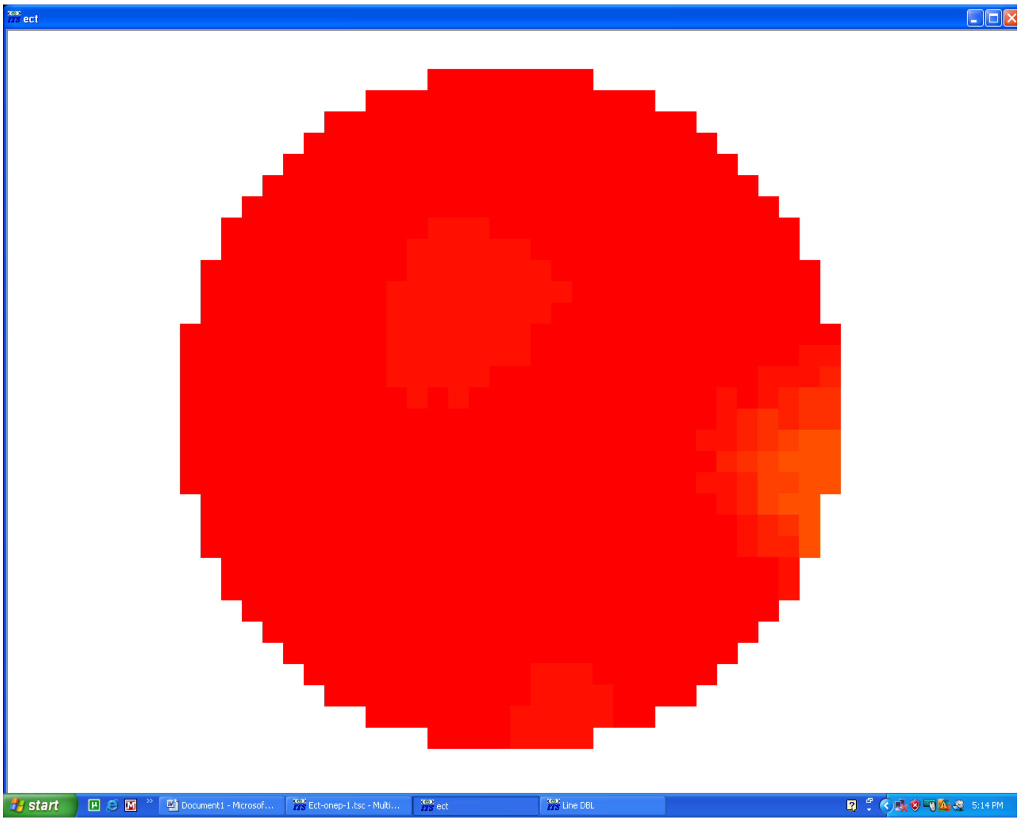

Figure 17: Resulting High Calibration Tomogram

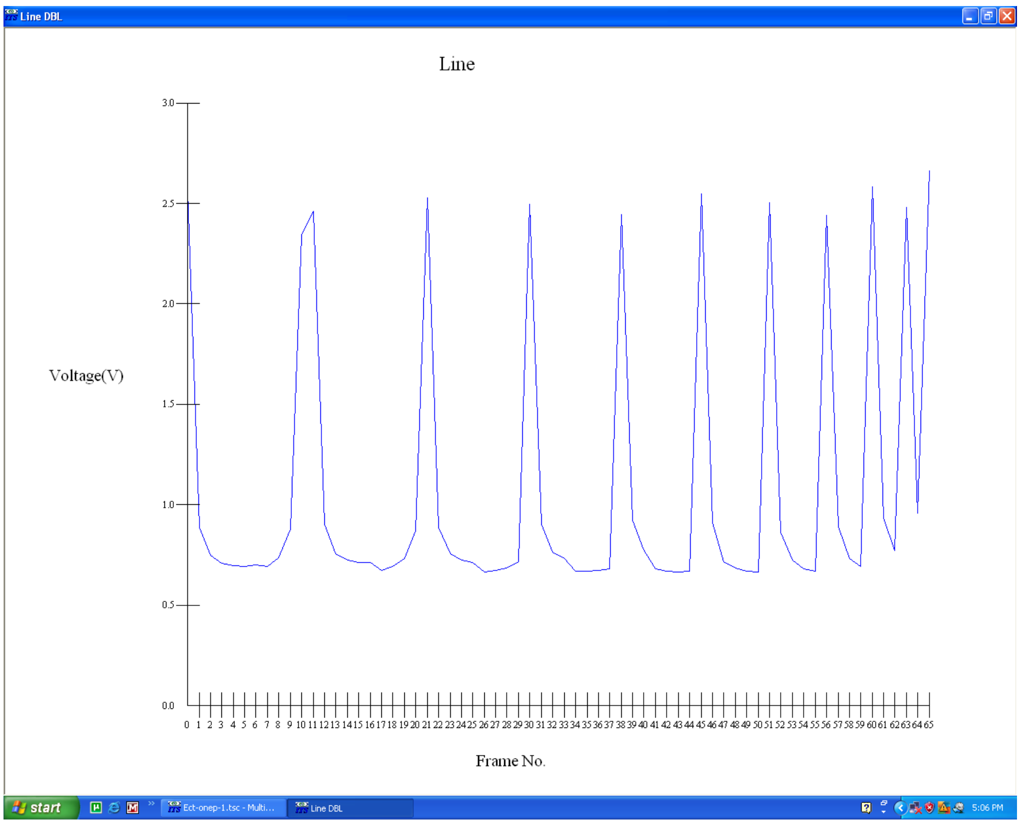

Figure 18: Resulting High Calibration Voltage Measurement

4.3 WAT Table

The waxy cooled crude oil used in this project was recovered at the Sepat Field owned by PETRONAS Carigali Sdn. Bhd. (PCSB). To get a better understanding regarding the waxy cooled crude oil properties and characteristics as well as the liquid and waxy phase within the 10°C to 50°C margin, a Wax Appearance Temperature (WAT) table from PCSB is used as reference.

WAT is the point whereby the crude oil will develop into waxy cooled or semi-solid state. The pour point on the other hand is defined to be the lowest temperature at which the crude oil will be in the liquid state.

Referring to the table below, the Sepat crude oil's WAT and pour point is both evaluated to be at 35°C. This shows that if the temperature of the crude oil goes below the critical 35°C temperature point, wax will start to appear and it will no longer be in the liquid state instead the crude oil will be semi-solid.

