INVESTIGATION OF ELECTRICAL CAPACITANCE TOMOGRAPHY FOR AGARWOOD DETECTION

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INVESTIGATION OF ELECTRICAL CAPACITANCE TOMOGRAPHY
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Thesis submitted in fulfillment of the requirements
for the award of the degree of
Bachelor Engineering (Hons.) Electrical Engineering (Electronics)

Faculty of Electrical & Electronics Engineering

UNIVERSITI MALAYSIA PAHANG

JUNE 2022

ACKNOWLEDGEMENTS

All praise be to Allah SWT the only one who the most merciful for providing the strength to complete this project. Throughout the whole journey of this project, I had to take help and guideline of some respected persons, who deserve our greatest gratitude. The completion of this assignment gives much pleasure. I would like to show my gratitude to Ts. Dr. Yasmin Binti Abdul Wahab, my course supervisor who giving me the opportunity conduct this project and providing invaluable guidance throughout this project. Her dynamism, vision, sincerity, and motivation have deeply inspired me. She has taught me the methodology to carry out the research and to present the research works as clearlyas possible. It was a great privilege and honor to work and study under her guidance.

I would like to thank the teaching and non-teaching staffs from Faculty of Electrical & Electronics Engineering for sharing their knowledge and lend us their facilities. And a special thanks goes for my beloved family and friends for the constant moral support and motivation. Their motivation keeps me going and bring the out the potential in me to give my all for this project.

Lastly, I would like to express my heartfelt gratitude to anyone who contributed to the process of succeeding this project. I hope that all the research done on putting this project into words would be one of a great use and would bring about a great inspiration.

ABSTRAK

Gaharu (Aquilaria Malaccensis) atau dikenali sebagai Gaharu di Malaysia, mempunyai nilai yang tinggi di pasaran dan minyaknya digunakan secara meluas untuk menghasilkan ubat-ubatan. Untuk mendapatkan gaharu yang matang dan berkualiti, masa yang lama diperlukan untuk menunggu pokok itu membesar dan berdasarkan penyelidikan yang sedia ada, manusia tidak dapat meramalkan penempatan dan kuantiti gaharu di dalam pokok. Projek ini bertujuan untuk menyiasat keupayaan kaedah tidak invasif untuk sistem tomografi kapasiti elektrik untuk memantau kuantiti gaharu dalam pokok. Berdasarkan penyelidikan yang sedia ada, kaedah tomografi yang biasa digunakan adalah berdasarkan pendekatan tomografi sonik, induktif magnet dan tomografi gelombang mikro. Tetapi masih tidak diketahui sama ada tahap variasi voltan adalah sedikit atau ketara di rantau dengan resin. Maka, projek ini membentangkan proses pembangunan untuk memodelkan peranti ECT (Electrical Capacitance Tomography) dengan menggunakan COMSOL Multiphysics. Perisian COMSOL Multiphysics dilaksanakan sebagai alat utama untuk memodelkan sistem ECT. 8 elektrod dimodelkan dalam 2 dimensi, dan ia berdasarkan pendekatan tidak invasif. Sistem ECT dibangunkan untuk mendapatkan taburan potensi elektrik antara elektrod apabila medan elektrik digunakan dan untuk menilai analisis prestasi model ECT yang dicadangkan dengan mengambil kira lokasi, bentuk dan saiz gaharu yang berbeza dalam pokok. Selain itu, penyebaran sensitiviti di dalam masalah ke hadapan diselesaikan dalam COMSOL dan dieksport ke dalam perisian MATLAB. Selepas itu, gambar tomogram bagi pokok kayu Gaharu diperolehi dengan menggunakan algoritma unjuran belakang linear (LBP) juga di dalam MATLAB. Nilai MSSIM digunakan untuk membuat analisa gambar-gambar yang diperolehi. Akhirnya, untuk saiz berbeza kayu gaharu (nilai MSSIM = 0.1052), kedudukan berbeza kayu gaharu (kanan atas) (nilai MSSIM = 0.1587) dan bentuk F (nilai MSSIM = 0.1081) adalah imej yang dibina semula hampir sepadan dengan imej rujukan kerana nilai MSSIM berjulat antara 0 hingga 1, 1 bermaksud padan sempurna imej bina semula dengan imej asal.

ABSTRACT

Agarwood (Aquilaria Malaccensis) or known as Gaharu in Malaysia, has high value in the market and its oil is widely used for producing medication. To get matured and quality agarwood, it needs to wait for the tree to grow and human experience cannot predict the placement and quantity of agarwood in a tree. The project aims to investigate the possibility of non-invasive method using electrical capacitance tomography for monitoring the quantity of agarwood in a tree. Based on the current research, the commonly applied tomography on method is based on sonic, magnetic inductive and microwave tomography approaches. But it is still unknown whether the voltage variations level are slight or significant in the region with resin. This work presents the development process for modeling an ECT (Electrical Capacitance Tomography) sensor using COMSOL Multiphysics. COMSOL Multiphysics software is implemented as a main tool to model the ECT system. The 8 electrodes are modeled in 2-dimensional, and it is based on the non-invasive approach. The ECT system is developed to obtain the electrical potential distribution between electrodes when an electric field is applied and to evaluate the performance analysis of proposed ECT model considering different locations, shapes, and sizes of agarwood in atree. Moreover, the sensitivity distribution using 64x64 pixels in forward problem was solved using COMSOL and export into the MATLAB software. Then, the tomogram images of agarwood were obtained using linear back projection algorithm (LBP) in the MATLAB software. Later, the MSSIM was used as the image analysis. In short, for agarwood different size (MSSIM value = 0.1052), agarwood different position (top right) (MSSIM value = 0.1587) and agarwood phantom F (MSSIM value = 0.1081) were the reconstructed image that closely matches with the reference image because the MSSIM value ranges is between 0 to 1, whereby the value 1 means the perfect match of the reconstructed image with the original one.

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LIST OF SYMBOLS

ε_r	Relative permittivity
ε_o	Permittivity of free space
E	Electric field
φ	Electric field potential distribution within the sensor
ρ_v	Volume charge density
D	Electric flux density
T	The number of excitation electrodes
R	The number of measuring electrodes
G_{LBP}	Potential distribution
L_{ji}	The sensitivity map at each i and j
J_{ji}	Sensor loss
S_{ij} (inc)	The potential measured for no agarwood
S_{ij} (tot)	The potential measured for agarwood

LIST OF ABBREVIATIONS

ECT	Electrical Capacitance Tomography
MIT	Magnetic Induction Tomography
MWT	Microwave Tomography
ERT	Electrical Resistance Tomography
EIT	Electrical Inductance Tomography
LBP	Linear Back Projection
MSSIM	Multi Scale Structural Similarity Index

CHAPTER 1

INTRODUCTION

1.1 Project Background

1.1.1 An Overview of Process Tomography

The term "Tomography" is coming from combination of Greek words there are "tomo" and "graph" which means a slice and picture [1].

Tomography is used in many fields of education and industry processes. In medical field, it is used to diagnostic patients, where X-rays have been used as sources of radiation to create images of bones. This method is very helpful for seeing the internal structure (bones) without any surgery. Tomography technology involves the acquisition of measurement signals from sensors located on the periphery ofan object, such as a process vessel or pipeline [1]. This reveals information on the nature and distribution of components within the sensing zone.

Most tomography techniques are concerned with abstracting information to form a cross sectional image. For example, a parallel array sensor (see Figure 1.1) is placed around the region of interest so that their sensing field interrogates a projection of suitable radiation across the subject,which is assumed to be of circular cross section. In order to explore the entire cross section, it is necessary to obtain other projections by rotating the subject in the direction normal to the direction of the sensor field or, preferably, by rotating the measurement sensors around the subject [1].

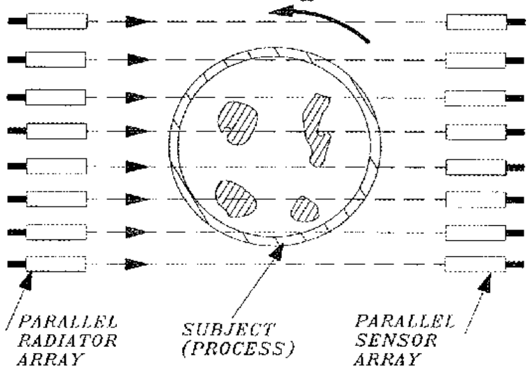


Figure 1.1 Use of projections to form an image [2]

1.1.2 Importance of Study

Electrical capacitance tomography (ECT) is a technique for image processing that was developed primarily for industrial purposes. The fundamental premise of ECT is to calculate the difference in permittivity produced by the addition of a new material or a change in the distribution of materials within an ECT system. The ECT sensor is comprised of a number of electrodes, often six, eight, twelve, or sixteen, which are arranged in a round conduction pipe or an insulating pipe around the outside or inside border [1] [3] [4].

ECT is mostly used in industrial applications for two or three-phase measurement of flow parameters. However, there is no strategy for agarwood in the ECT technique yet. Because ECT is low energy, low frequency, and non-radioactive, it is safe to use in any circumstance, including hazardous waste, high voltage, or electromagnetic radiation [10]. Due to the technology's low energy consumption, it is also useful for rural places with limited access to electricity. Often, a simple solar powered battery will be enough to power an ECT device. For agarwood detection, the current research that had been done by other researchers are only based on simulated magnetic inductive tomography [14] and microwave tomography [15]. As a result, electrical capacitance tomography is proposed in this project whereby the varying electrical permittivity of the agarwood will be the primary concern for this simulation model of the ECT system.

1.2 Problem Statement

Basically, current research on the monitoring of the quantity of agarwood in a tree are applied by magnetic inductive tomography and microwave tomography method. But, it is still unknown whether the voltage variations level is slight or significant in the region with resin. Therefore, this project is to propose an ECT system that uses a non-invasive approach to detect the condition which is locations, sizes, and shapes of agarwood.

1.3 Objectives

The objectives of this project comprise of the following:

i. To model the ECT system using COMSOL Multiphysics softwarefor detecting agarwood.
ii. To construct the image using suitable algorithm.
iii. To evaluate the performance analysis of proposed ECT model consideringdifferent locations, shapes, and sizes of agarwood.

1.4 Scope of Projects

The scopes of this project are:

i. Use 8 electrodes of ECT sensor.
ii. The material for each of the electrodes are gold with (1.143) value of relative permittivity and (4.10E10^7) value of electrical conductivity.
iii. The diameter for wood is 600mm and agarwood 181mm.
iv. 9 types phantoms of agarwood.

1.5 Structure of Thesis

The essential elements of this thesis are introduction, literature review, methodology, results and discussion and conclusion. The introduction chapter is to brief an overview of tomography, importance of study, problem statement, objectives, and scopes of project. Furthermore, the literature review discusses published information about tomography and electrical capacitance tomography. Besides, the chapter on methodology explains the approaches used to model the ECT system using COMSOL Multiphysics software. Then, reconstruct the image with linear back projection (LBP) algorithm using MATLAB software. For the result and discussion part, it shows the results and analysis for the simulation in COMSOL Multiphysics software and also for the simulation in MATLAB software. Finally, the conclusion chapter is the most important chapter that concludes all the project works for this non- invasive technique of electrical capacitance tomography.

CHAPTER 2

LITERATURE REVIEW

2.1 Process Tomography

2.1.1 Introduction

The term "tomography" refers to the analysis of data from sensors positioned on the perimeter of an object, such as a main tank or piping [2]. Additional projects must be created to examine the whole cross-sectional area, either by turning the object in the direction normal into the sensor direction of the field or by effectively turning the detecting sensor around the object [2].

Tomography consists of hardware-based procedure that includes sensor and measuring circuitry, image reconstructing software, and a display device for displaying the produced picture [2]. The sensor will determine the presence of things inside the detecting zone. After undergoing image reconstruction algorithm processing and being shown on a personal computer, the information and distribution of components will be revealed in the form of a cross-sectional image. For instance, this project investigates the conditions of the different types of agarwood including their sizes, position, and shapes.

Agarwood has been subjected to a number of tomographic measurement techniques, including Magnetic Inductive Tomography (MIT), Microwave Tomography (MWT), Electrical Resistance Tomography (ERT), Electrical Impedance Tomography (EIT), and Electrical Capacitance Tomography (ECT). When taking tomographic tests, the parts are comparable and may be classified into four distinct categories: sensors, electronic measurement, data collection, and result presentation [1].

2.1.2 Magnetic Induction Tomography

Magnetic Induction Tomography (MIT) is a non-invasive, contactless imaging technique for mapping a material's passive electrical properties, including conductivity, permittivity, and permeability [9]. MIT is an imaging technique that makes use of the eddy current effect to determine an object's electromagnetic properties [5]. It is also referred to as eddy current tomography, electromagnetic induction tomography, electromagnetic tomography (EMT), eddy current testing, and eddy current tomography. The technique is used in non-destructive testing and geophysics and may find applications in the process industry and in medicine. Additionally, it is used to create three-dimensional images of passive electrical properties (PEP), which has applications in brain imaging, cryosurgery monitoring in medical imaging, and metal flow visualization in metal working processes. MIT induces eddy currents in the material by applying a magnetic field via an excitation coil. Thus, eddy currents alter the distribution of the excitation magnetic field, which is measured by the sensing coils [6].

2.1.3 Microwave Tomography

Microwave tomography (MWT) is a new biomedical imaging technique with enormous promise for non-invasive evaluation of soft tissue functioning and functional problems [21]. MWT system is composed of both hardware and software components. Data is collected from the sample under test by the equipment. A transmitting antenna directs electromagnetic waves toward the material under examination, for example, such as human body for medical imaging. Theoretically, no electromagnetic wave will be reflected if the sample is formed entirely of homogenous material and is infinite in size [21]. Any abnormality having different characteristics for example, electrical or magnetic than the surrounding homogeneous material may reflect a part of the electromagnetic wave. The greater the difference in qualities between the anomaly and the surrounding medium, the stronger the reflected wave. In a monostatic system, this reflection is caught by the same antenna; in bistatic systems, it is collected by a distinct reception antenna. To improve the imaging system's cross-range resolution, many antennas should be spread throughout an area (called the sample area) with a spacing less than the operational wavelength [21]. Mutual coupling between antennas located adjacentto each other, on the other hand, may reduce the accuracy of the gathered signals.

2.2 Electrical Capacitance Tomography

Electrical Capacitance Tomography is a technique for obtaining information about the contents of vessels. It is based on the dielectric distribution of the material inside the vessel [1]. The basic idea is to install a number conducting plates (electrodes) around the periphery of the vessel. The images can be constructed based on a signal obtained at each of the receivers of the capacitor electrodes [3]. The design of ECT sensors is closely linked to the capabilities of the capacitance measuring equipment to be used with the sensor. An ideal capacitance measuring system will have a very low noise level, a wide dynamic measurement range, high immunity to stray capacitance to earth and be able to carry out measurements at high speed.

There are several journals that give the idea and to understand the concept types of tomography is shown in Table 2.1.

