ELECTROMAGNETIC FLUX MODELLING OF AC FIELD OVER PLANAR MICROARRAY DOT ELECTRODES USED IN RAPID DIELECTROPHORETIC LAB-ON-CHIP DEVICE

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ABSTRACT

This research presents a simulation procedure to determine electromagnetic flux produced by planar microarray electrode used in dielectrophoretic lab-on-device. Recently, dielectrophoretic lab-on-device was a useful technique that offers a simple microarray electrode for sorting and manipulating particles. Here, the finite element method (FEM) (COMSOL package) has been employed to model and simulate this model. The electrode model was developed by using three different conductive materials such as copper, gold and indium tin oxide (ITO). Based on Clausius-Massotti factor, frequency, conductivity and permittivity of particles and conductive medium play an importance role in the production of dielectrophoresis force. Thus, in order to simulate and determine the production of electromagnetic field, this microarray electrode was applied with different frequencies values which are 50Hz, 100Hz, 1 KHz, 50 KHz and 500 KHz; and different conductive medium such as distilled water, air at 1 atmosphere (atm) and yeast solution. Statistical analysis made based on the simulation result has shown that copper produced a wide range of electromagnetic flux density compared with other 2 materials. Besides, different conductive medium applied did not bring any changes towards the electromagnetic flux density produced.

ABSTRAK

Penyelidikan ini dijalankan untuk membina satu prosidur simulasi bagi menentukan ketumpatan fluk electromagnetik yang dihasilkan oleh 'planar microarray electrode' yang digunakan pada alat 'dielectrphoresis lab-on-chip'. Dewasa ini, penggunaan alat 'dielectrphoresis lab-on-chip' telah menawarkan pelbagai kelebihan di dalam bidang bioperubatan, antaranya ialah menawarkan alat yang ringkas untuk tujuan penyusunan dan manipulasi zarah ataupun sel. Bagi projek ini, 'finite element method' atau FEM yang diaplikasikan pada perisian Comsol Multiphysics telah digunakan untuk memodelkan dan mensimulasikan fenomena tersebut. Disini, model elektrod telah dibina dengan menggunakan 3 bahan yang berlainan iaitu tembaga, emas dan indium tin oxide (ITO). Selain itu, menurut factor Clausius-Massoti kekuatan daya 'dielectroporesis' yang dialami oleh zarah adalah bergantung kepada frekuensi yang dikenakan, kekondusian dan ketelusan zarah serta medium. Oleh itu, untuk mengetahui perubahan yang dialami oleh ketumpatan fluk electromagnetic, frekuensi berbeza telah dikenakan iaitu 50Hz, 100Hz, 1KHz, 50 KHz dan 500KHz. Selain itu, 3 medium berlainan kekonduksian dan ketelusan juga telah digunakan iaitu air suling, udara berketumpatan 1 atm dan juga larutan yis. Analisis statistik yang dibuat berdasarkan graf yang dihasilkan dari simulasi menunjukkan tembaga adalah bahan yang dapat menghasilkan pelbagai nilai ketumpatan fluk electromagnetic berbanding bahan lain. Selain itu, penurunan ketumpatan me dan electromagnetik dapat dilihat apabila frequensi melebihi 50KHz dikenakan malah penggunaan medium berlainan juga tidak menunjukkan sebarang perubahan terhadap medan electromagnetic yang dihasilkan.

UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

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Alhamdulillah. Thankful for Allah s.w.t for His love and blessing, I manage to finish this project.

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Aizreena Azaman

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DEP	Dielectrophoresis
FEM	Finite element method
$\mathbf{F_{DEP}}$	Force of dielectrophoresis
KCL	Potassium Chloride
ITO	Indium tin oxide
ε	Permittivity
σ	Conductivity
μ	Permeability
Re [K (w)]	Clausius-Massotti factor
E	electric field
RMS	Route means square
r	Radius of particle
$\tilde{\emptyset}$	Potential phasor
Re	Real component
Im	Imaginary component
V	Voltage
B	Electromagnetic flux density
H	Electromagnetic field intensity

LIST OF APPENDICES

- Table of Electromagnetic flux density recorded for variety frequencies applied.
- SPSS Result of the value of electromagnetic flux for each material against frequency applied.
- COMSOL Multiphysics 3.3 Guide for AC Power Electromagnetic Mode.

CHAPTER 1: INTRODUCTION

1.1 Background

The dielectrophoresis (DEP) is an electromagnetic technique that capable to manipulate cells. It used to describe the motion of particles in non-uniform electrical field. This technique was first introduced by Pohl in 1951. After that moment, the application of dielectrophoresis has become widen including characterizing the myriad of mammalian cells such as yeast, neuron, platelets (Pommer *et al*., 2008), human leukaemia cells (Fatoyinbo *et al*, 2011) and many more.

Recently, DEP electrode has shown a positive result when it was fabricated as lab-on-chip device. Lab-on-chip device is the integration of laboratory components such as heaters, pumps, sensors and reactors that built into a single device with size as small as a postage stamp (Hughes, 2002). Thus, DEP lab-on-chip offers a simple device that can perform an analysis which normally requires more than one laboratory equipment.

Furthermore, in year 2008, DEP microarray electrode have been developed (Fatoyinbo, *et al*, 2008).The development of programmable DEP microarray electrode allows the production of stable waveform generation within a range of 1 KHz to 50 KHz from 10 to 15 $V_{p\text{-}p}$ of supplied power. This electrode consist of parallel dots microarray that receive different frequency signal allowing multiple experiments conducted simultaneously and real-time data to be collected (Kadri, 2010).

Due to these abilities and developments, dielectrophoresis lab-on chip device have a great potential to offer a better solution for mass productions, portability and easy to operate in many areas such as drug testing tools, cell therapeutics, medical diagnostic, and even in tissue engineering field. It is also promises a great solution especially in biomedical field such as for monitor changes in cell viability; isolate viable and culture able cells with less or no biological damage; monitor changes in surface morphology and many more (Pethig,2010).

The variety in design has led to a great development of DEP. Unfortunately in designing process; there is no specific tool or methods that can be used as a preliminary testing for the design model. Other than that, there is no specific guide in selecting a conductive material that can be used to build the DEP electrode to fit certain electric field range.

1.2 Research Objective

The objective of this research is to build a simulation model as part of process in designing DEP electrode which adapted from parallel version of the dot microarray electrodes proposed by Fatoyinbo, *et al.* (2008). Besides, this research will be done to analyse the effect of different properties of the model towards electromagnetic flux density strength produce. Thus, the model will simulate by using three different materials such as copper, gold and indium tin oxide under a different frequencies value and different conductive medium environment. This analysis result will guide the design of novel dielectrophoretic electrode.