Table 5: Wax Appearance Temperature (WAT) Table

Field	Fluid	Location	WAT/Cloud Pt (°C)	Pour Point (°C)	Wax Content (wt%)
Angsi	Oil	Malaysia	39	26	12
Anding Utara –1	Oil	Malaysia	61	30	11
J4	Oil	Malaysia	32	27	26
D21	Oil	Malaysia	41	32	22
Penara	Oil	Malaysia	68	51	24
Sepat	Oil	Malaysia	35	35	18
Malikai	Oil	Malaysia	22 (CWDT)	18	5
Diyaberkir	Oil	Turkmenistan	36	17	17
Thang Long	Oil	Vietnam	60	36	19
Topaz	Oil	Vietnam	49	30	12
Chinguetti	Oil	Mauritania	39	15	5
Adar	Oil	Sudan	66	42	27
Owez	Condensate	Turkmenistan	17	-3	4
Rehmat	Condensate	Pakistan	22	19	15
Mehar	Condensate	Pakistan	41	-12	3
Mashrykov	Condensate	Turkmenistan	20	-3	1

4.4 Raw Resistance (Ω) Distribution

From the static experiment, the author obtained a Raw Resistance (Ω) graph of 66 readings for every 5°C change of temperature of the 10°C to 50°C margin. This represents the distribution of Raw Resistance (Ω) over temperature. The distribution of Raw Resistance (Ω) is well within the boundaries of the High and Low Calibration thus the data can be accepted. From the graph, the author can note that electrode 9, 10 and 11 may sometimes be faulty.