Table 2.1 Current research on tomography

NO.	AUTHOR	TITLE	METHODOLOGY
1.	Nurfarahin Ishak, Chua King Lee, Siti Zarina Mohd Muji (2021)	A Simulation Magnetic Induction Tomography (MIT) For Agarwood	- 8 channel coils - 7 channel coils receiver and 1 channel coil transmitter
2.	Mohd Hafiz Fazalul Rahiman, Soh Ping Jack, Thomas Tan Wan Kiat (2021)	Microwave Tomography For Agarwood Detection	- 8 electrodes and 12 electrodes - Suggest Newton's One-Step Error Reconstruction (NOSER)
3.	Qiang Du, Baodong Bai, Peipei Pang, Li Ke (2012)	An Improved Reconstruction Method Of MIT Based On One-step NOSER	- Using Newton's One-Step Error Reconstruction (NOSER)

NO.	AUTHOR	TITLE	METHODOLOGY
4.	Parham Hashemzadeh, Panagiotis Kantartzis, Ali Zifan, Panos Liatsis, Sven Nordebo, Richard Bayford (2010)	A Fisher Information Matrix Interpretation Of The NOSER Algorithm In Electrical Impedance Tomography	- 16 electrodes - Using Newton's One-Step Error Reconstruction (NOSER)
5.	Parham Hashemzadeh, Panagiotis Kantartzis, Ali Zifan, Panos Liatsis, Sven Nordebo, Richard Bayford (2010)	Optimization Of Geometrical Parameters Of ECT Sensor For Power Cable Insulation Detection	- 8 electrodes - Linear Back Projection (LBP) Algorithm
6.	Parham Hashemzadeh, Panagiotis Kantartzis, Ali Zifan, Panos Liatsis, Sven Nordebo, Richard Bayford (2010)	A Comparative Study Of Different Methods Using Electrical Capacitance Tomography For Water-dominated Multiphase Vertical Flows	- 8 electrodes - Landweber Algorithm - Tikhonov Algorithm - LBP Algorithm
7.	Cagdas Gunes, Shah Chowdhury, Qussai M. Marashdeh, Fernando L. Teixeira (2017)	Displacement - Current Phase Tomography And Electrical Capacitance Tomography For Air-water Flow Systems	- 12 electrodes - Landweber Algorithm
8.	Marco A. Rodriguez Frias, Wuqiang Yang (2018)	Dual-modality Four-wire Electrical Capacitance And Resistance Tomography	- 8 electrodes - Landweber Algorithm
9.	Lifeng Zhang, Menghan Zhang (2021)	Image Reconstruction Of Electrical Capacitance Tomography Based On Optimal Simulated Annealing Algorithm Using Orthogonal Test Method	- 12 electrodes - Simulated Annealing (SA) Algorithm - LBP Algorithm - Landweber Algorithm

NO.	AUTHOR	TITLE	METHODOLOGY
10.	Wenbin Tian, Mimi Faisyalini Ramli, Wuqiang (2017)	Investigation Of Relaxation Factor In Landweber Iterative Algorithm For Electrical Capacitance Tomography	- 8 and 12 electrodes - Landweber Algorithm
11.	Yinyan Liu, Yuchi Deng, Yi Li (2017)	Experimental Investigation Of Gas-oil Two-phase Flow Using Electrical Capacitance Tomography	- 8 electrodes - LBP Algorithm
12.	Lifeng Zhang, Jing Liu, Pei Tian (2015)	Six Rotating Electrodes Exciting-measuring Mode For Electrical Capacitance Tomography System	- 12 electrodes - Landweber Algorithm

2.2.1 Principles of Electrical Capacitance Tomography (ECT)

An ECT consists of a set measurement electrode mounted symmetrically inside or more typically outside an insulation pipe. A typical ECT system consists of a sensor built up of 6, 8, 12 or 16 electrodes, a capacitance measurement circuit, a central control unit and a control PC [1] [3]. In ECT, a 6 of electrodes are usually used in visual combustion flame in engine cylinder, 8 electrodes are used for imaging wet gas separator, 12 electrodes are used in measuring three component flow which are gas, oil and water, while 16 electrodes are used in the process of imaging nylon polymerization [3] [12].

The capacitance measurement circuit or also recognized as the signal conditioning circuit is used to obtain data and transform the measurement readings into digital. A central control unit is built to synchronize all the operations and to transfer the data to a computer. The computer receiving the reading of the measurements must store the data obtained, regenerate images from the integral measurements and take action feedback to control the flow.

The signal conditioning system consists of several parts, such as capacitance measurement circuit, amplifying circuit, filter circuit and finally AC to DC converter circuit [1]. Other than that, a high frequency sine wave generator or electric potential is also required as the excitation source for the sensor electrodes [1]. The electronic devices output the data and send to the data acquisition system for analog to digital conversion purpose. The digital data will be sent to computer for analysis and image reconstruction. The topology of an ECT system is shown in Figure 2.1.

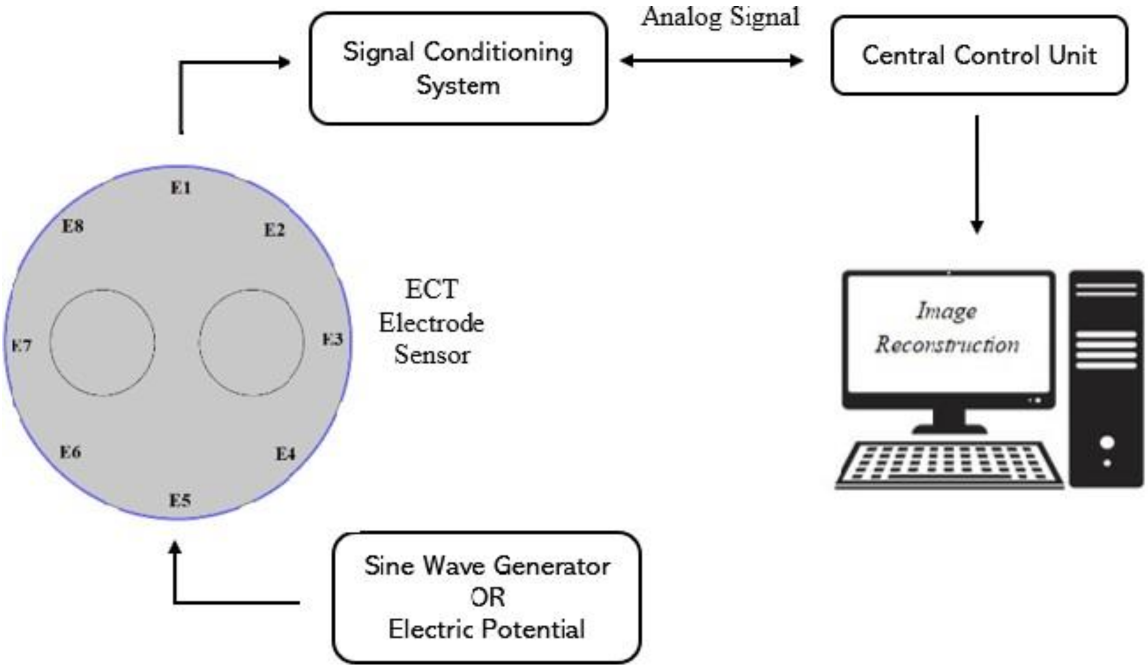


Figure 2.1 ECT system topology

The requirements for the electrical capacitance tomographic imaging are that multiple electrodes should be arranged around the boundary of the region and the capacitance between all the combination pairs of the electrodes should be measured in order to perform a 'body scan' of the imaging volume. ECT is most successful when applied to materials such as oils, plastics, dry powders and under favorable circumstances pure water, all of which have low electrical conductivity [1]. So, this approach is believed suitable to be applied for agarwood.

A complete cycle for a common ECT system measurement is started with the first channel (named as electrode 1) act as the excitation electrode. When the transmitteris supplied with a sine wave, all other channels will set to the ground and act as receivers and receive the capacitor values. It is corresponding to the dielectric between the transmitter and each of the receiver [1]. For a complete measurement cycle, all channels will become as transmitter and receiver.

The sensing electronics then take measurements for all possible combination pairs of electrodes. Specifically, for capacitance tomography measurements, the surface of the electrode needs to be sufficiently large to provide sufficient signal. However, in this project, the focus is only on the simulation part. So, no hardware development is built.

2.2.2 Mathematical Equation of ECT System

The electrostatic field is used in the ECT system's mathematical equation. Ref. [11] demonstrates the relationship between the permittivity spatial distribution and measured capacitance, which may be obtained from Maxwell's equation as in Equation 2.1. Gauss' Law expresses the dielectric flux density, D.

$$\nabla \cdot D = \rho_v \qquad 2.1$$

The volume charge density is denoted by ρ_v, while the divergence operator is denoted by ∇. Given that only one electrode is stimulated at a time and the other electrodes serve as receivers in an ECT system. The total electric flux across all electrodesurfaces can be predicted to be zero. Hence, the volume charge density is equally zero.

$$D = \varepsilon E \qquad 2.2$$

$$E = -\nabla \varphi \qquad 2.3$$

With ∇is the gradient operator so we have

$$D = -\varepsilon \nabla \varphi \qquad 2.4$$

The spatial permittivity distribution is denoted by ε, while the electric field intensity denoted by E and also φ is the electric field potential distribution within the sensor. As in Equation 2.4 into Equation 2.1 giving Poisson's equation.

$$\nabla \cdot (\varepsilon(x, y) \cdot \nabla \varphi(x, y)) = 0 \qquad 2.5$$

For a two-dimensional scenario that includes the x and y axes, the $\varepsilon(x,y)$ is the two-dimensional relative permittivity distribution with boundary conditions equal to $\varphi = V_C$ for the first electrode and $\varphi = 0$ for the subsequent electrodes.

2.3 Invasive & Non-Invasive Techniques

Invasive sensors are those that are placed inside the vessel, whereas non-invasive ones are those that are placed outside of it. Non-destructiveness, non-intrusiveness, and non-invasiveness are all desirable qualities in a tomography sensor. Pipeline integrity shouldn't have to be compromised in any way for this to work [1]. The advancement of non-intrusive and non-invasive approaches has been shown to have a significant impact on the user's comprehension of the fundamental hydrodynamics of multiphase reactors, according to previous study.

Sensing method advancements have had a significant impact on the state of the art in non-invasive techniques. As a rule, the non-invasive instruments do not require the removal of the process material from the vessels or pipeline. According to the Ref. [1], some of the benefits of using non-invasive devices are as follows:

a. Keeping away from anything that might poison or contaminate clean materials.

b. Reducing the potential for harm while working with hazardous materials such those that are toxic, radioactive, explosive, flammable, or corrosive.

c. Helping with tool installations and maintenance even while the plant is running is feature.

2.3.1 Invasive Technique

The invasive technique is another configuration that places the electrodes inside of the pipe. If the pipe has metal walls, an insulated liner must be used to hold the electrodes in place once they are installed. Sensors with electrodes inside of the pipe eliminate the non-linearity issues exhibited by sensors with external electrodes and, if the highest accuracy is required, it should be used instead of a unit with external electrodes. Despite, it is being more difficult to design and construct from a mechanical standpoint [8].

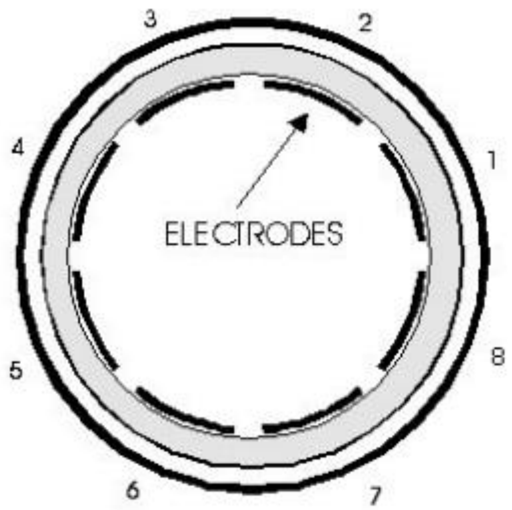


Figure 2.2 ECT with internal electrodes [23]

2.3.2 Non-Invasive Technique

Capacitance sensors for circular-cross-section pipes are typically specialized modules developed for each unique function. From a purely structural perspective, the simplest configuration consists of an earthed outer screen enclosing a nonconducting pipe section surrounded by an array of capacitance electrodes with uniform spacing between them. This setup is preferable because it prevents the electrodes from coming into touch with the pipe's internal fluid, which might lead to contamination. Furthermore, when dielectric materials are added within the sensor, the response of sensors with electrodes on the outside of the pipes wall might be very non-linear. Since the sensor wall adds a new (and harmful) series coupling capacitance to the cross-capacitance measurements, this effect occurs [8].

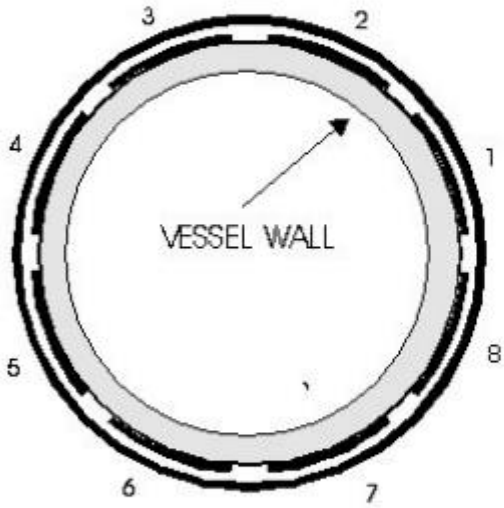


Figure 2.3 ECT with external electrodes [23]

2.4 Linear Back Projection Algorithm

Once the sensor data is collected, it will be used in the picture reconstruction process. Both iterative and non-iterative techniques may be used for picture reconstruction [1]. To get measurable data from cross sectional pictures of multiphase pipe flow, high-quality reconstruction of capacitance tomography data is required [1].

An illustration of a non-iterative method is linear back projection (LBP) algorithm. Even though it's a popular technique, linear back projection can't handle complicated object distributions [1] while being quick and easy to be used. The LBP algorithm's speed and efficiency in creating images are two of its main features [22].

In order to recreate a picture of an electric potential distribution after it has been somewhat perturbed by changes in the dielectric characteristics of the computational domain, the LBP method provides a straightforward technique. In order to do this, we linearize a normalized form of the forward problem, which we define as the weighted back-projected of each normalizing measurement along the zone of sensitivity, given by the corresponding Jacobian matrix [15].

Although LBP is regarded fast and practical to implement, it often demonstrates low-quality reconstruction due to reconstruction distortions and picture rolls-off from the center of the image. If you want to blur the image, you may use the LBP function or filter, where r is the radius of a circle centered on the highest count density [15].

LBP requires only the multiplication of the computed Jacobian matrix, $J_{ji}\,(x,y)$ by its corresponding sensor loss. Equation 2.6 is the mathematical equation for LBP in discrete form for ECT. Meanwhile, the sensor loss $J_{ji}\,(x,y)$ is calculated based on Equation 2.7 in terms of normalization and the L_{ji} is the sensitivity map at each i and j.

$$G_{LBP}(x,y)=\sum_{j=1}^{T}\sum_{i=1}^{R}L_{ji}\times J_{ji}(x,y) \qquad 2.6$$

$$J_{ji}=\frac{S_{ij}^{inc}-S_{ij}^{tot}}{S_{ij}^{inc}} \qquad 2.7$$

Where T represents the number of excitation electrodes, R represents the number of measuring electrodes, S_{ij}^{inc} is the potential measured when there is no agarwood in the wood (homogenous), S_{ij}^{tot} is the potential measured when there is agarwood in the wood (non-homogenous) and G_{LBP} is the potential distribution obtained using LBP.

2.5 Summary

In this chapter, numerous types of tomography sensors have been described. From the information above, it can be concluded that each type of tomography sensor has its benefit and shortcoming. Different tomography sensor is suitable for imaging certain types of fields. ECT has an advantage in measuring the variations in the dielectric properties of materials which make it suitable to be used as an imaging technique for agarwood detection.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This study focuses on the design and simulation of an ECT system for agarwood using COMSOL Multiphysics software. As a result, outside electrodes must be chosen rather than inside electrodes. Figure 3.1, shows an ECT measuring flow system where the ECT sensor consists of 8 electrodes attached equidistantly along the periphery of the tree (wood).