1.3 Dissertation Structure

This dissertation will include the following topic in the order displayed;

a) Chapter 2 described a sufficient literature review on the topics of dielectrophoresis (DEP), the fundamental theory of DEP force, lab-on-chip device technologies, the available design of DEP electrode and the used of numerical method which is finite element method (FEM) analysis to evaluate the electrode design.
b) Chapter 3 mentioned a description of the design and development of the simulation model using Comsol Multiphysics 3.3 software.
c) Chapter 3 also stated a description of the work undertaken in validating the experiment such as the model setting for simulation process
d) Chapter 4 described a discussion on the results attained from the simulation process and statistical analysis to describe the results.
e) Chapter 5 illustrated an overall conclusion based on the work undertaken for the project, including a brief summary of future work that needs to be completed

1.4 Scope of Research

The following is a list of activities participated towards the completion of this research project:

a) Design and development of simulation model microarray electrode for 3 different materials by using Comsol Multiphysics 3.3 software.
b) Simulation of the model in different frequency supplies and different conductive medium.
c) Comparison making based on the results obtained.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This section will cover relevant background information gained from the review of the literature that relates to the three primary aspects of the project, namely the design and development of the DEP microarray model using Comsol Multiphysics 3.3package, the production of electromagnetic flux density based on different conductive material and the effect of frequency on DEP phenomenon.

The review will start on the theory of dielectrophoresis followed by lab-on-chip device and previous research on the design of DEP electrode. After that, the review continued with the characteristic of conductive material and the finite element method (FEM) that being used to analyze the electrode model.

2.2 Dielectrophoresis (DEP)

The idea of dielectrophoresis was first discovered by Hatfield when he tried to separate the valuable mineral cassiterite from a large excess of quartz material. Hatfield realized the problem in electromagnetic separation was the generation of strong non-uniform electrical field even approaching the weakest electromagnetic field without caused any of dielectric breakdowns. Then, this idea was continued by Pohl who applied this theory to solve problem regarding of removing carbon-black filler from polyvinyl chloride samples. Then, he proceed his efforts in the development of methods and theories for dielectrophoresis characterization and separation of biological cells

Over past 10 years, there are more than thousands research have been conducted in dielectrophoresis field (Pethig, 2010). This area is expected to face a huge growth due to its ability to integrate with advanced technologies like the used of thin film techniques or CMOS technology in fabricating the electrode. Besides, advanced in development of sophisticated electronic design has enhanced dielectrophoresis system by including some optical sensor or even the used of microcontroller for monitoring and manipulating purpose respectively. The existences of new materials like silicone polymer, silica glass or even indium tin oxide have given more choices for researchers in development of DEP system.

In general, dielectrophoresis (DEP) is a promising method for the separation and classification of biological cells in a miniaturized format. This technology allows cells to be manipulated electronically while suspended in a micro fluidic channel. Several dielectrophoretic configurations have been designed and fabricated using micro-electro-mechanical-systems (MEMs).

If in the early age, the application of dielectrophoresis was more towards industrial application such as mineral sorting, assembling of micro component and manipulating fluid droplets as mentioned before, now the focus is diverge into biomedical application and it is expecting keep growing in future.

2.3 Theory of Dielectrophoresis (DEP)

According to Pohl in 1951, dielectropherisis can be defined as "the motion of suspensoid particles relative to that of the solvent resulting from polarization forces produced by an inhomogeneous electric field". Polarization forces produced known as DEP force, which play an important role for manipulating and separating of target cells.

Particles can either moved toward or away from higher electrical gradient area. There are 2 factors that influenced the effectiveness of particle movement in DEP which are polarisability of the particle and its medium. These factors are differing from the electrophoresis phenomenon where mobility of ion depends on their total charge, size and shape.

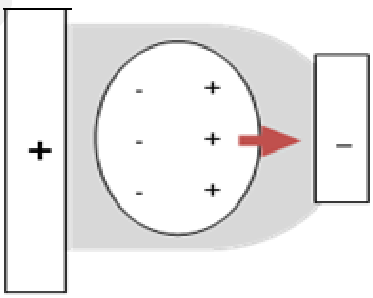


Figure 2.1: A schematic diagram of positive DEP (pDEP)

Based on figure 2.1 above, positive DEP (pDEP) occurs when the particles are more polarisable than the surrounding medium, the induced dipoles align with the electric field and the particles move towards regions of higher field. Meanwhile, negative DEP (nDEP) occurs the particles are less polarisable than the surrounding medium, the induced dipoles will align against the applied field, causing the particles to move to regions of lower field strength. The DEP force can be described by the following question below (Hughes, 2002);

$$F_{DEP} = 2\pi r^3 \varepsilon_m Re[K(\omega)] \nabla E^2 \tag{2.1}$$

where r is the cell radius, ε_m is the permittivity of the medium surrounding the cell, K(ω) is the complex Clausius- Mossotti factor, ∇ is the Del vector operator and E is the electric field strength in route means square (RMS) value.

Clausius- Mossotti factor is used to analyze the effective polarisability of the particles. According to Jones (1995), when Re [K (ω)] > 0 pDEP phenomenon will occur meanwhile when Re [K (ω)] < 0, nDEP phenomenon will occur. Furthermore, normally for spherical particles, the interval range of Re [K (ω)] is between −0.5 and 1. Clausius-Mossotti factor can be defined as equation below (Hughes, 2002);

$$K(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* - 2\varepsilon_m^*} \tag{2.2}$$

where ε_p^* and ε_m^* are the complex permittivity of the particles and medium respectively. Furthermore, ε^*can be determined using the equation below (Kadri, 2010);

$$\varepsilon^* = \varepsilon - \frac{j\sigma}{\omega} \quad (2.3)$$

where σ is conductivity, ε is permittivity and ω is the angular frequency of the applied AC electric field.

Frequency applied by AC input will affect the polarisability of the particles (Pethig, 2010). By looking at equation 2.3, if the conductivity of particles predicted to be increased by a given frequency, the complex permittivity will be decrease as well as Clausius-Mossotti factors. This frequency exploitation strategy has played an important role in particles separation where it linked to the different of polarisability of particle in the population.

Other than that, frequency has also play an important role in electromagnetic field produced. This condition has been mentioned by Muller *et al.* (1996) where the strength of electric field increased at higher frequency range up to MHz.

2.4 Lab-on-chip device

The "lab-on-chip" concept emerged to describe the integration of laboratory components such as heaters, pumps, sensors and reactors that built into a single small device which usually in microns. It is a simple device that can perform an analysis which normally requires more than one laboratory equipment like blood test. For dielectrophoresis, this concept have been adapted to replace the used of needle or probe electrode to generate electric field. It have improved by the application microelectronic fabrication where a conductive material patterned onto a plate or insulating substrate such as silica glass.

In dielectrophoresis analysis like particles separation, gold is a common conducting material used meanwhile glass was used as insulating substrate because it allowing other optical techniques to be used for particles detection and measurement. The first device reported to use micro engineering approaches was the dielectrophoretic fluid integrated circuit built by Washizu, Masuda, and Nanba (IEEE) in 1990. This device integrated all cell-handling components onto one substrate with photolithography techniques where it was successfully in handling biological cells.

This concept has encouraged more researchers to perform a range of function using dielectrophoresis, from particles separation, trapping to analysis. With efficient capability in separating, isolating and analyzing cell together with simplicity in the system have also providing a great possibility of using dielectrophoresis in stem cell biology and medicine (Pethig *et al.*, 2010). Currently, dielectrophoresis been used as a part of a huge system such aspolymerasechain reaction (PCR), electroporation or biochemical methods for dell detection and using dielectrophoresis primarily as a method for isolating specific cells at a preliminary stage (Hughes, 2010).