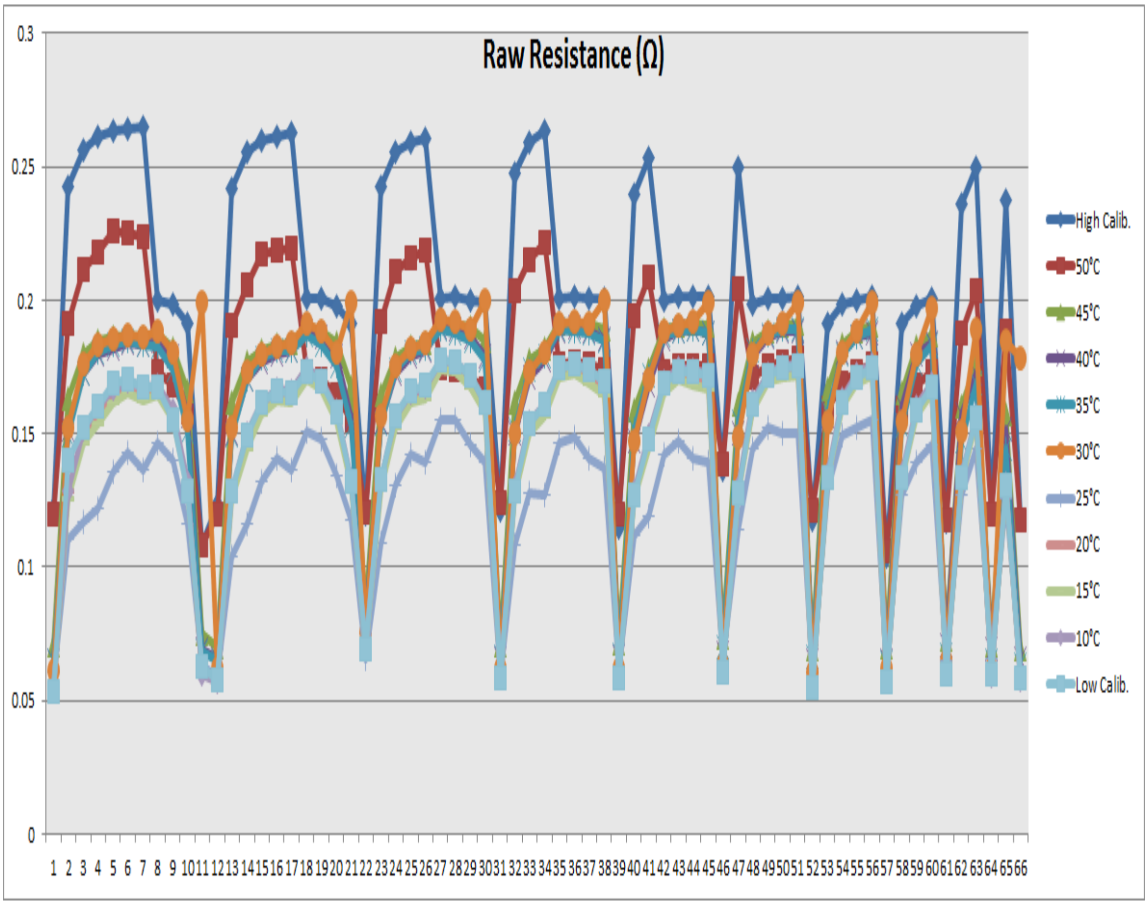

Figure 19: Raw Resistance (Ω) Distribution Graph

4.5 Raw Resistance (Ω) Distribution and Temperature (°C) Relation

In order to get the relationship between the distributions of Raw Resistance towards temperature, the author analyzed five sets of data with studies the reading between adjacent electrodes, every 2 electrodes, every 3 electrodes, every 4 electrodes and every 5 electrodes.