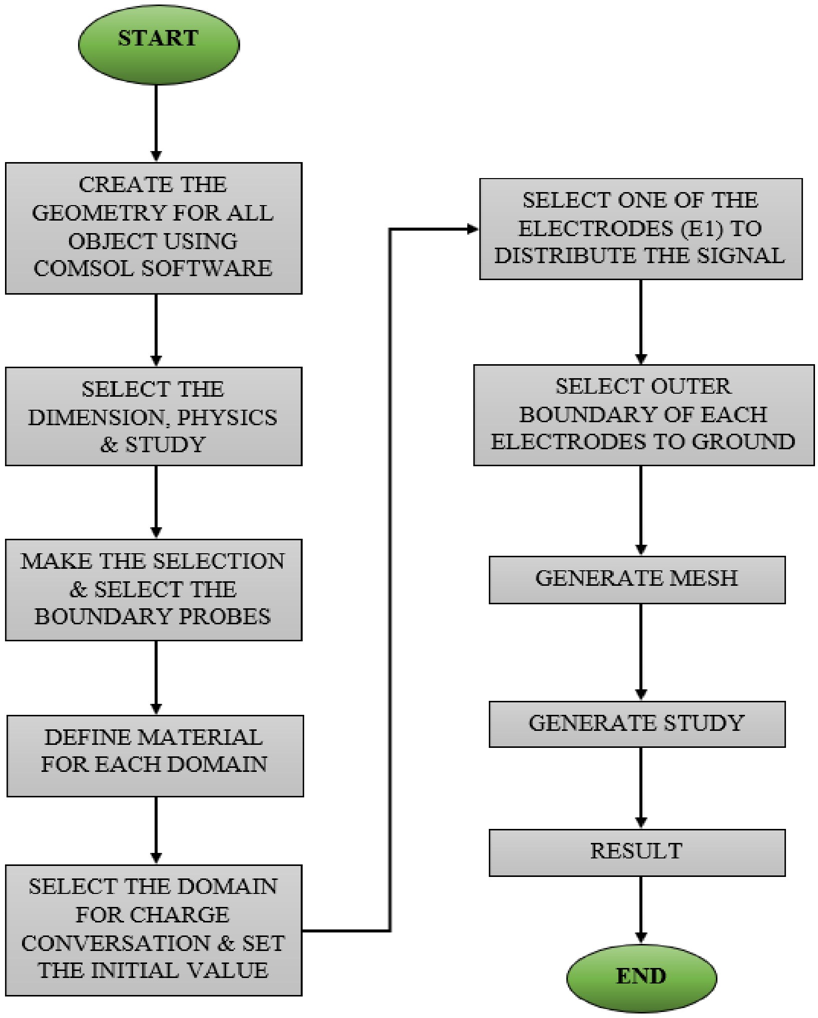


Figure 3.1 Basic flow process in COMSOL Multiphysics

3.2 Software Tool

In developing the geometry part, COMSOL software had been used to set up all the geometry and also design all the objects. COMSOL is used to design the objects, shape, size and all the measured parameters. COMSOL also is a general-purpose simulation software used in all fields of engineering, manufacturing, and scientific research. The software brings fully coupled multiphysics and single-physics modeling capabilities, simulation data management, and user-friendly tools for building simulation applications [14].

COMSOL Multiphysics was also utilised to simulate the design throughout the simulation phase. It was selected because it comprises linked processes or systems involving many concurrently occurring physical fields, as well as the study and understanding of these processes and systems. COMSOL Multiphysics is an interdisciplinary research topic that encompasses several scientific and engineering fields. COMSOL Multiphysics is a field of study that is founded on mathematics, physics, application, and numerical analysis. Partial differential equations and sensor analysis are often used in the mathematics. Physics is a broad term that encompasses a variety of physical processes, such as heat transmission, pore water flow, concentration field stress and strain, dynamics, chemical reactions, electrostatic and magnetostatic interactions. Figure 3.2 depicts the COMSOL Multiphysics environment in which the design may be simulated.

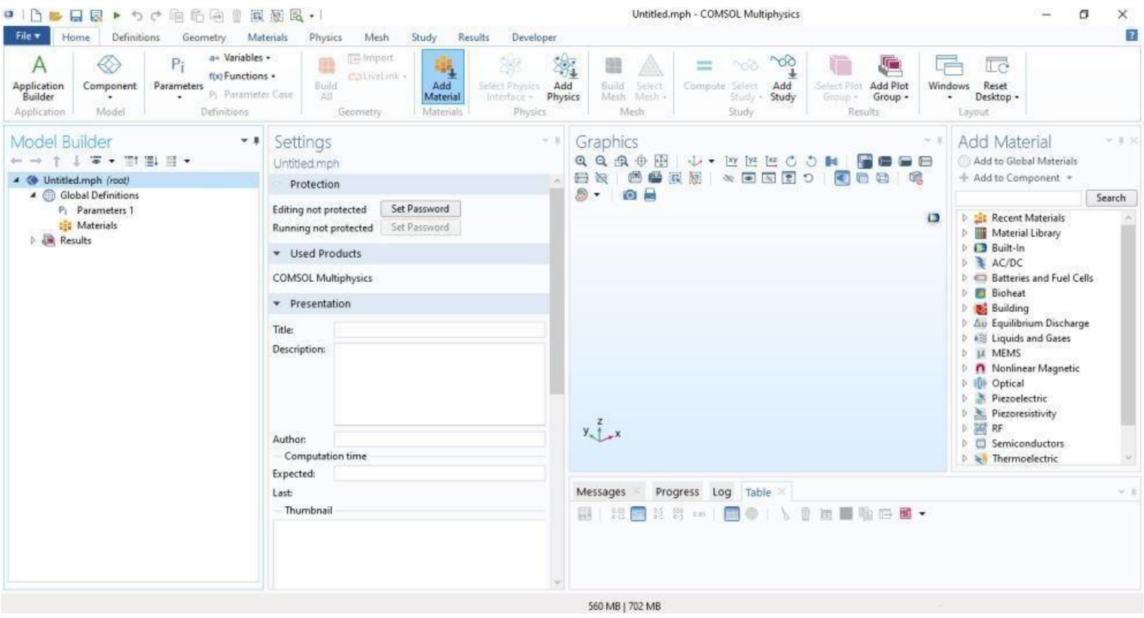


Figure 3.2 Environment of COMSOL Multiphysics

3.3 Design the ECT model using COMSOL Multiphysics

The first step to develop the numerical modeling is by drawing the circle shape of a tree (wood) with a certain diameter using the COMSOL software. For this case, the parameters such as diameter of the agarwood and the dimension of the electrode of the drawing geometry are based on the literature review. For electrode design, it used with circular arc from library in COMSOL software as the part or segment of the circumference of a circle. More importantly, the setup of the parameter before using the COMSOL software is essential in simulation and real implementation. For this project, there are a few parameters geometry that were set as fixed in COMSOL Multiphysics as illustrated in Table 3.1.

Table 3.1 Parameters of geometry

List of Parameters	
Items	**Parameters**
Number of electrodes	8
Diameter of wood	600mm
Diameter of agarwood	181mm
Electrode stretch angel, θ (90% of angle)	$\frac{360°}{8\ electrode} = 45°$ & $\frac{90}{100} \times 45° = 40.5°$
Thickness of electrode	2.5mm

Then, all parameters were be inserted into the COMSOL software and the design was shown in the Figure 3.3, Figure 3.4 and Figure 3.5.

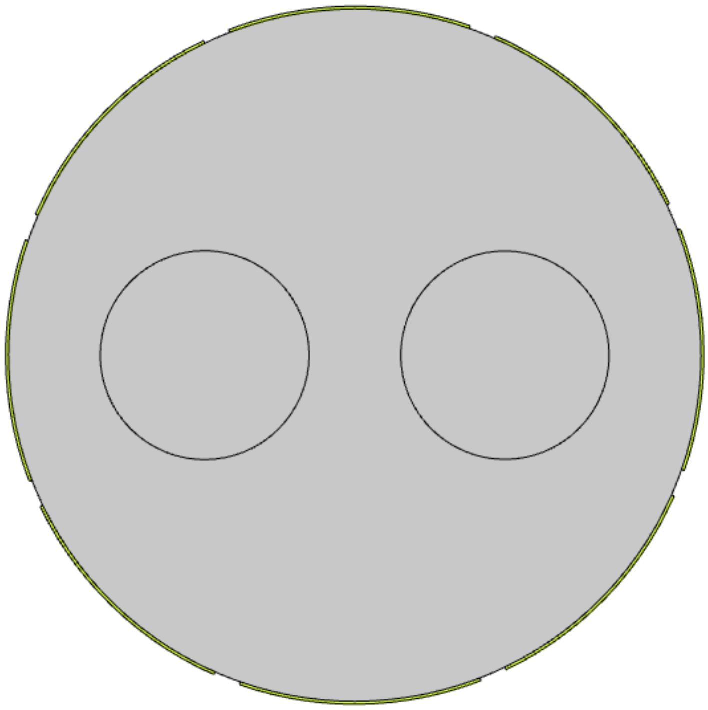


Figure 3.3 The 2D geometry of the 8 electrodes

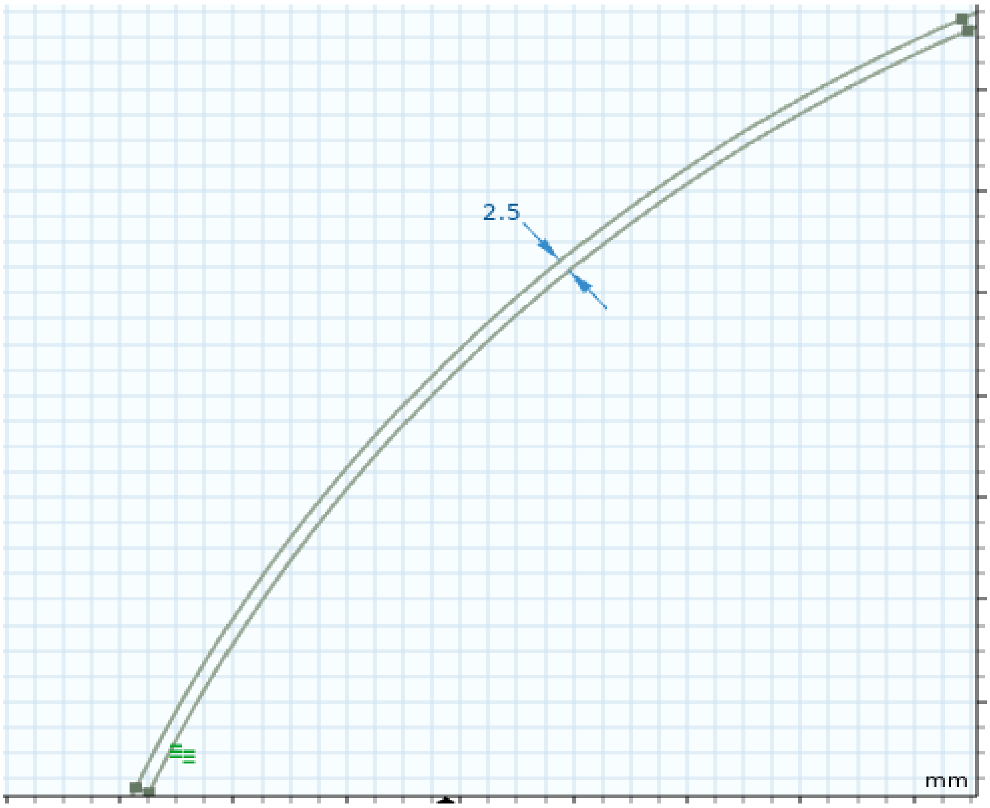


Figure 3.4 The 2.5 mm thickness of the electrode

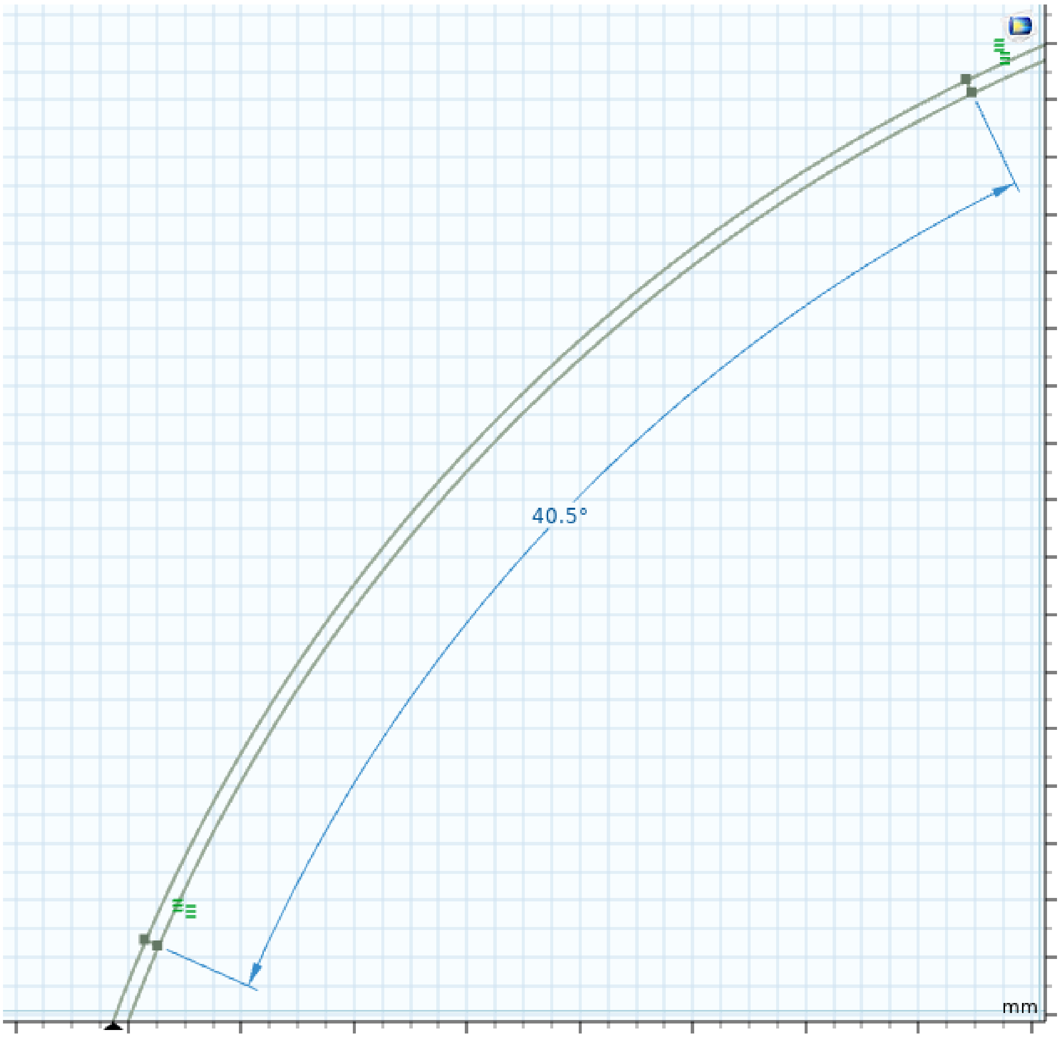


Figure 3.5 The 40.5° stretch angel of electrode

3.4 Preparing for Simulation using COMSOL Multiphysics software

The simulation of the ECT system using COMSOL Multiphysics for a sensor model with 8 electrodes can be done into the following steps:

i. Selecting the dimension of space, the physics, and the subject of the project topic

ii. Select the electrical value and wave type

iii. Define the bounding conditions

iv. Specify the content that will be used in each domain

v. Set the electrical properties of the domain

vi. Creating the mesh

vii. Generating the study

The two-dimensional (2D) of the 8 electrodes ECT is illustrated in Figure 3.6. The detail of the physical sensor can be found in Table 3.2.