2.5 DEP microelectrode design

The simplest dielectrophoresis device set up for handling cells commonly will be consisted by microelectrode, gasket and ground plane (Kadri, 2011). A gasket sandwiched in between the electrode and ground plane (ITO layer) as shown in figure 2.2.

Microelectrode is the part that will generate the electric field for the whole system. Meanwhile, the gasket is use to create a chamber for the cell suspension to be placed. Polymer material like polyresin that offer a good transparency and easily formed is suitable to make a gasket. Normally, ground plane did not required in dielectrophoresis system, but it is use in order to create 3-dimension electric field. ITO layer have been used as ground plane in Kadri (2010), design due to its optical transparency and also conductivity which make a monitoring process easier.

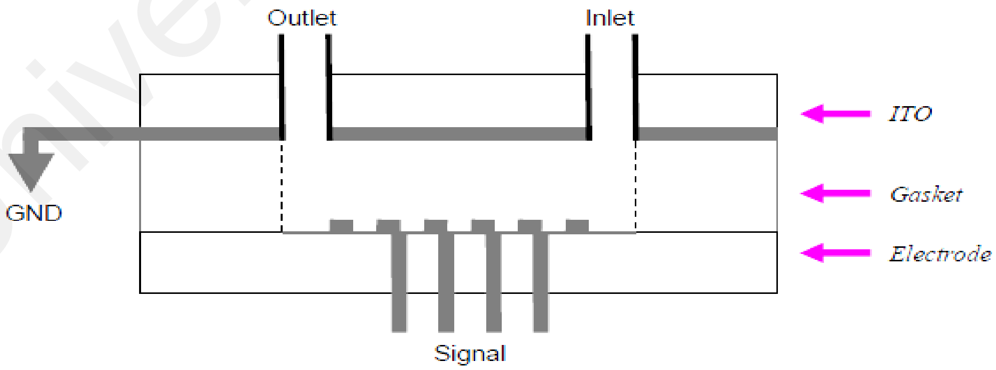


Figure 2.2: A schematic diagram of the dielectrophoresis device by Kadri (2010).

This project focused on the design of microelectrode which is the main part of dielectrophoresis device. The design of microelectrode is generally depends on the research needs. The generation of desirable strength electric field and its effect either positive or negative must be prepared to meet the purpose of study.

Since this phenomenon has been introduced, there are only a limited number of microelectrode designs that have been employed to conduct DEP studies. For separating purpose, there are a few designs from Becker *et al.*, (1995), Qiu *et al.*, (2002), Suehiro *et al.,* (2003),and Gascoyne *et al.*, (1992) meanwhile for characterisation studies, three dimensional designs have been introduced such as Hübner *et al.*, (2005) and Labeed *et al.*, (2006).

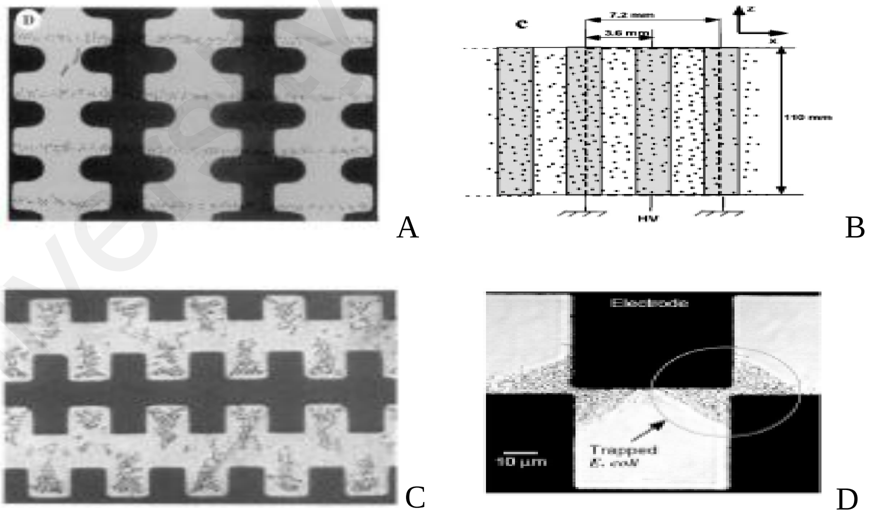


Figure 2.3 : A selection of electrode designs used for separating purpose; a) from Becker *et al.*, (1995); b) Qiu *et al.*, (2002); c) Suehiro *et al.*, (2003),and d) Gascoyne *et al.*, (1992).

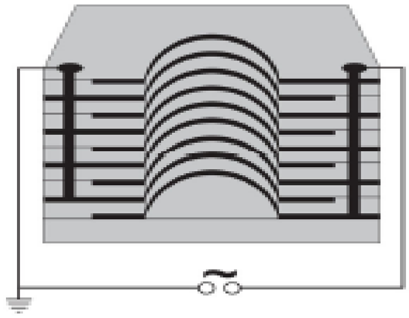


Figure 2.4: A selection of electrode designs used for characterizing studies

(Hübner *et al.*, (2005) and Labeed *et al.*, (2006))

One dimensional electrode can be used for most routine protein and nucleic acid separation. Besides, two dimensional and three dimensional electrodes are suitable for characterization of particle and finger printing application.

In order to observe and analysis the efficiency of the electrode in producing the required electrical field for dielectrophoresis purposes, the dot microarray electrode system by Fatoyinbo *et al.* (2008) will offer the suitable and simplest design. The circular dots design will offer better DEP effects where it can create a three dimensional axisymmetrical electrical gradient and possible to apply individual waveform at each dot. Figure 2.5 shows the electrode design for current research that adapted the design from Fatoyinbo *et al.* (2008) as shown in figure 2.5.

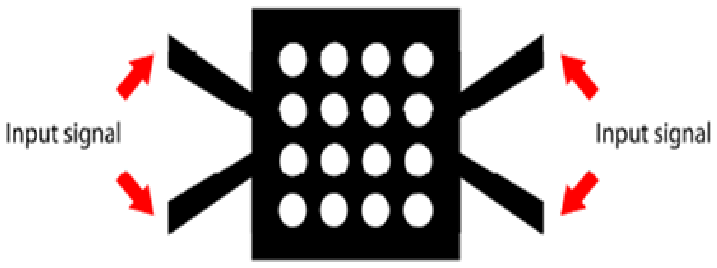


Figure 2.5: Electrode design by Fatoyinbo *et al.* (2008).