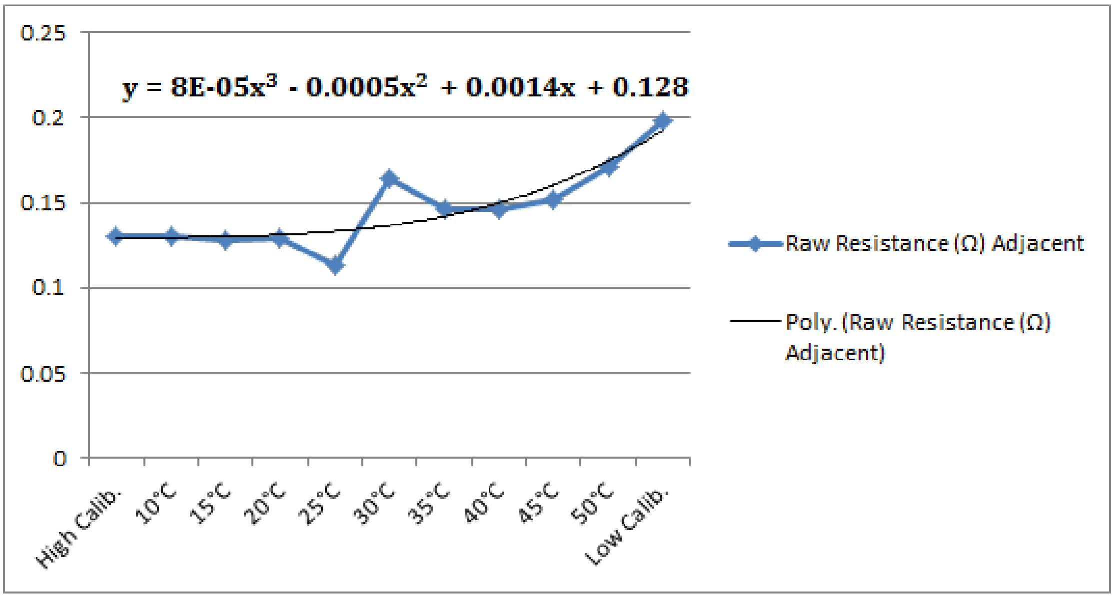

Figure 20: Raw Resistance (Ω) vs Temperature (°C) Graph for Adjacent Electrodes

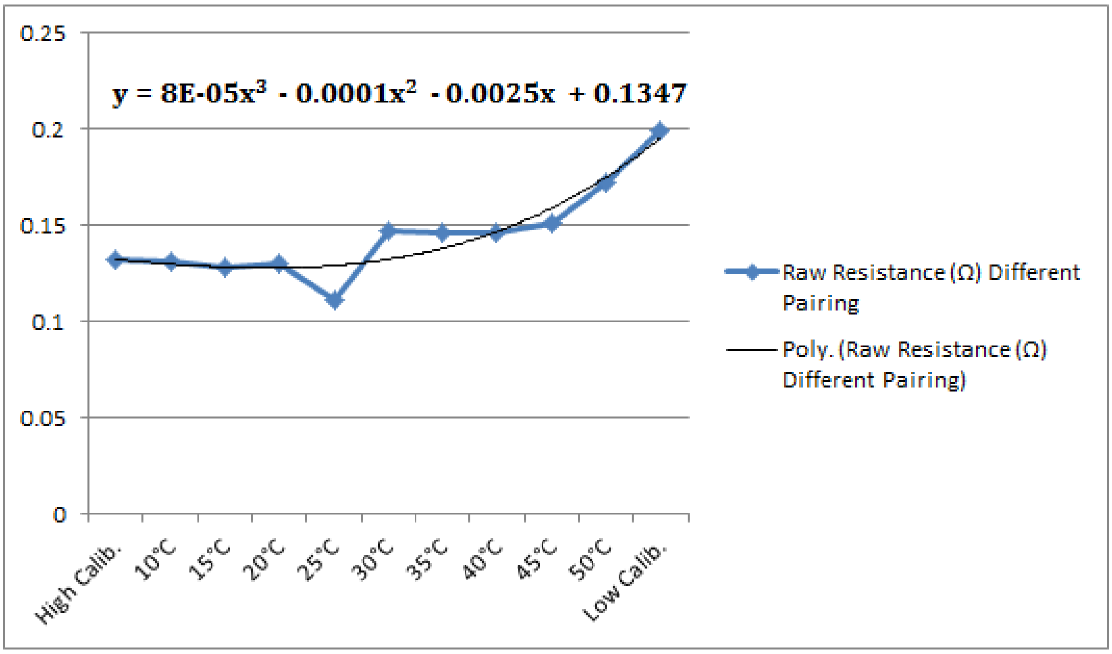

Figure 21: Raw Resistance (Ω) vs Temperature (°C) Graph for Different Pairing

Table 6: Electrodes Pairing

Pairing	Electrodes Pairing							
Adjacent Electrodes	1;2	1;12	2;3	3;4	4;5	5;6	6;7	7;8
Skip 1 Electrodes	1;3	2;4	2;12	3;5	4;6	5;7	6;8	X
Skip 2 Electrodes	1;4	2;5	3;6	3;12	4;7	5;8	X	X
Skip 3 Electrodes	1;5	2;6	3;7	4;8	4;12	X	X	X
Skip 4 Electrodes	1;6	2;7	3;8	5;12	X	X	X	X
Skip 5 Electrodes	1;7	2;8	3;9	X	X	X	X	X

Table 6 shows the pairing in which the Raw Resistance (Ω) reading is obtained towards every change in Temperature (°C). Electrodes 9, 10 and 11 are not taken into consideration since they are faulty.

Figure 20 and 21 are the resultant graphs from Table 6. Basically Figure 21 the result for the pairing other than the Adjacent Electrodes Pairing as all 5 pairings resulted in the same graph.

From Figure 20 and 21 obtained from the Table 6 data, the author can observe that the distribution of Raw Resistance (Ω) is directly proportional towards the change in Temperature (°C). It can also be observed that there is a slight drop in each graph at the 25°C point upon reaching the crucial WAT and Pour Point which represents the properties of the crude oil which is undergoing a phase change.

Chapter 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The Static test will be performed to characterize the waxy cooled crude oil using the ERT method. Ongoing studies are needed in order to fully understand the project especially regarding the functionality of ERT sensor and the change in characteristics and properties of the crude oil towards temperature. The sensor consists of 16 electrodes. The concept of ERT revolves around the theory of resistance and conductivity of given medium secluded in an area.

The conductivity will typically be measured by injecting a known or controlled electrical current into the flow, the voltage drop between two electrodes along an insulated section of the pipe will be measured. Resistance can be calculated using the Ohm's Law and later converted into a conductivity measurement.