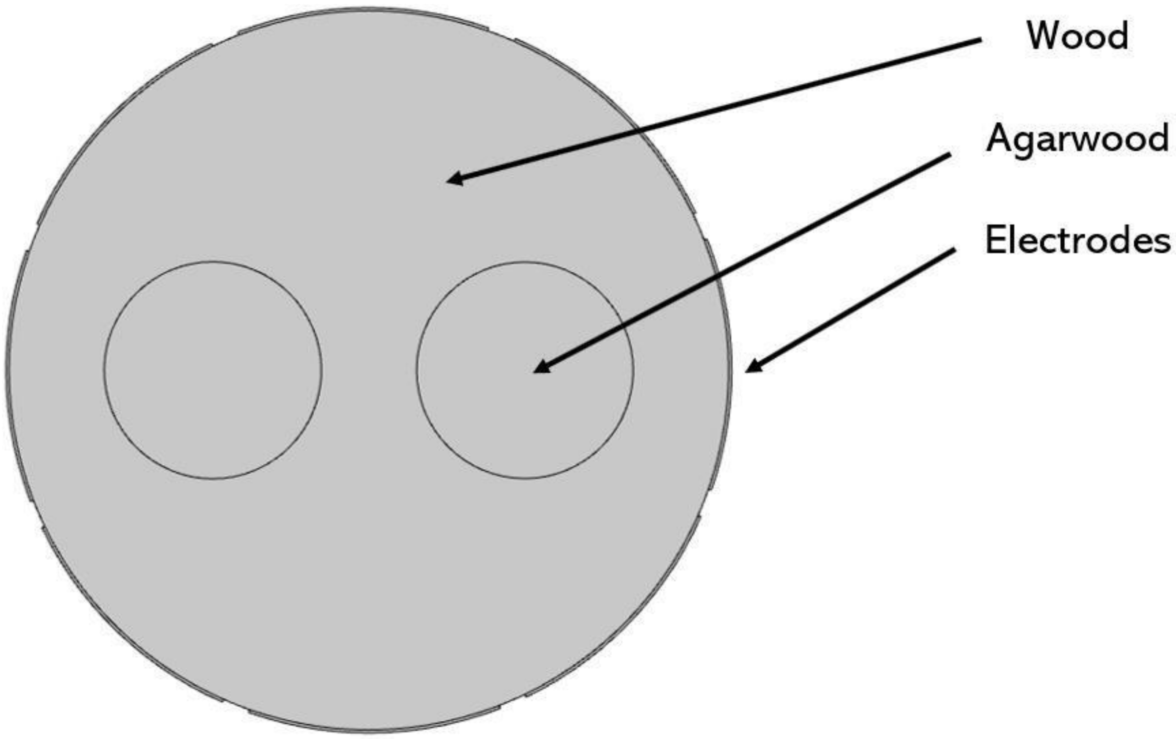


Figure 3.6 The 2D of the 8 electrodes ECT

Table 3.2 The detail of the physical sensor

Domain	Parameter	Value
Wood	Diameter	600mm
	Material	Wood (pine)
	Relative Permittivity, ε_r	3.17944
Electrode	Number of Electrode	8
	Stretch Angle of Electrode	40.5º
	Thickness of Electrode	2.5mm
	Material	Gold
	Relative Permittivity, ε_r	1.143
Air	Relative Permittivity, ε_r	1
Agarwood	Diameter	181mm
	Material	Wood (pine)
Agarwood (Sample A)	Relative Permittivity, ε_r	2.84180
Agarwood (Sample B)	Relative Permittivity, ε_r	1.60002
Agarwood (Sample C)	Relative Permittivity, ε_r	1.71432

The electrical value for the electrode was set by 20Vdc for injected to the electrode source as shown in Figure 3.7. In this project, it only focuses on the simulation part so it was decided to use only the dc voltage to avoid complexity in modelling the ECT system. Besides, the dc signal is chosen because it obtained a positive value reading as well as avoiding a very small voltage reading value.

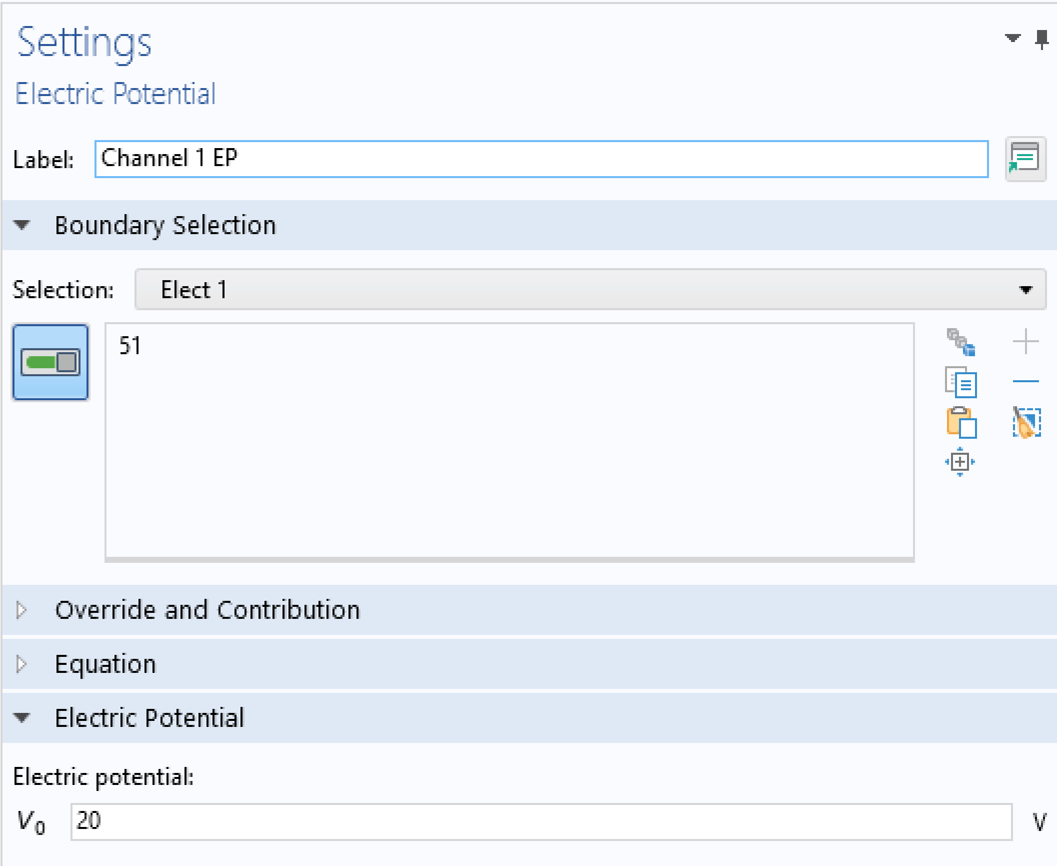


Figure 3.7 Electrical potential value

Figure 3.8 and Figure 3.9 demonstrate how to choose electrodes and set up border probes for electrodes 1 through 8. As seen in Figure 3.10, these procedures were used to label each channel (electrode 1 through electrode 8). This procedure may also be used to simplify the material in the ECT model and the electrical characteristics of the boundary.

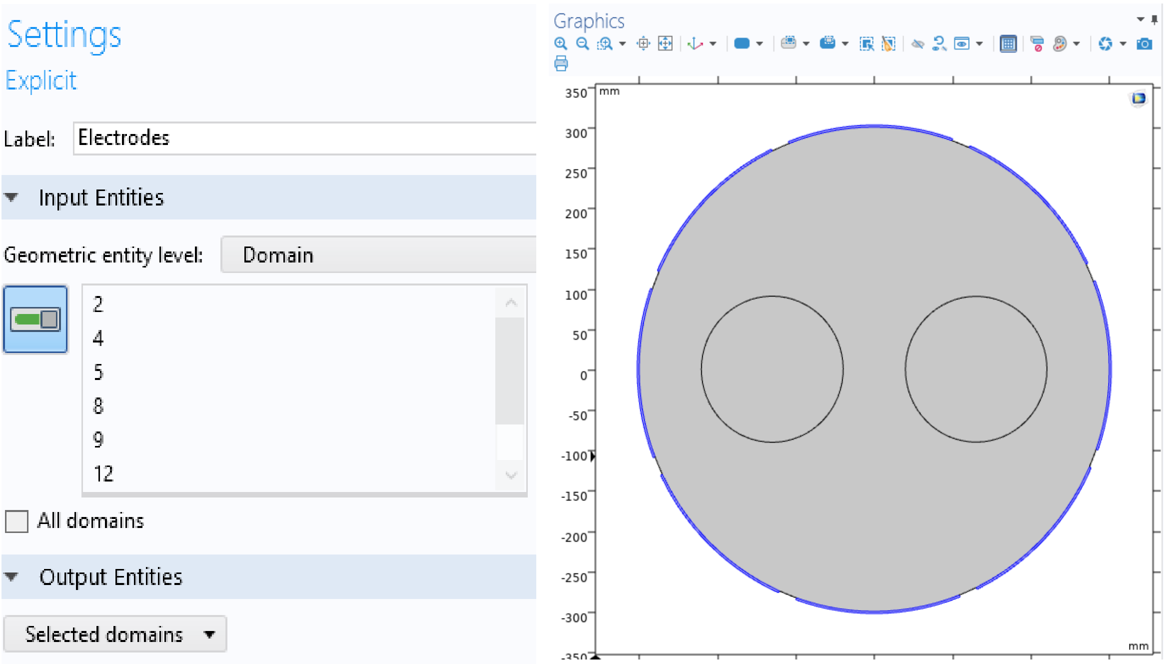


Figure 3.8 Selection for electrode domain

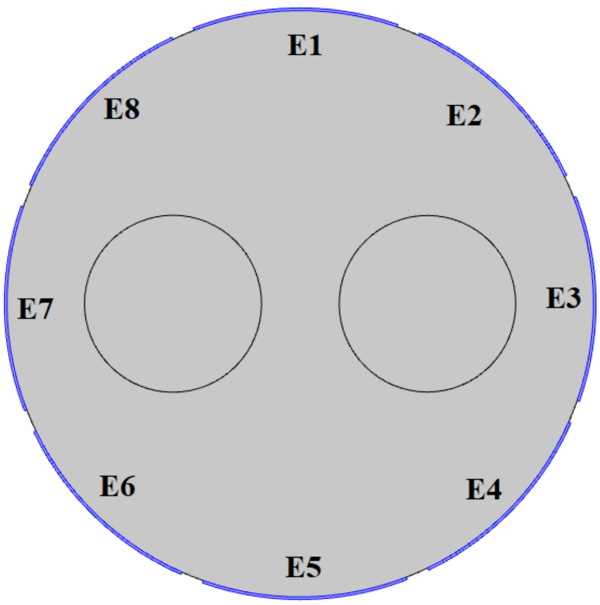


Figure 3.9 Label for 8 channels of the geometry (E1 until E8)

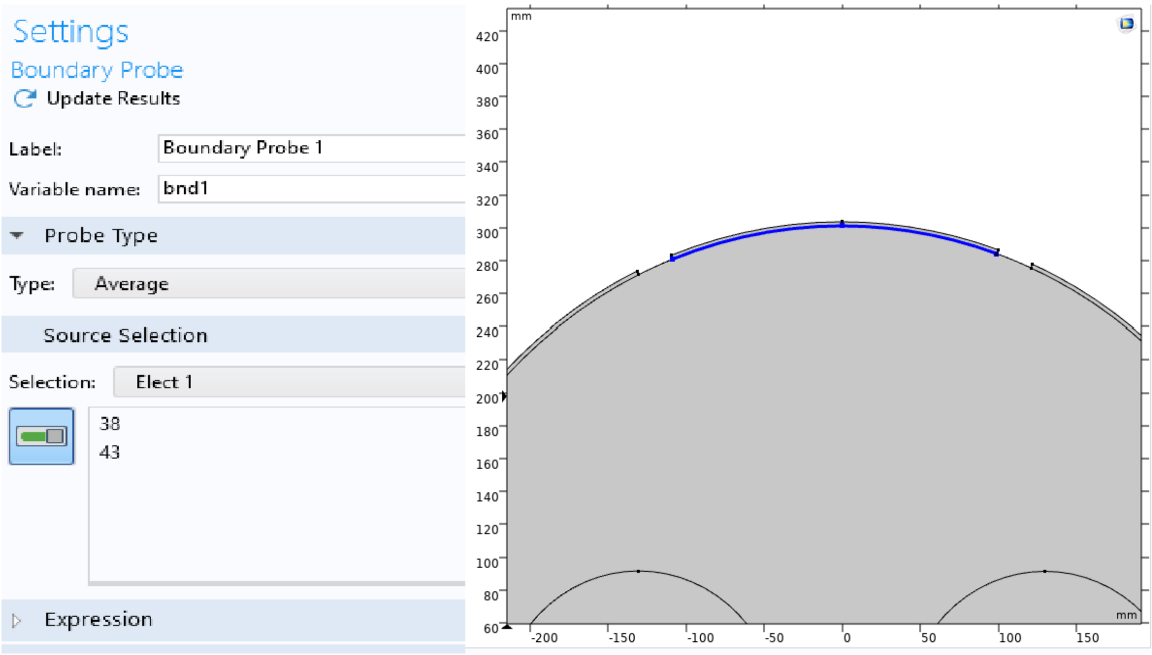


Figure 3.10 Example of set up the boundary probe for channel 1

The electrode 1 boundary was selected for distributing the electrical potential as shown in Figure 3.11 and the outer of each electrode was set to ground (V=0V) as shown in Figure3.12.

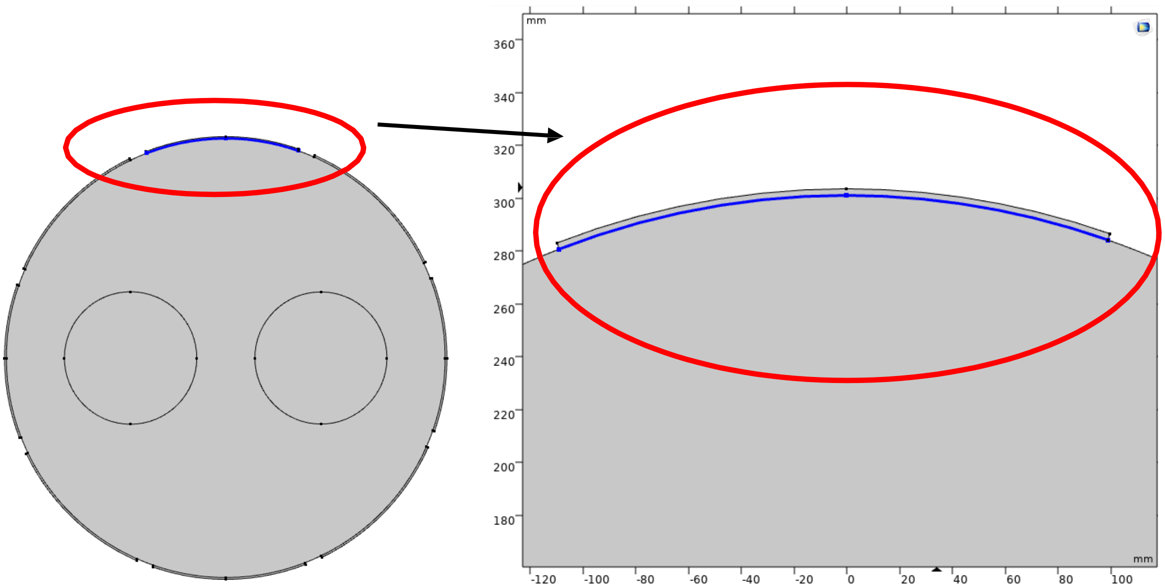


Figure 3.11 Selection of the electrical potential at excitation channel

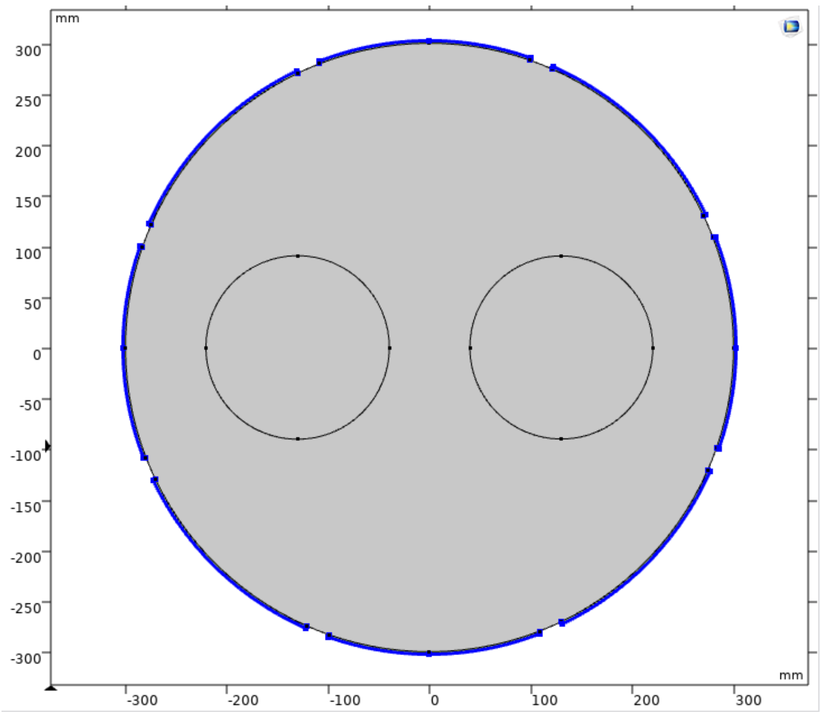


Figure 3.12 Set ground for each outer electrode

Actual presentation of ECT model is shown in Figure 3.13.