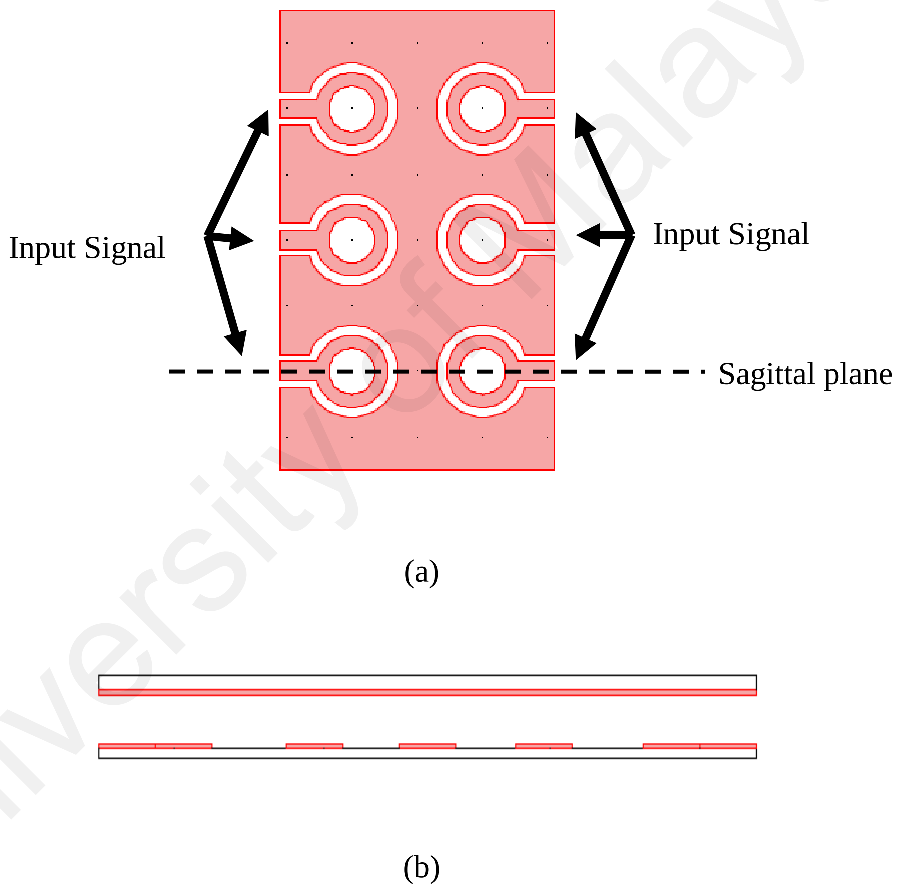


Figure 2.6: Schematic configuration of DEP device for current research where, (a) microarray electrode and (b) sandwiched electrode from sagittal plane view

2.6 FEM Analysis

Computer aided approaches can make the design process easier. In order to achieve an optimum design of the electrode, some approaches have been developed such as topological optimization procedure. The procedure introduced by G.H. Yoon and J. Park in 2010 was based on the mathematical analysis like Laplace equation to find a proper structure of the electrode.

Besides, the integrated approach introduced by D. Su and D. Qin (2003) for the design of worm gear have also encourage the usage of computer aided in designing work. Here, they integrated three procedures which are numerical analysis, three-dimensional simulation and finite element analysis. As a result, it provides an optimum design of worm gear.

In design process, numerical analysis method used mathematical equation to solve geometrical or structure modifying. The most commonly used numerical approximation in structural analysis is the Finite Element Method (FEM). Finite element method is widely used to solve dynamic and static problems such as solid or fluid mechanics, electromagnetic, biomechanics and many more which normally described in term of partial differential equation (PDE).

In finite element method, a structure will be transformed into an assembly of elements or components with several forms of connection between them. The behaviour of each element is characterized by the element's stiffness or flexibility relation. Thus, the system's stiffness and flexibility can be determined.

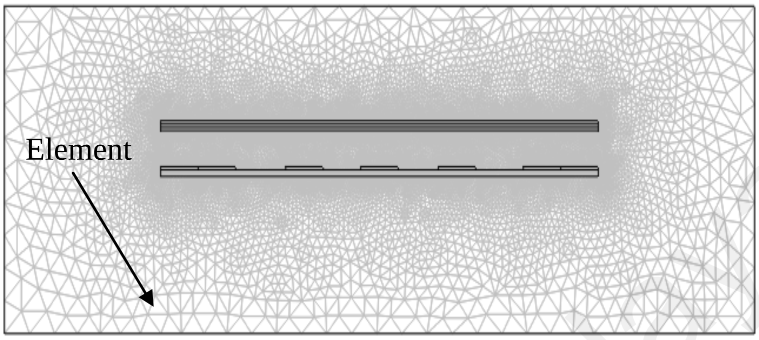


Figure 2.7: Example of electrode structure that converted into an assembly of elements.

According to N. G. Green *et al.* (2002), numerical approaches such as point charge, charge density, and finite difference and integral equation methods can be used to determine electric fields and DEP forces from electrode arrays. Here, the force equations are written in term of real and imaginary component of the field phase. The DEP force was described as in equation below (N. G. Green *et al.*, 2002);

$$< F_{DEP} >= \frac{1}{4} v Re[\alpha] \nabla (|Re[\tilde{E}]|^2 + |Im[\tilde{E}]|^2)$$

$$= \frac{1}{4} v Re[\alpha] \nabla (|\nabla \emptyset_R|^2 + |\nabla \emptyset_I|^2)$$

Then, FEM used to generate a mesh of triangular elements and solved the equation using partial different equation (PDE).

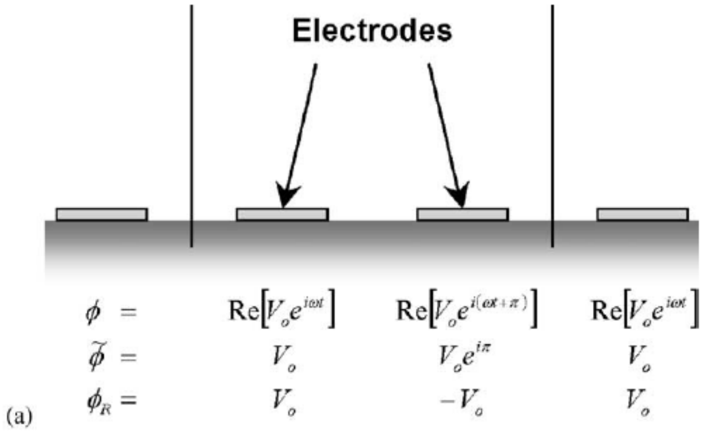


Figure 2.8: A schematic diagram of the electrode array with 2-phases applied as in dielectrophoresis experiments by N.G Green *et al.* (2002). The vertical lines mark the period over which the system repeats. Also shown are the values for the potential $\emptyset$; the potential phasor $\tilde{\emptyset}$ and the value of $\emptyset_R$ on each electrode. The imaginary part of the phasor, $\emptyset_I$ is zero everywhere.

Thus, finite element method analysis offers a fast and simplest way of determining DEP and travelling wave forces. Besides, FEM analysis provides a flexible tool for modification and optimisation. Boundary condition and also the characteristic of materials used included in the analysis to create a proper volume of the electrode model.

Nowadays, there are several finite element method software available such as ANSYS, FEM CAD, ALGOR and including Comsol Multiphysics. In year 2011, Comsol News magazine has reported that Comsol software have been used widely in simulation of as lithium-ion battery for Greener Ford vehicles, microscopic magnetic field simulation, modelling of electromagnetic waves in thermonuclear fusion plasma and many more. Due to this capability, Comsol may have a good potential to be used in DEP analysis.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This section will cover methodology involved in system design and development. This project consists of a model simulation process and analysis. The simulation process will conduct in variety of condition and supplies. The methodology will start on the development of simulation model. Then it will continue by the simulation in several condition and analysis for the desired observation.