The project is relevant and feasible since it is a study which overlaps the Oil & Gas and Instrumentation & Control industry and with the equipment and time available, the author is confident that the outcome of the project; characterization of waxy cooled crude oil will be a useful information to be used by any personals related to the study.

Another application of ERT is Seismic Studies in Oil & Gas whereby Geophysicist compares the value of obtained Raw Resistance (°C) to predict the Earth layers. This project shows that ERT is also appropriate to be implemented on pipelines at producing oilfields to predict the characteristic of the crude oil produced especially during emergency or maintenance shutdown with different temperature conditions.

5.2 Recommendation

Thorough understanding the objective of this project is very important in order to predict and anticipate the result of the experiment and to make sure the project is done within the allocated time. Consistent meeting with the supervisor is needed to avoid doing mistakes which would affect the overall result of the project.

Throughout working on this project, safety is prioritized especially because the material used in this project; crude oil, is highly flammable and will be ignited with the slightest of error especially when current is injected inside the ERT sensor.

Calibration of the ERT sensor has to be done for every online measurement to make sure that the sensor is working well in order to get the best results. Modification and repair needs to be done whenever necessary since the sensor is very fragile and may produce poor results due to deterioration of the electrodes as well as external disturbance. It is best to consult the lab technician if the ERT sensor or Data Acquisition System is not working properly.

Since the ERT sensor is placed in a container filled with water, coating has to be used to cover the electrodes from being spoilt. It is also recommended to make sure no wires are exposed to water as this will lead to a very harmful situation.

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