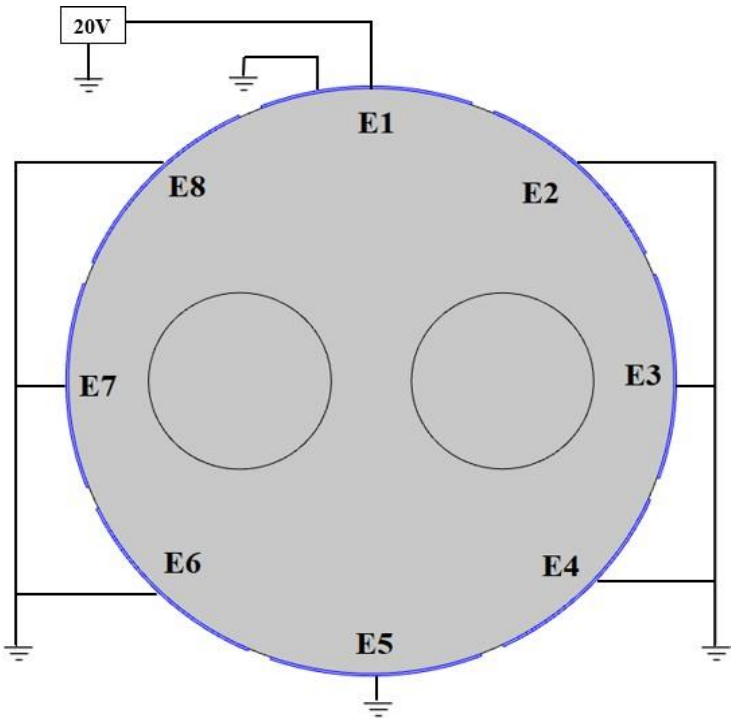


Figure 3.13 Actual set up of ECT model

After that, the mesh of ECT model was generated. In this simulation, it used a fine mesh of element size. The geometry is classified according to its shape or element type, the geometry's size, density, and number of components and the component's quality. The time it takes to solve a model, the amount of memory needed to solve the problem, how the solution is interpolated across nodes, and the precision of the result are all factors that influence how a problem is solved. Figure 3.14 shows the finite element meshing in 2D of the 8 external electrodes of ECT model. The study was generated to obtain the results such as surface, streamline and contour. Also, the probes were evaluated to get the receivers data.

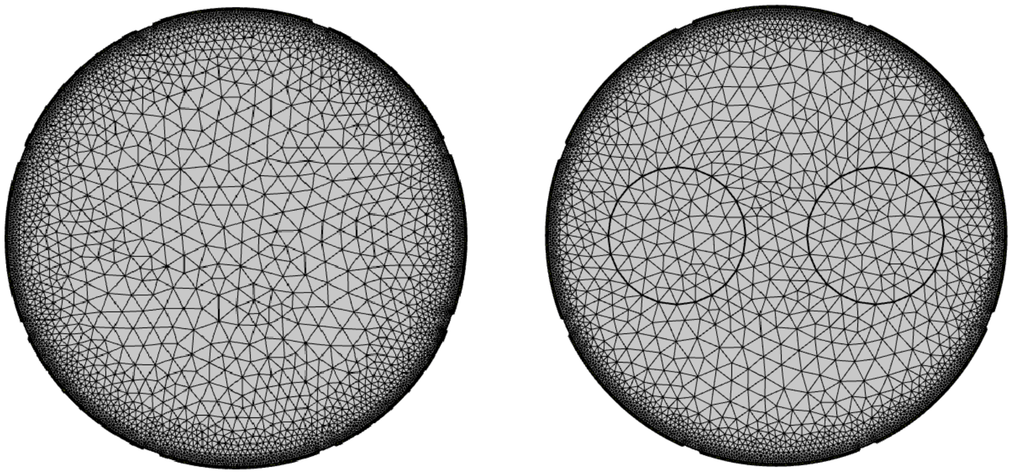


Figure 3.14 FEM Meshing; (a) No agarwood (fine mesh), (b) With agarwood (fine mesh)

3.5 Electrical Potential Distribution

After defining the boundary condition and subdomain setup, the electrostatic solver is utilised to compute the electrical potential distribution, since it has a higher performance for calculating Laplace and Poisson equations.

Finally, the model electrode-pairs' electric potential distribution is obtained. Figure 3.15 illustrates the distribution of electrical field lines when electrode 1 is set as excitation electrode and other electrodes were set as detection electrodes.

Figure 3.15 shows an electrical field distributions that exist between any two electrodes are not straight. The field lines are curved instead, and it prove the soft field behavior of the ECT system [11]. The purpose of a streamline plot is to visually represent a vector quantity, which is particularly helpful for viewing flow behavior. The purpose of contour plots is to visually depict the fluctuation of a single variable in a subdomain using lines of constant magnitude. So, from the Figure 3.15, boththe streamline and contour line pass smoothly through the wood to the receiver electrodesdue to non-existing of the agarwood.

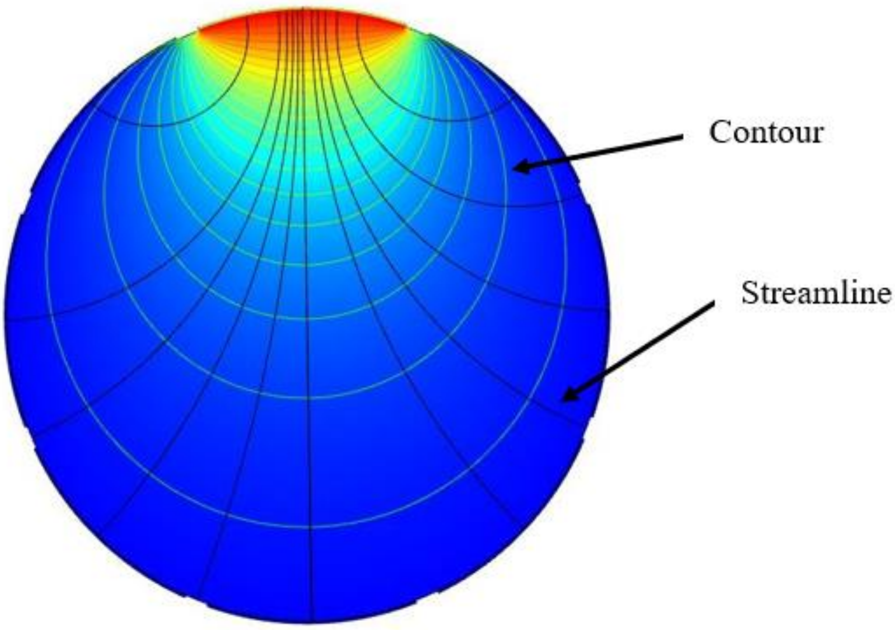


Figure 3.15 Electric field & potential lines for single excited electrode (channel 1 as excitation electrode)

3.6 Image Reconstruction using MATLAB Software

The Equation 2.6 in sub-topic 2.4 was formed as the basis for the mathematical model of LBP and it was applied in the MATLAB software. Figure 3.16 demonstrates the flow procedure in getting the tomograms. The process phases were illustrated in Appendices A, B, and C.

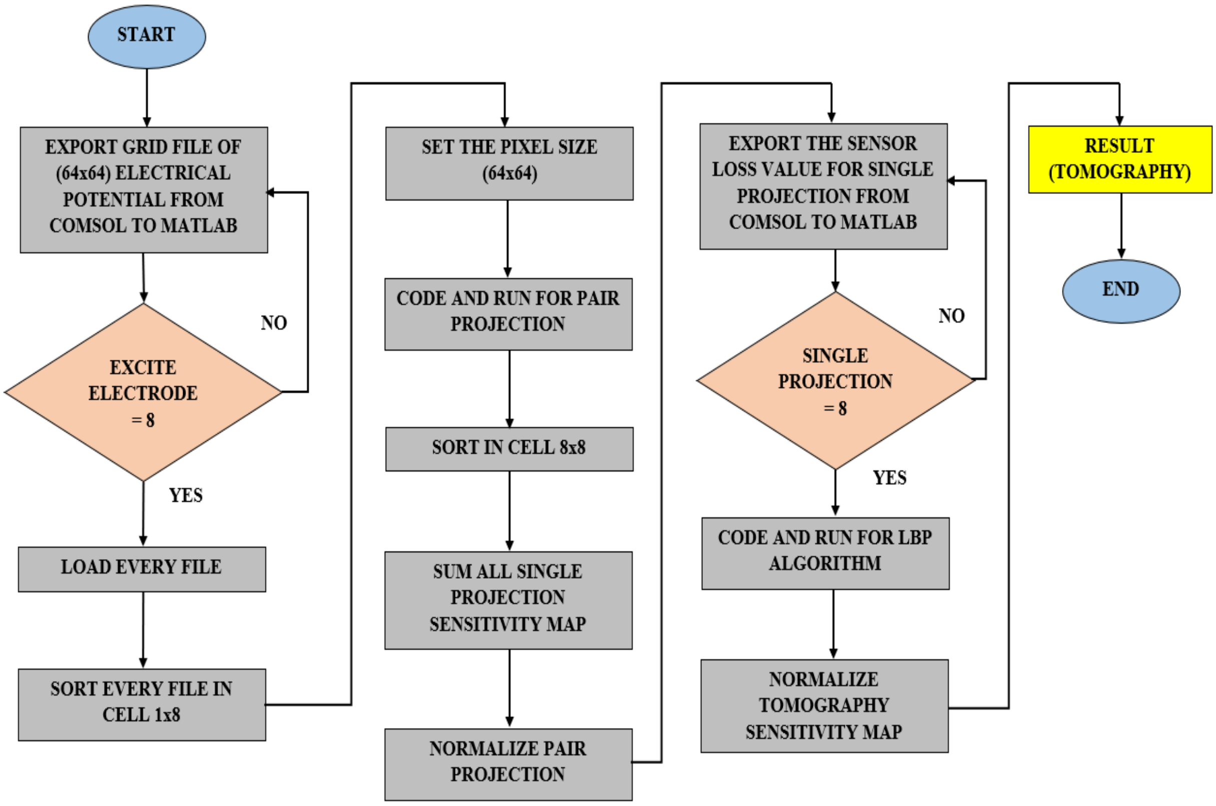


Figure 3.16 Basic flow process of image reconstruction using MATLAB software

Multi scale structural similarity (MSSIM) is a visual metric used to determine the loss in perceived picture quality due to compression or transmission losses. The detail equation for MSSIM can be referred in Ref. [24]. To function properly as a full reference metric, it needs a reference image (image 1) and the result image (image 2). Furthermore, MSSIM is used to examine the tomograms' effectiveness. MSSIM index is a method for measuring the similarity between two images. The MSSIM values ranges between 0 to 1, 1 means perfect match the reconstruct image with original one. When the MSSIM index value is high, the reconstructed picture closely matches the reference image [24].

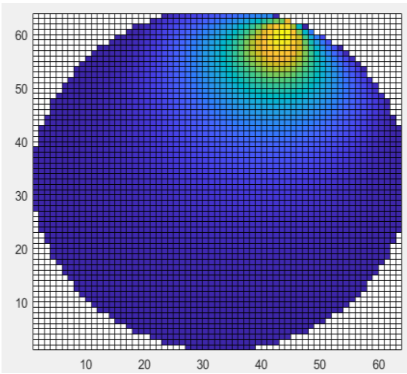
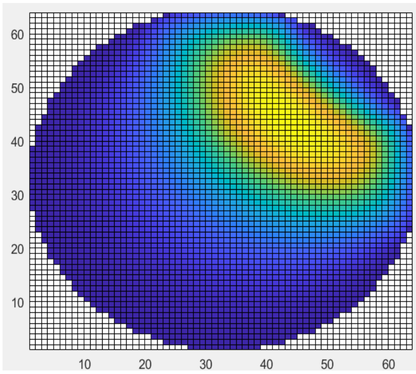
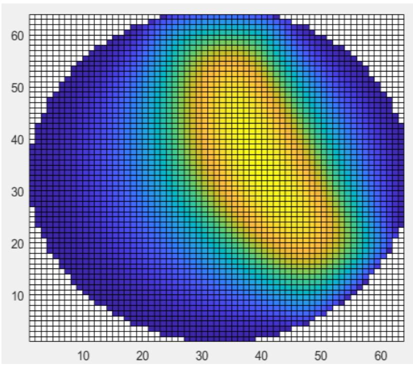
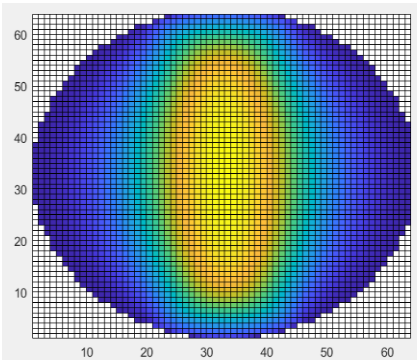
3.6.1 Forward problem and Inverse Problem

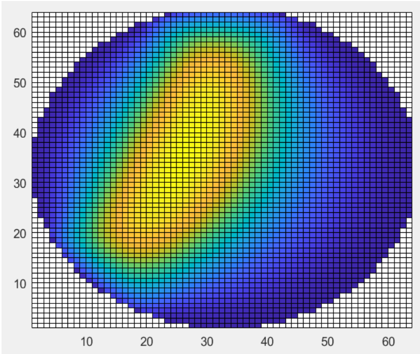
For each of the excitation, the sensitivity maps in forward problem are needed before producing the tomogram images [15]. A sensitivity map, also known as the sensitivity coefficient is computed from the electric potential distribution, $E(x,y)$ for a different excitations, j in finite element analysis software. One element L_{ji} of this matrix defines the electric potential, $E(x,y)$ changes at a measurement spot due to a slight perturbation in the permittivity of one element, *Ɛr (x,y)* of the model as shown in Equation 3.1 [15].

$$L_{ji} = \frac{\partial E(x,y)}{\partial \varepsilon_r (x,y)} \qquad 3.1$$

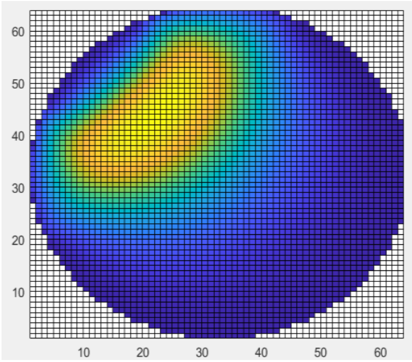
Homogenous (wood) is the reference material for the normalized sensitivity maps, an excitation at electrode j = 1 and measurements at electrodes i = 2,...,8 respectively. Table 3.3 shows the normalized sensitivity maps of excitation at electrode j = 1 with corresponding measurements at electrodes i = 2,…,8 electrodes setup.