3.2 Development of Simulation Model

This project use Comsol Multiphysics 3.3 package which relies on finite element method. This software allows the geometry studied which it will divide into finite element mesh.

Comsol package offers variety of application mode for equation-based modelling. Thus, a suitable application that fit the research purpose need to be chosen. Furthermore, in 2010, Roger Thunvik has introduced a few steps to define the characteristic of the physical design using this software. These steps will be implemented for simulation works. Figure 3.2 shows the flow chart of the steps by Thunvik (2010).

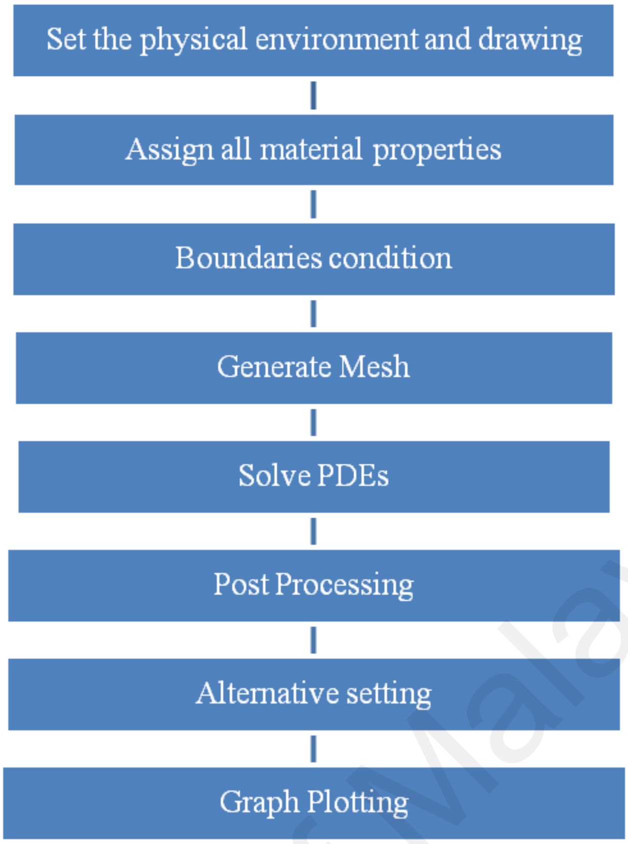


Figure 3.2: A flow Chart of steps to set physic parameter and for simulation process.

a) Set the physical environment and drawing

For this research, AC power electromagnetic mode will be used. This application mode commonly used when studying motors, transformers, and conductors carrying alternating currents.

For AC power electromagnetic mode, the analysis will be based on partial differential equation (PDE) which represents physic model using Ampere's Law as mentioned below (COMSOL, 2008);

$$\nabla \times H = J + \frac{\delta D}{\delta t} = \sigma E + \sigma v \times B + J^{e} + \frac{\delta D}{\delta t} \tag{3.1}$$

The equation above used to describe a static-state model. The relationship of electromagnetic field intensity, ***H*** has been explained in term of current density, ***J***, electric flux density, ***D***, electric field intensity, ***E***, electromagnetic flux density, ***B*** and electromagnetic velocity, ***v***. Furthermore, some equation have been introduces to manipulated the design in term of harmonic-state with the electric scalar potential, V and electromagnetic vector potential***, A*** as shown below (COMSOL, 2008);

$$B = \nabla \times \mathrm{A} \tag{3.2}$$

$$E = -\nabla V - \frac{\delta A}{\delta t} \tag{3.3}$$

For this project, there are 3 different conductive materials with different properties which are copper, gold and indium tin oxide (ITO) will be used. Therefore, constitutive relation is need to describing to macroscopic properties of the material in a closed system. Generally for linear material, the constitutive relation as mention below (COMSOL, 2008);

$$B = \mu_o \, \mu_r \, H \tag{3.4}$$

$$D = \varepsilon_o \, \varepsilon_r E \tag{3.5}$$

Where ε_o is permittivity of the vacuum which has value approximately $\frac{1}{36\pi}10^{-9}F/m$ while $\mu_o$is permeability of vacuum with value of $4\pi10^{-7}H/m$. Then, by including all the equation 3.2,3.3,3.4 and 3.5 above, the Ampere's Law equation can be written as (COMSOL, 2008);

$$(j\omega\sigma - \omega^2\varepsilon_o)A + \nabla \times (\mu_o^{-1}\nabla \times A - M) - \sigma v \times (\nabla \times A) + (\sigma + j\omega\varepsilon_o)\nabla V = J^e + j\omega P_z \tag{3.6}$$

The above equation represents the model in mathematical expression and it will be used to run the finite element method (FEM) analysis. After selecting a suitable mode, the drawing process can be started. Here, only 2-dimension drawing is allows in AC power electromagnetic mode. Thus, the model was drawn according the sagittal plane view of the electrode as mention in figure 3.3.

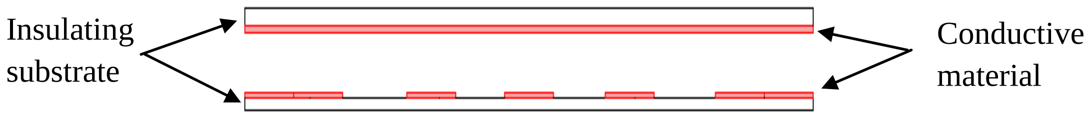


Figure 3.2: The sagittal plane view of the electrode model

The sandwiched electrode is model as a rectangle plate. The insulating substrate is model with length of 1.75mm and height of 10µm. Meanwhile, the ‘dot’ ring also modelled in rectangular shape with 150µm of width and height of 10µm.Other than that, this model was placed in a box with size of 3mm x 1mm. This box will play a role as conductive medium for the electrode. After completing the drawing process, the next procedure is to include the parameter and variable that represent this model.

b) Assign all material properties

In order to insert the properties for the model, a few setting are required to be set such as subdomain setting, boundaries setting, point setting, scalar variable, properties, equation system, ODE setting and many more. These settings are located under the **Physics** button as shown in figure 3.4.