Table 3.3 Normalized sensitivity maps of excitation at electrode *j* = 1 with corresponding measurements at electrodes *i* = 2,…,8 electrodes setup

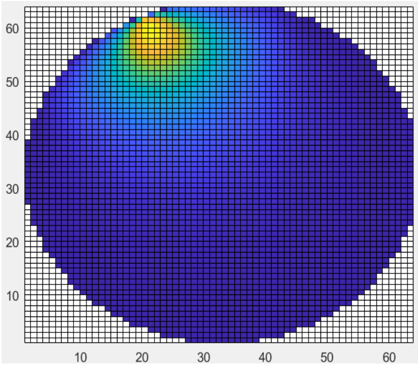
 a) *j*=1 , *i*=2	 b) *j*=1 , *i*=3
 c) *j*=1 , *i*=4	 d) *j*=1 , *i*=5



e) j=1 , i=6



f) j=1 , i=7



g) j=1 , i=8

From the mesh of the forward model without the components formed in air and electrodes as illustrated in Figure 3.14 (a) and (b), each sensitivity map is generated. All mesh elements in the area between the excitation and the measuring electrode have excellent sensitivity. Between nearby electrodes, the sensitivity is extremely low, decreasing as the distance increases. Due to this reason, the distortion in the image reconstructed may occurred [15].

In ECT, an inverse problem is aimed at identifying the image from the electromagnetic field distributed around it. Using the LBP method, researchers were able to create the tomographic images in this investigation. The signal from the sensor is sent to the MATLAB software. The MATLAB software processes the information obtained and reconstruct cross-sectional images. The example of sensor loss reading were illustrated in Appendices D.

3.7 Summary

In this chapter, the method started with the designing and modelling of ECT using COMSOL Multiphysics software. The preparation of simulation consists of eight steps which were choosing the space dimension, physic, and study, setting the electrical value and type of wave, setting the boundary conditions, defining material for each domain, setting electrical properties in the domains, generating the fine mesh and generating study. Then, the simulation was performed to observe the electrical potential distribution of ECT design. Lastly, the image reconstruction for LBP is performed out in MATLAB software.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter consists of the results and discussions of the electrical potential distribution using COMSOL Multiphysics software. The simulations for electrical potential distribution were divided into for 4 samples. The first simulation was for only wood (without agarwood) conditions. The others simulation was continued with agarwood and with different relative permittivity value. The value of each samples was from the method of the Magnetic Inductive Tomography journal [7]. Noted that, all the results of the simulations in COMSOL Multiphysics applied channel 1 as the source. Besides, there are 9 types of phantoms were used as the results for the image reconstruction part in MATLAB software.

4.2 Results and discussion

4.2.1 Result of Samples Wood without Agarwood

In the first part of the simulation, the only wood (without agarwood) was tested. The electrical potential distribution streamline (black colour) and contour (green line) were observed due to the relative permittivity of wood only as shown in Figure 4.1. The value of this simulation electrical potential was obtained and plotted into line graph that shown in Figure 4.3.

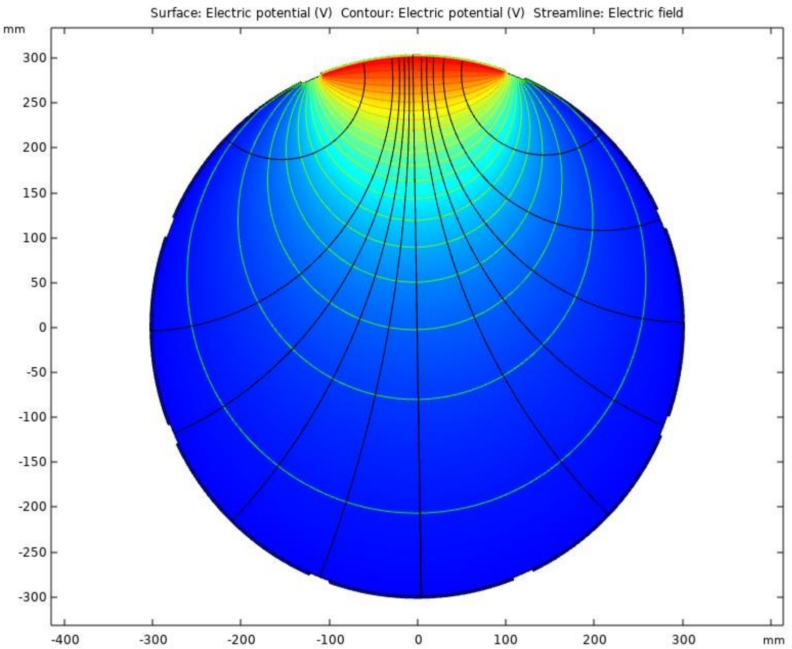


Figure 4.1 Electrical potential distribution when channel 1 set as excitation signal

The streamline and the contour were not distorted when it approaching to the wood due to non-existing of the agarwood. This nature phenomena can be confirmed by plotting the wood (no agarwood) of electrical potential between interaction electrode 1 (excitation electrode) and the other 7 electrodes (receivers) as shown in Figure 4.2 and the line graph as shown in Figure 4.3.

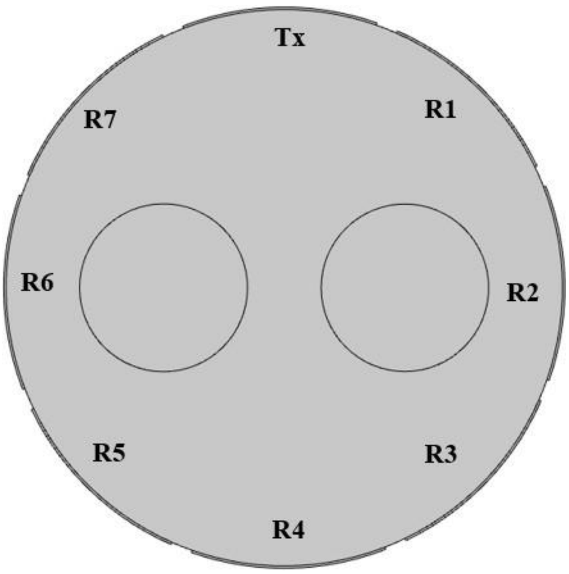


Figure 4.2 The position of the receiver when the electrode 1 as a transmitter

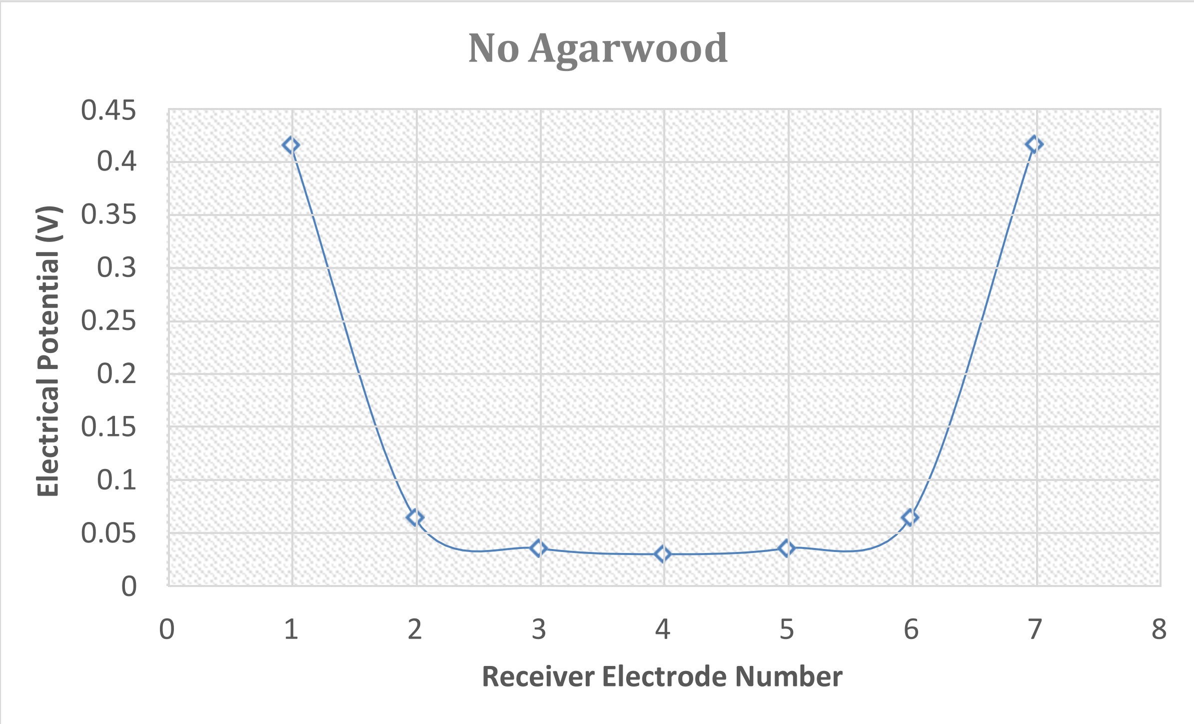
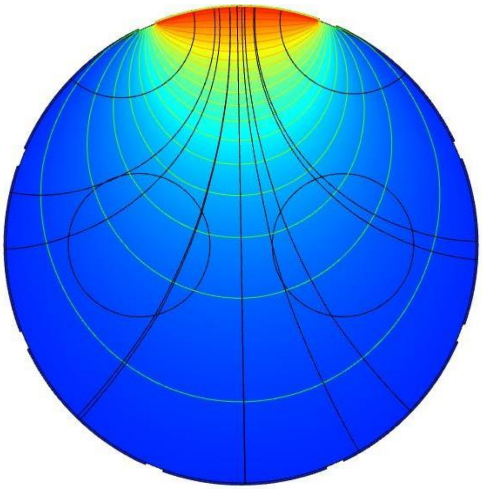
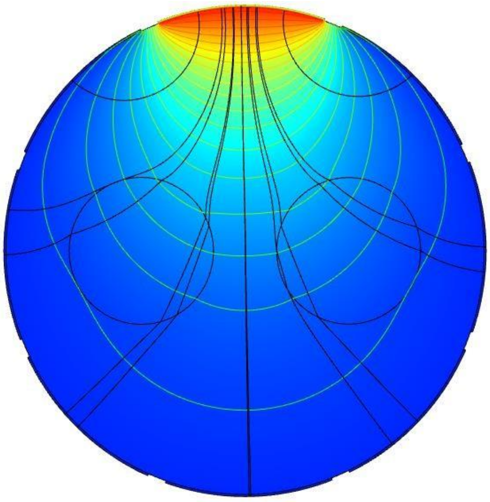
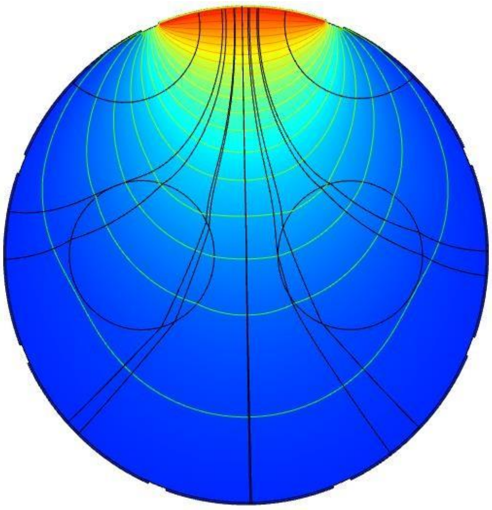


Figure 4.3 The value electrical potential for wood (no agarwood)

4.2.2 Results for the 3 Samples of Agarwood (Sample A, Sample B & Sample C)

After the simulation of wood had been tested in this project, the project was continued with three different samples. By using same procedure and this time with agarwood, the different samples of the agarwood were measured. There are three different samples of the agarwood were tested. Each of the samples has different electrical relative permittivity value. The Table 4.1 shows the result with streamline and contour of agarwood with different samples of agarwood. The values of electrical potential for all samples were obtained and the line graph was compared with result of wood only as illustrated in Figure 4.4.

Table 4. 1 Result for 3 samples of agarwood (sample A, B & C)

SAMPLES	STREAMLINE & CONTOUR
Agarwood (Sample A) Relative Permittivity, ε_r = 2.84180	
Agarwood (Sample B) Relative Permittivity, ε_r = 1.60002	
Agarwood (Sample C) Relative Permittivity, ε_r = 1.71432	

From Table 4.1, with images contour and streamline, it can be clearly seen that the agarwood (sample A) had less distortion compared with the other samples, while the distortion of agarwood (sample B) and agarwood (sample C) are no significant difference, but agarwood (sample C) had a little more distortion compared to agarwood (sample B).

Besides, as nature phenomena, when there is a difference value in relative permittivity, the streamline and contour will be distorted. This can be observed from the streamline and contour images of this samples in Table 4.1. When the agarwood was presented, the streamline and contour were distorted due to the difference in relative permittivity.

From Table 4.1, the result of agarwood from sample C had a greater distortion compared to agarwood of sample B and sample A. It shows that the decrementof the relative permittivity value of agarwood would result in the higher effect of distortion. The line graph for 3 samples of agarwood and wood was shown in Figure 4.4.