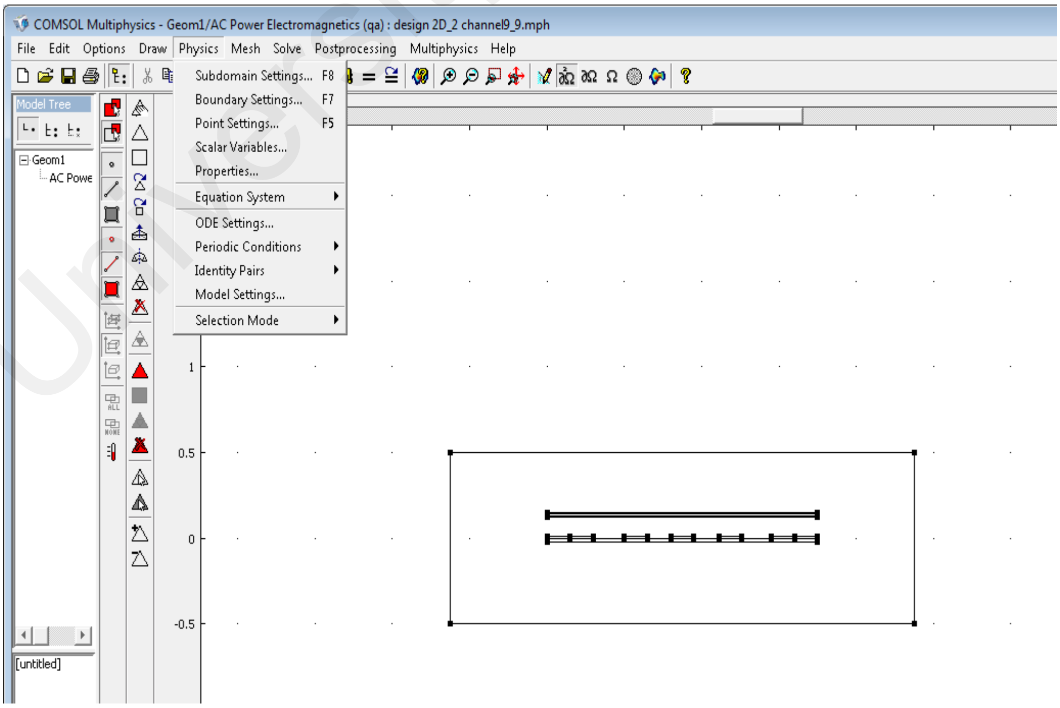


Figure 3.3: Settings list under **Physics** button.

Generally, **Sub domain s**etting is used to assign the material properties. By clicking the **Sub domain Settings** button, the properties like the type of material, its permeability, its relative permittivity, conductivity and its electric parameters such as its potential different can be set according to the material used. Figure 3.5 shows the **Sub domain Setting** window.

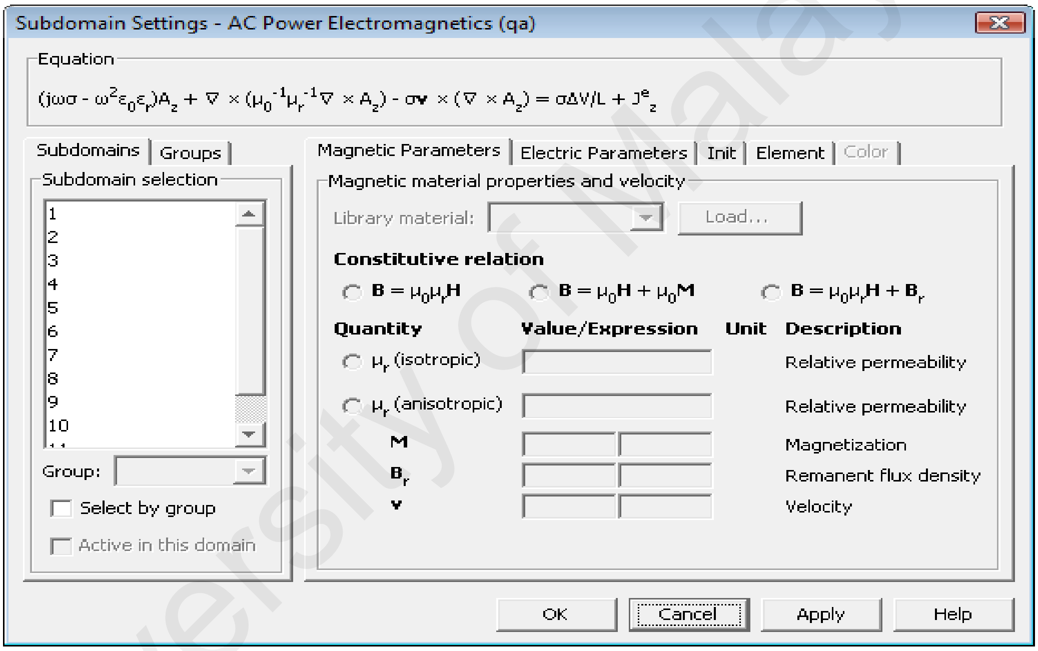


Figure 3.4: **Sub domain Setting** window.

Since there are 3 different materials that will be evaluated using this approach, there will be different models with different sub domain setting are required. All the material used which are gold, copper and ITO are linear material, thus it can be considered as isotropic material. But, those materials have different permittivity constant that also known as dielectric constant and electrical conductivity. Meanwhile, the potential difference given to both positive and negative terminal is about 10V. The constant are mention in the Table 3.1 below.

MATERIAL	RELATIVE PERMITTIVITY (ε_r)	RELATIVE PERMEABILITY (μ_r)	ELECTRIC CONDUCTIVITY (σ)
Copper	18.1	1	5.96×10^7 S/m
Gold	6.9	1	4.52×10^7 S/m
ITO	9.0	1	1.3×10^7 S/m

Table 3.1: The constant for the materials

As mention before, the surrounding box which represents the environment for the electrode also must be setting to mimic the environment needed. Here, this project requires the electrode to be in a normal air condition, distilled water condition and yeast solution that dispersed in KCL concentration. The sub domain setting for the surrounding box is based on the constant below;

MATERIAL	RELATIVE PERMITTIVITY (ε_r)	RELATIVE PERMEABILITY (μ_r)	ELECTRIC CONDUCTIVITY (σ)
Air (1 atm)	1	~1	0S/m
Distilled water	78.57	~1	1.5×10^{-4} S/m
Yeast concentration	50.6	1	5.5×10^{-4} S/m

Table 3.2: The constants used for conductive medium.

These 3 different conductive medium will be applied to the 3 electrode from different conductive materials. Figure 3.6 below shows the electrode placed inside the surrounding box which indicate the medium.

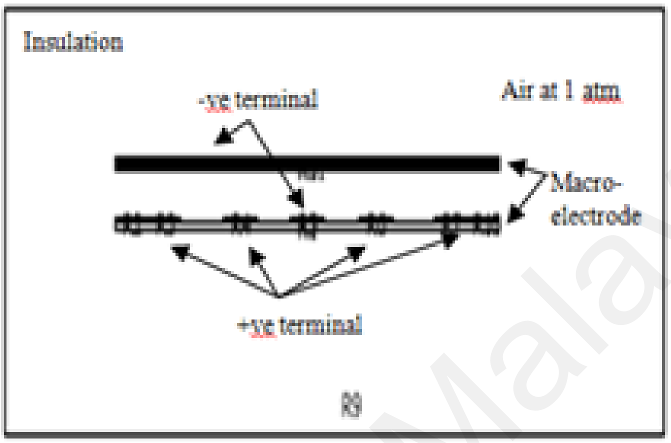


Figure 3.5: The electrode inside the surrounding box

c) Boundaries Condition

Next, boundaries condition must be set. Generally, electromagnetic field problem can be deal with 3 kinds of boundary condition such as Dirichlet, Neumann and mixed boundary conditions. In AC Power Electromagnetic physics mode, Neumann boundary condition is used. This is because some of electromagnetic field problem may involve condition along the boundary such that the normal derivative of the potential function at the boundary. This can be described as continuous function as mention as equation below.

$$\frac{dV}{dn} = f \tag{3.1}$$

In Comsol, boundaries setting can be done by clicking **Boundaries Setting** button as shown in Figure 3.7.