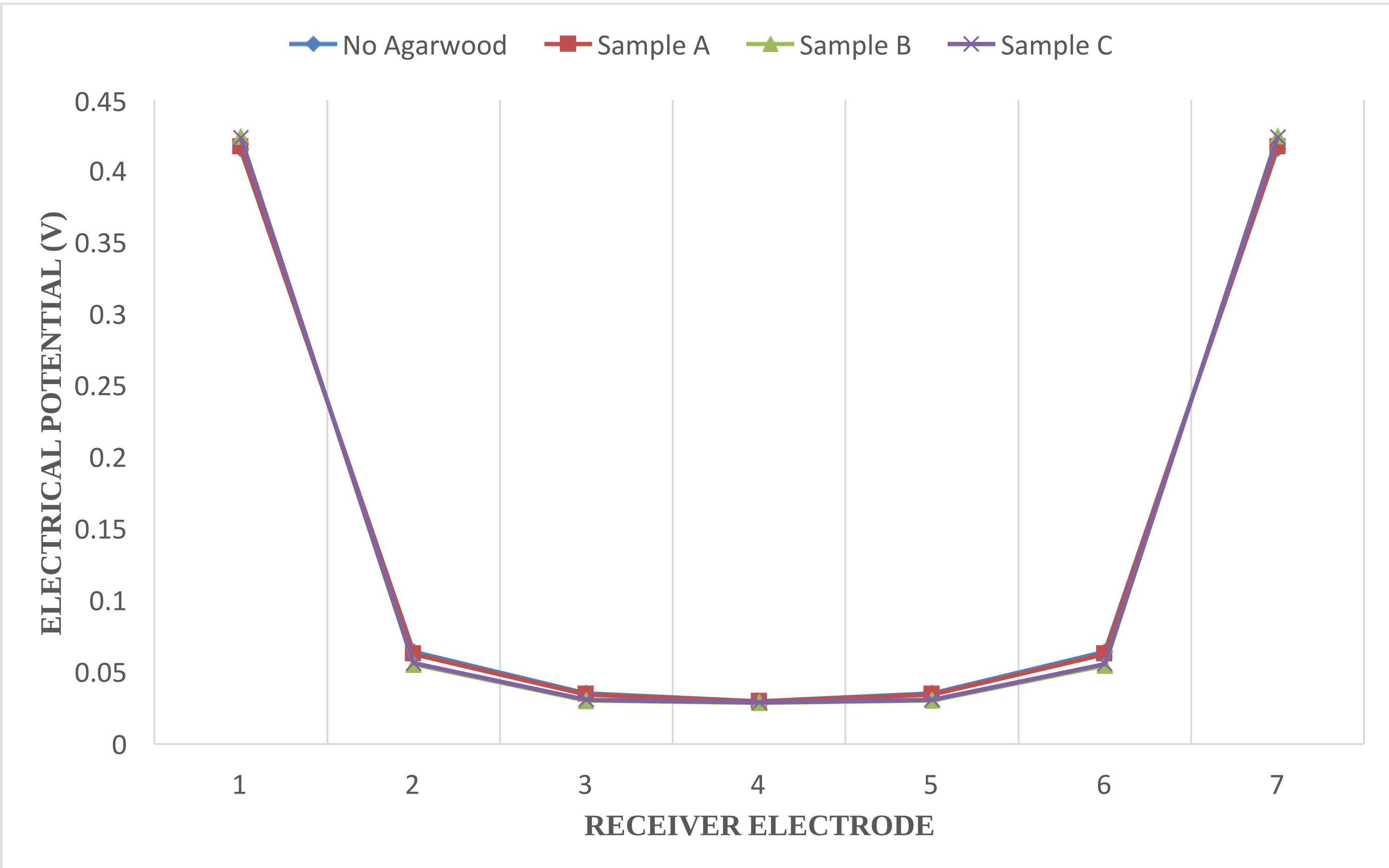


Figure 4. 4 The value electrical potential for agarwood (Sample A, B & C)

Based on the comparison between each of the line graph conditions with the wood (no agarwood), there were always appear the decrement of electrical potential at the receivers. This effect was due to the path of transmitter that projects the electric potential to the targeted receiver blocked by the obstacle. Hence, the reading of electrical potential at the receiver would decrease because of the blocked path. From another perspective, the decrement of the value relative permittivity of the agarwood, would affect the increment of the distortion in the wood.

4.2.3 Results for Image Reconstruction of Different Types of Tested Agarwood

After the simulation of three samples of agarwood had been simulated in COMSOL Multiphysics software, the image reconstruction for the samples of agarwood was obtained. For this part, it is only used the electrical relative permittivity value of agarwood sample C. This is because the value of electrical relative permittivity of agarwood sample C had a greater distortion compared to agarwood sample B and agarwood sample A. The algorithm of LBP was used to generate the tomograms in MATLAB software of the 9 types of phantoms (agarwood).

Table 4.2 shows the tomogram of the single agarwood with 60mm radius, different size with 120mm radius and different position (top right) with 60mm radius. Besides that, Table 4.3 shows the tomogram of the phantom A, phantom B and phantom C, while the Table 4.4 shows the tomogram of the phantom D, phantom E and phantom F. For all the results, it presented the geometry, contour with streamline, reference image, tomogram and MSSIM index.

Table 4.2 Image reconstruction for different sizes and positions of agarwood

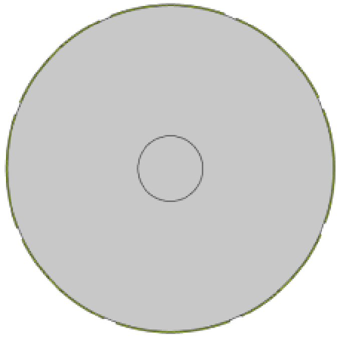
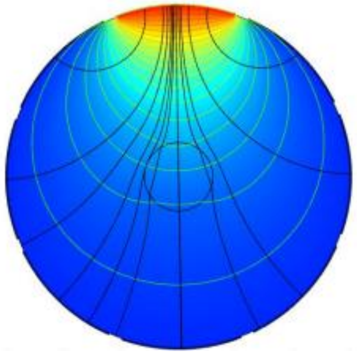
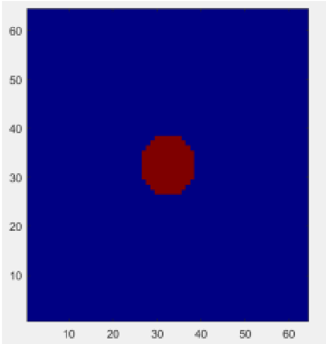
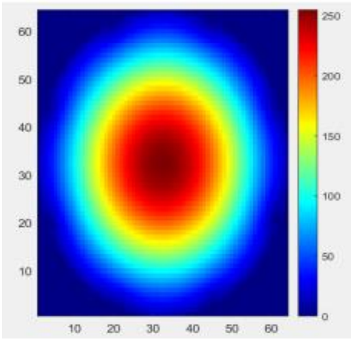
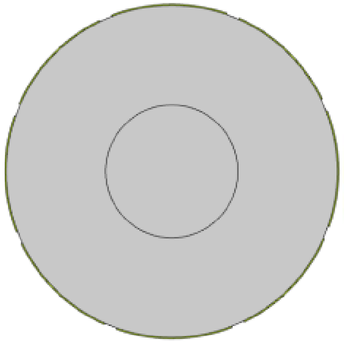
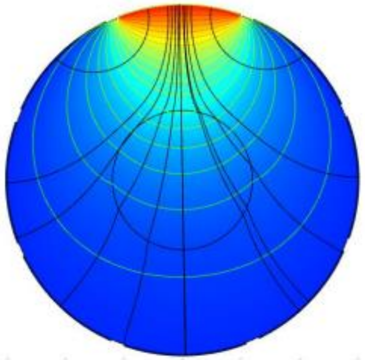
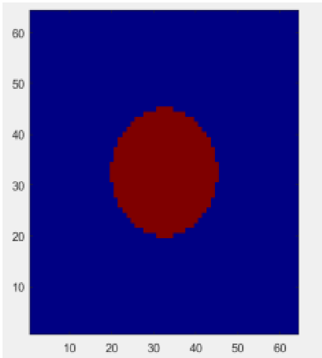
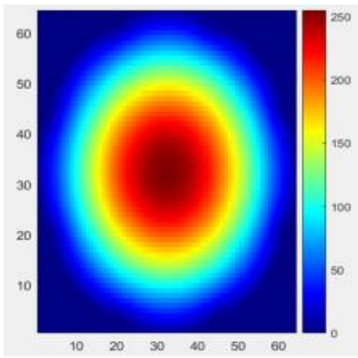
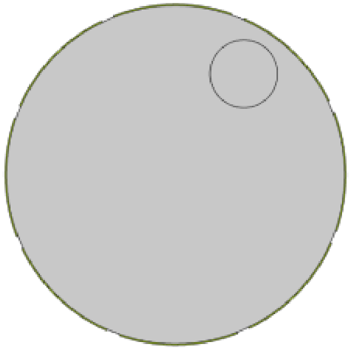
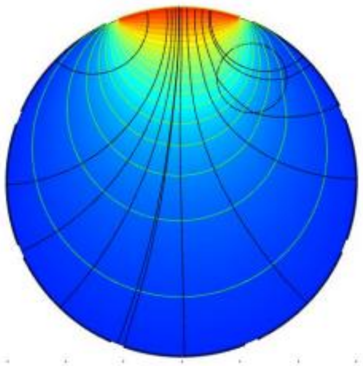
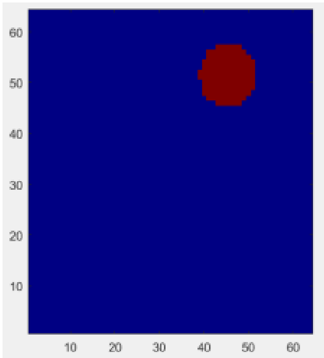
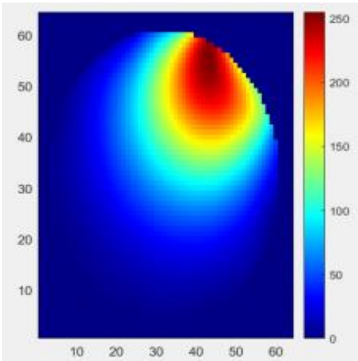
Phantom	Geometry	Contour & Streamline		Tomography	MSSIM
Single 60mm					0.0370
Diff. Size 120mm					0.1052
Diff. Position (Top Right)					0.1587

Table 4.3 Image reconstruction for different multiple phantoms of agarwood

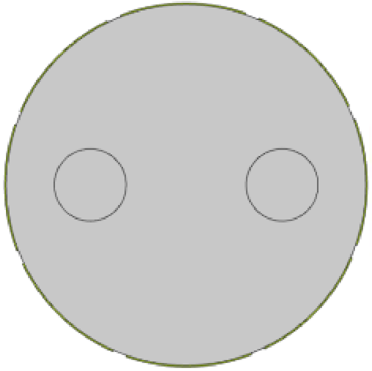
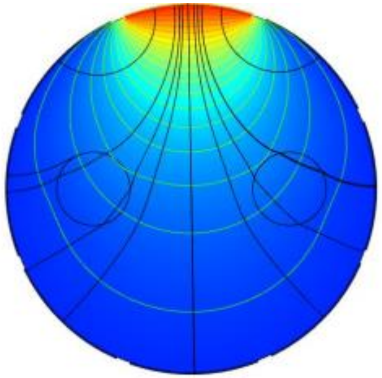
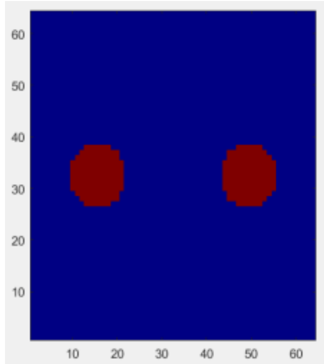
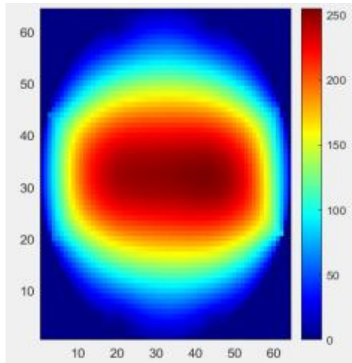
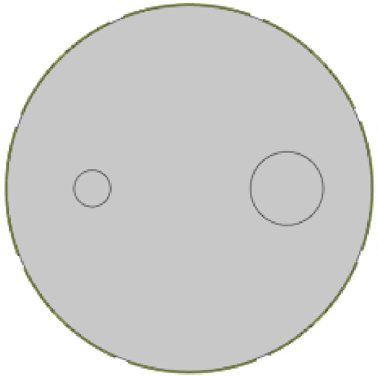
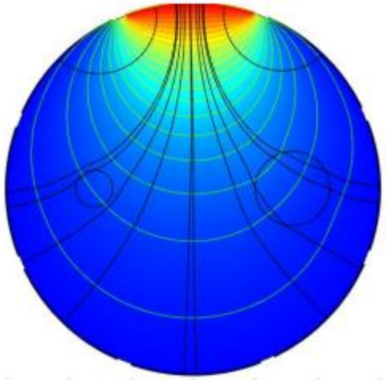
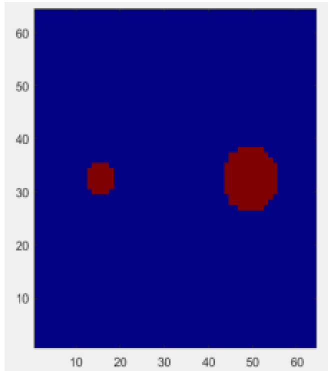
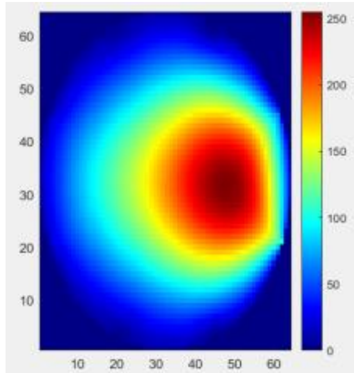
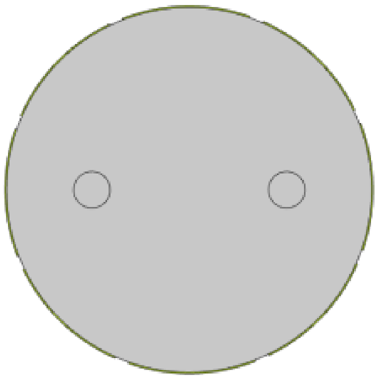
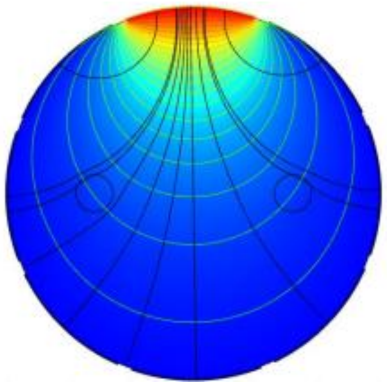
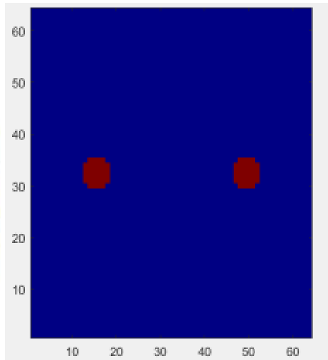
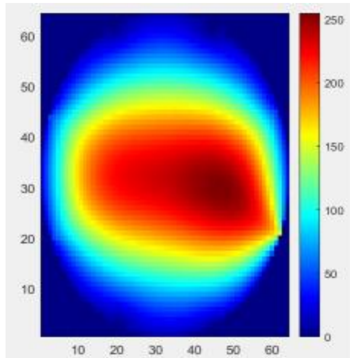
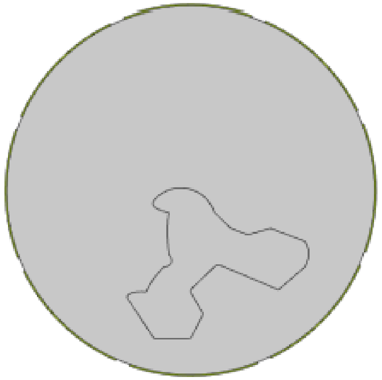
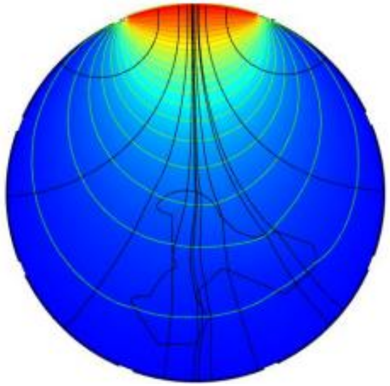
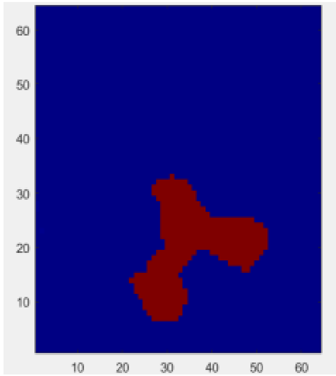
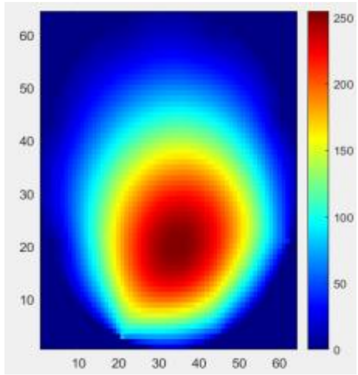
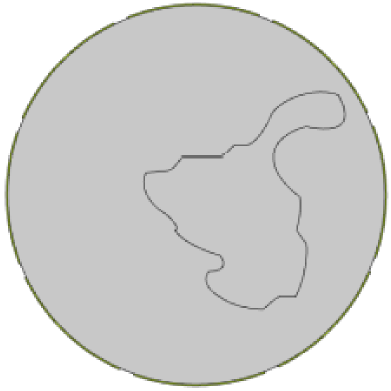
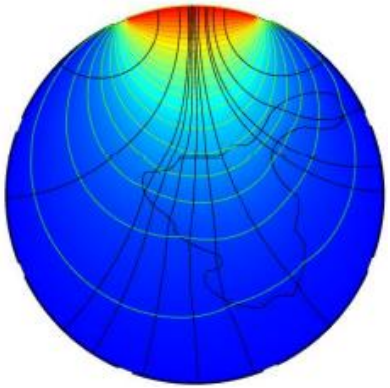
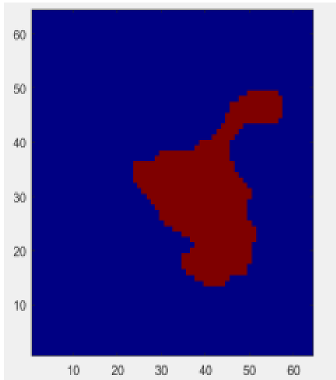
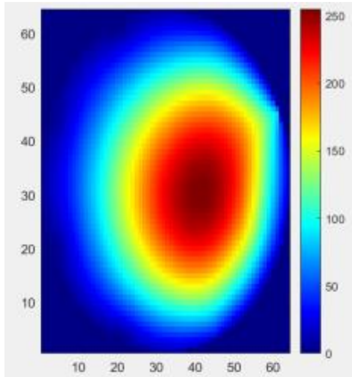
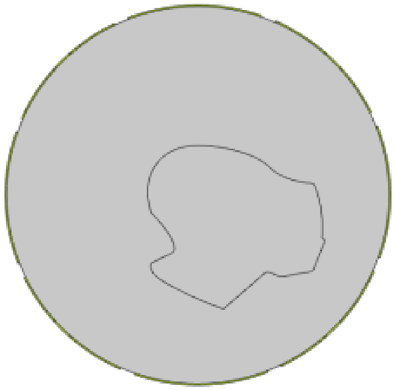
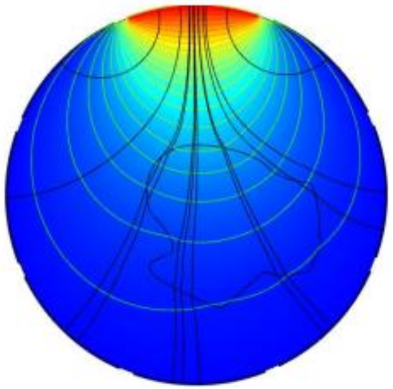
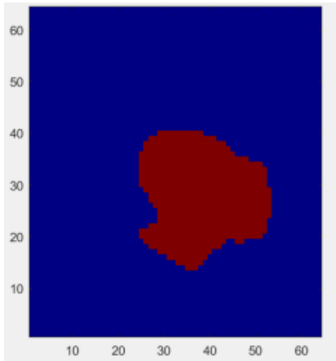
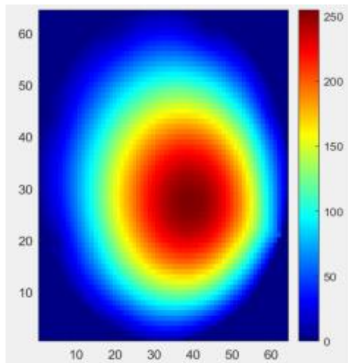
Phantom	Geometry	Contour & Streamline	Ref. Image	Tomography	MSSIM
Phantom A					0.0430
Phantom B					0.0405
Phantom C					0.0260