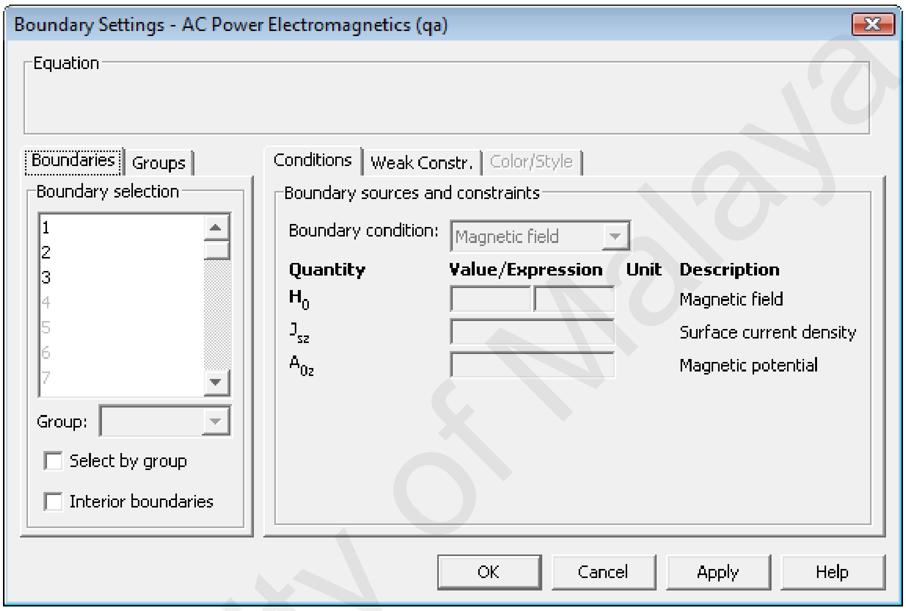


Figure 3.6: **Boundaries setting** window

The outer boundaries which represent the electrode environment modelled as the surrounding box are defined as insulating which means that there is no current flow across the boundaries. The continuity conditions are used for the rest of the boundaries at the electrode model so that the electric current is continuous across the interior boundaries. Figure below shows the boundaries setting for the electrode.

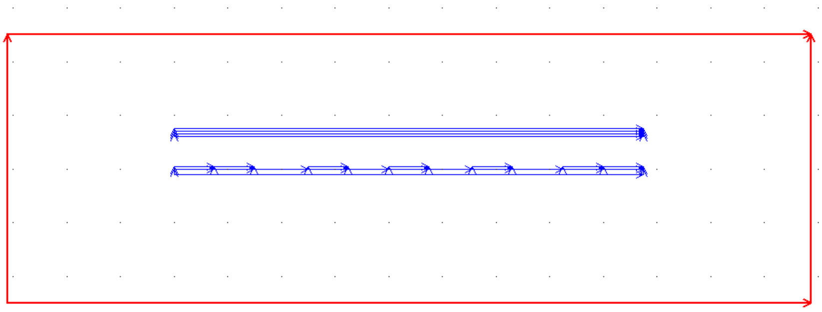


Figure 3.7: The boundaries setting for the electrode where red lines represent insulating while blue lines represent continuity condition.

d) Generate Mesh

After completing the properties setting, the model can be analyzed by using finite element method (FEM). But before running this analysis, the electrode model must be transform into mesh. The mesh can be form after clicking **Initialize Mesh** button. In order to refine the mesh, **Refine Mesh** button can be clicked.

The combinations of free mesh for environment and mapped mesh for the electrode was used to achieve an efficient FEM model. Besides, the number of mesh will be automatically generates by the software. Figure 3.8 below shows the mesh profile for the model.

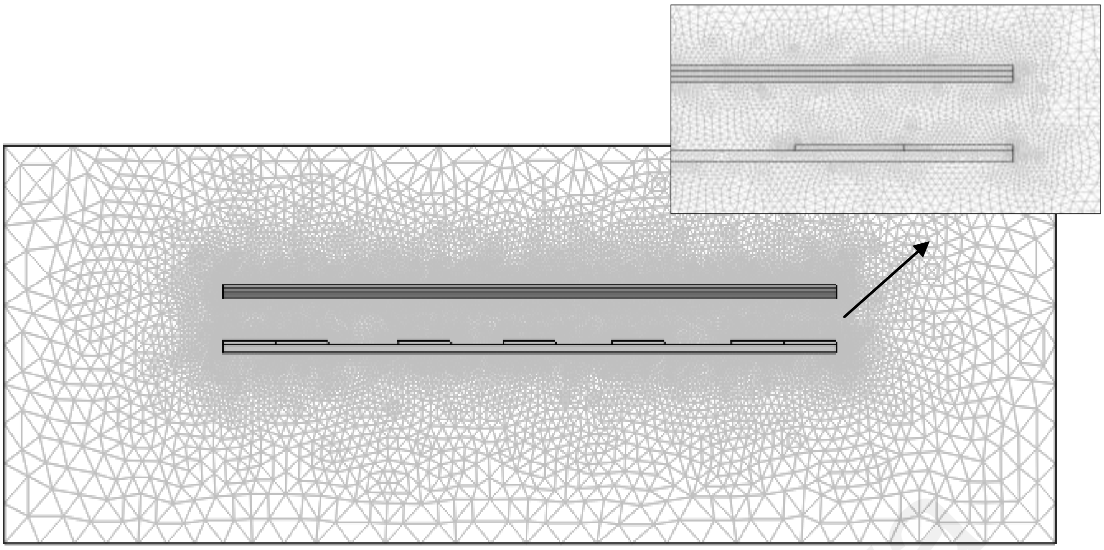


Figure 3.8: Mesh profile of the model. Inset shows the closed-up of the macro-electrode mesh.

e) Solve PDE's

The next step is solving partial differential equation of the model. This can be done by clicking **Solve** icon. This process normally required about 10 seconds to complete the analysis for 2-dimension model. The period for solution time normally depends on the complexity of the model.

f) Post Processing

Post processing step use to select the require parameter needed to be process. Here, by clicking **Plot Parameter** button, requires plotting type and parameter can be choose as shown in figure 3.9 below;

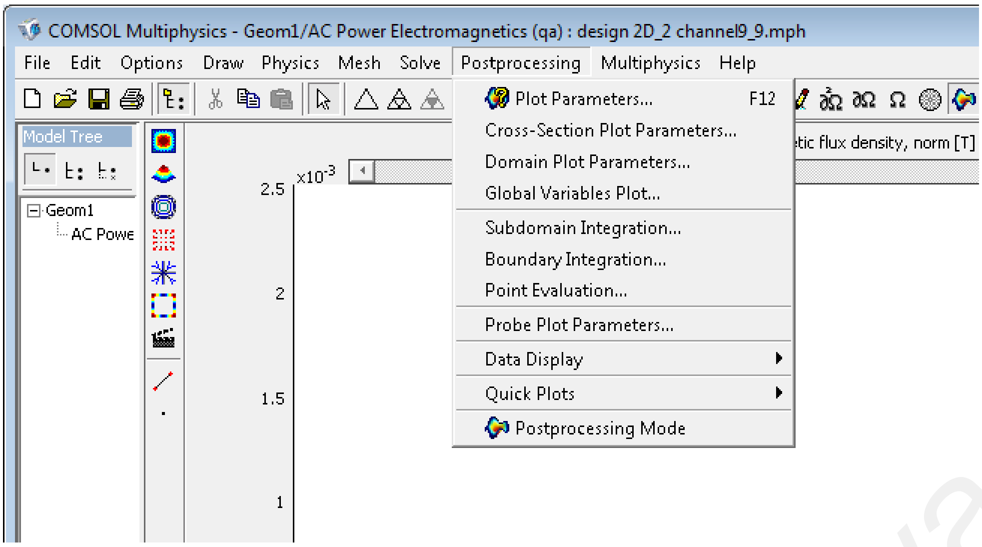


Figure 3.9: **Post processing** window.