Table 4.4 Image reconstruction for different shape of agarwood

Phantom	Geometry	Contour & Streamline	Ref. Image	Tomography	MSSIM
Phantom D					0.0563
Phantom E					0.0902
Phantom F					0.1081

Based on Table 4.2, Table 4.3, and Table 4.4, it can be observed that all the tomograms were almost identical. It is possible because the LBP method is essentially rebuilt in the image reconstruction. Because of the blurring effect in LBP, the quality of the picture is degraded. A larger MSSIM index is seen when the agarwood's size is greater, even if all tomograms appear to be the same in appearance. It is possible for the LBP to provide a higher quality tomogram when a larger agarwood is present.

It was also demonstrated that LBP could produce a tomogram that identified the various tested of the agarwood samples. For the phantom D, the value of MSSIM was low, this is because despite the size was larger, but the position of agarwood is far from the excitation electrode (electrode 1), while the value of phantom E and phantom F is high compared with phantom D because the position of agarwood are near with excitation electrode (electrode 1) compared to phantom D. The MSSIM value for phantom C was the lowest due to its location being further away from the electrode and the presence of a little agarwood with a 30mm radius. The disadvantage of the LBP was that the tomogram's ability to accurately record the agarwood's position decreased with increasing distance between the agarwood and the sensor.

The tomograms in phantom A were blurred because of the 2 bigger agarwood with radius 60mm. As previously stated, this was due to the smearing effect. Smearing in LBP algorithm was enhanced by increasing the number of agarwood inside wood and therefore resulting in the blurriness of tomograms.

4.3 Summary

For wood and agarwood samples, the difference in relative permittivity results the distortion of the streamline and contour. Moreover, based on the result of the line graphs, it can be seen that the decrement of value relative permittivity agarwood would result in the increment of distortion of contour and streamline. For an image reconstruction part using MATLAB software, it is only used the electrical relative permittivity value of agarwood sample C. This is because the value of electrical relative permittivity of agarwood sample C had a greater distortion compared to agarwood sample B and agarwood sample A. It shows that the MSSIM index for result different position (top right) has the higher value because the agarwood is near with electrode 1 and the lowest value is phantom C because the agarwood is small with 30mm radius.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The objectives of this project generally have been achieved. Based on this project, ECT has been modeled using COMSOL Multiphysics software to be applied in agarwood detection with non-invasive approach. For the development of the ECT, the 8 rectangular gold electrodes with 2.5mm thick were used. The model ECT was then developed and simulated based on non-invasive approach using COMSOL Multiphysics software. The transmitter set up in the simulation was 20Vdc, which was received by the 7 receivers. When the obstacle was presented, the simulation revealed that the contour and streamline would be distorted. Then, the testing of ECT model was continued with three samples with different value of relative permittivity agarwood. Besides, when the agarwood was presented, the streamline and contour at the agarwood would be distorted due to the difference in relative permittivity value.

The data from the COMSOL Multiphysics software was then investigated by producing a tomogram using LBP algorithm. It was used to explore the distribution of components inside the sensing zone. When the agarwood was smaller, the LBP algorithm displayed a better tomographic quality. The LBP algorithm's smearing impact increases as the sizes of agarwood increases, resulting in a blurrier tomogram. Although the agarwood position is not as obvious and accurate as it should be, the LBP algorithm was still capable to produce a satisfied tomogram.

5.2 Problems Faced

The primary issue faced while working on this project was a lack of understanding in doing ECT. The required facts and specifics regarding ECT are not mentioned in reference journals. There were different sources of reference materials for the ECT procedure, but the difficulty for ECT was that there was not much to discuss, as most of the information given was about common ECT with an industrial approach. Therefore, for the methodology of this project, researches regarding other types of tomography with non-invasive technique application were used as the reference.

The software was used in this project, which is COMSOL Multiphysics software. This software was depending on the computer performance. And this is first time that were used. Computing and running this software with lack of knowledge about this software are time-consuming process. Hence, a well-organized plan was required before starting the simulation of this software.

5.3 Future Work Recommendation

For the recommendation, several ideas for future projects have been generated by this project for example, another method may be used to reduce the smearing effect around the agarwood such as Filtered Back Projection, NOSER or Tikhonov Regularization. Besides that, the sensor loss reading can be improved by increasing the number of electrodes and the number of pixels in the forward problem can be increased in order to get a better tomogram of agarwood.

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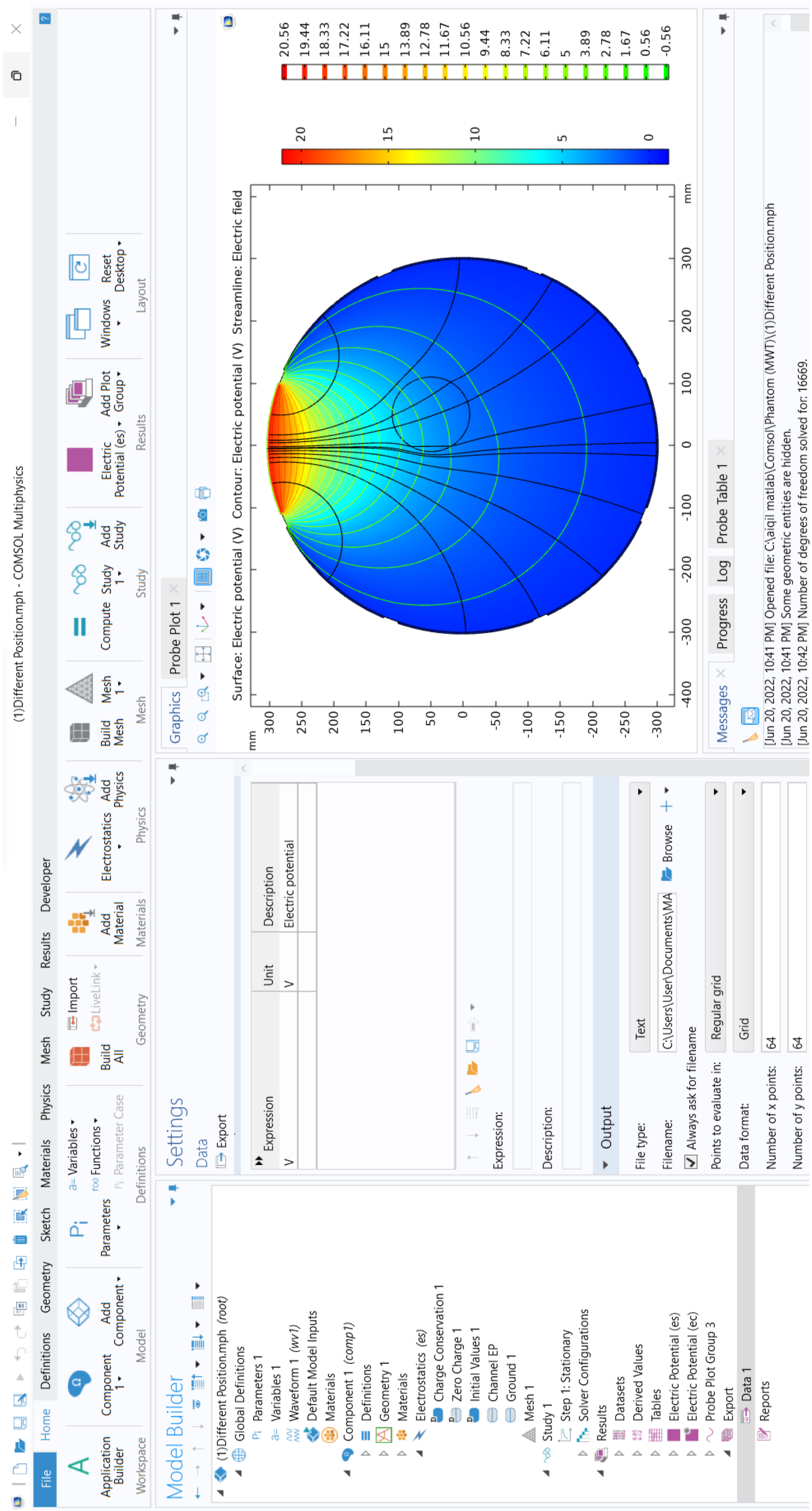
APPENDICES

Appendix A: Export an electrical potential data of single projection from COMSOL software



Appendix B: Coding for calculate sensor loss/signal loss

```
%%Clear work space
clear all;

%%Load the sensor reading for fullwood(Homo) and with agarwood(Non Homo)
%%Make sure the sensor reading value are electrical potential
%%If have N electrodes make sure the table are NxN for both
load Homo;
load NonHomo;

%%Make a repsentation for fullwood(Homo) and agarwood(Non Homo)
A=Homo;
B=NonHomo;
%%Calculate sensor loss
SL=(A-B)/A;
```

Appendix C: Coding for image reconstruction algorithm

```
clear all;

%%Load all single projection file(make sure save as .mat)
load E1;
load E2;
load E3;
load E4;
load E5;
load E6;
load E7;
load E8;

%%Load the sensor los
load SL;

%%Sort the file in cell 1xN
EachProj={E1 E2 E3 E4 E5 E6 E7 E8};


 %%Set the number of electrode//Set the pixel
 N=8
 pixel=64;
 r = pixel/2; % radius


 %%Pair projection N x N cells
 for i=1:N
    ei=EachProj{1,i};

 for j=1:N
    ej=EachProj{1,j};
     m= ei.*ej;
    Epair{i,j}=m;
  end
 end
```

```
%Loop weighted balance map/ total map
W = EachProj{1};
for i=1:8
 W = W + EachProj{i};
end

%Normalization of pair projections
for i=1:8
 for j=1:8
 norm = Epair{i,j}./W;
 NormEpair{i,j}= norm;
 end
end

%LBP formula
DispMap= zeros(pixel);
for Tx=1:N
 for Rx=1:N
 DispMap= DispMap + (SL(Rx,Tx)*NormEpair{Rx,Tx});
 end
end
%%-------Fixed scale 0 to 1------
normDispMap=DispMap; % rename display image
a = min(normDispMap(:));
b = max(normDispMap(:));

for Tx = 1:pixel;
 for Rx = 1:pixel;

 normDispMap(Tx,Rx) = ((normDispMap(Tx,Rx)-a)./ (b-a))*1;
 %%Eliminate NaN value at norm DispMap ; if not matlab cant plot img
 e=normDispMap(Tx,Rx);
 d=isnan(e);
 e(d)=NaN;
 normDispMap(Tx,Rx)=e;

 end
end
```

```
%Displaying map
subplot(1,2,1);
pcolor(normDispMap(1:pixel,1:pixel))
imageCenter=[32.5,32.5];
title('reconstructed image(rescaled 0-1)');
shading interp; % To hide the grid line from pcolor

colormap (jet) % Change color map to jet colour
colorbar % Display colorbar at RHS
subplot(1,2,2);
imagesc(normDispMap(1:pixel,1:pixel))
set(gca, 'YDir', 'normal')
```

Appendix D : Example of sensor loss reading for data Phantom F

SL

8x8 double

	1	2	3	4	5	6	7	8	9
1	0	-0.0177	0.0356	0.2724	0.2372	0.0773	-0.0146	-0.0117	
2	-0.0175	0	-0.0172	0.1971	0.2779	0.1899	0.0751	-0.0164	
3	0.0371	-0.0172	0	0.0253	0.2385	0.2993	0.2505	0.1570	
4	0.2716	0.1945	0.0225	0	-0.0115	0.1442	0.2458	0.2906	
5	0.2371	0.2769	0.2394	-0.0132	0	-0.0146	0.0368	0.1470	
6	0.0782	0.1896	0.2997	0.1432	-0.0154	0	-0.0158	-0.0151	
7	-0.0144	0.0742	0.2502	0.2456	0.0363	-0.0160	0	-0.0120	
8	-0.0105	-0.0175	0.1561	0.2906	0.1470	-0.0159	-0.0119	0	
9									