For this research, parameter requires are the electromagnetic flux density of each material. This parameter can be shown by using **Surface** plot.

g) Alternative Setting

Some alternative setting will be added to meet the research purpose. Here, this electrode model is requires to apply with 5 different frequency source which are 50Hz, 100Hz, 1KHz, 50KHz, and 500 KHz. This set of frequencies have been choose by following approaches done by Kadri (2010), where the experiment were conducted in frequency range between 20Hz to 4MHz.

This setting can be applied by changing the frequency variable in **Application Scalar Variable** option under the **Physic** button as shown in figure 3.10.

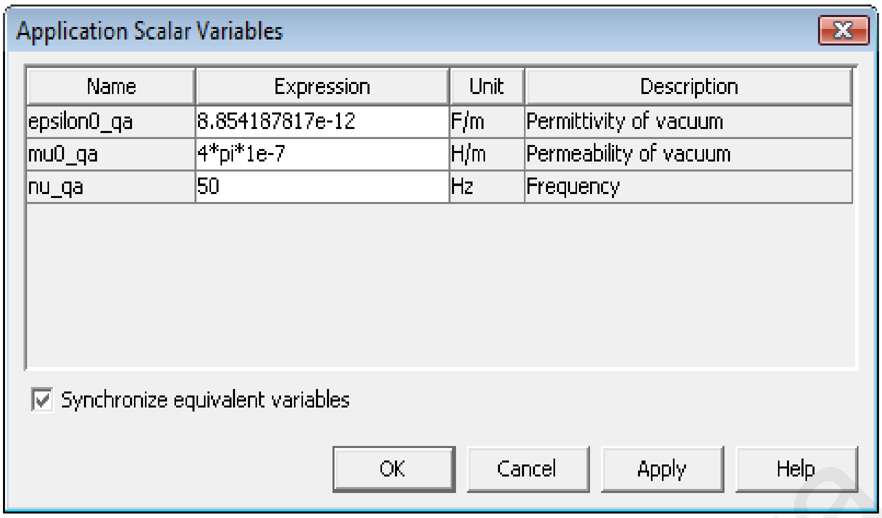


Figure 3.10: Application Scalar Variable window.

The frequency will be adjusted according to the research requirement by changing the value in frequency column.

h) Graph Plotting

Finally, simulation result will be plotting using **2D Surface Plot**. This plotting technique will give a clear view on electromagnetic field produce.

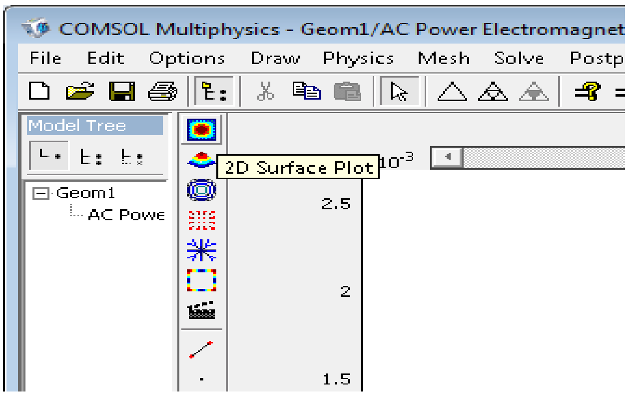


Figure 3.11: **2D Surface Plot** button

CHAPTER 4: RESULT AND DISCUSSION

4.1 Introduction

This section will briefly discuss about the result obtain from both simulation and experiment results. The electromagnetic flux density produces by the 3 different materials will be compared to obtain the suitable conductive material for DEP microelectrode. After that, a few problems that occur along this research will be discussed and further recommendation will be stated for future development.

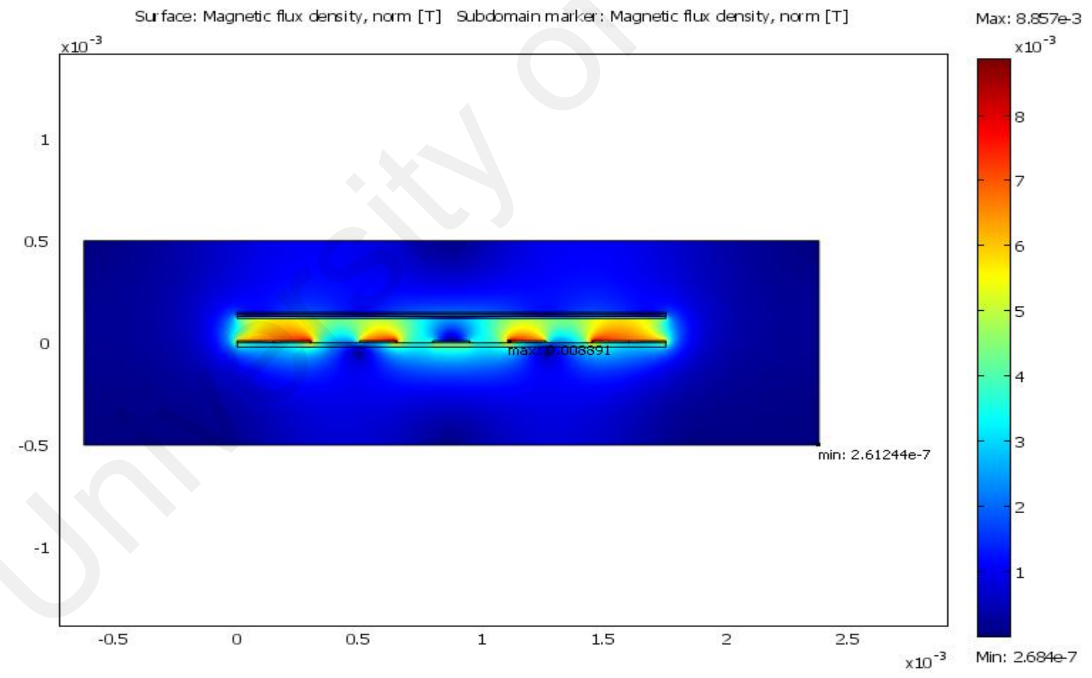
4.2 Simulation Result

Since the simulation process have been conducted to observe a certain parameter that play an important role in producing electromagnetic field for DEP phenomenon, here the results explained in a few part as mentioned below;

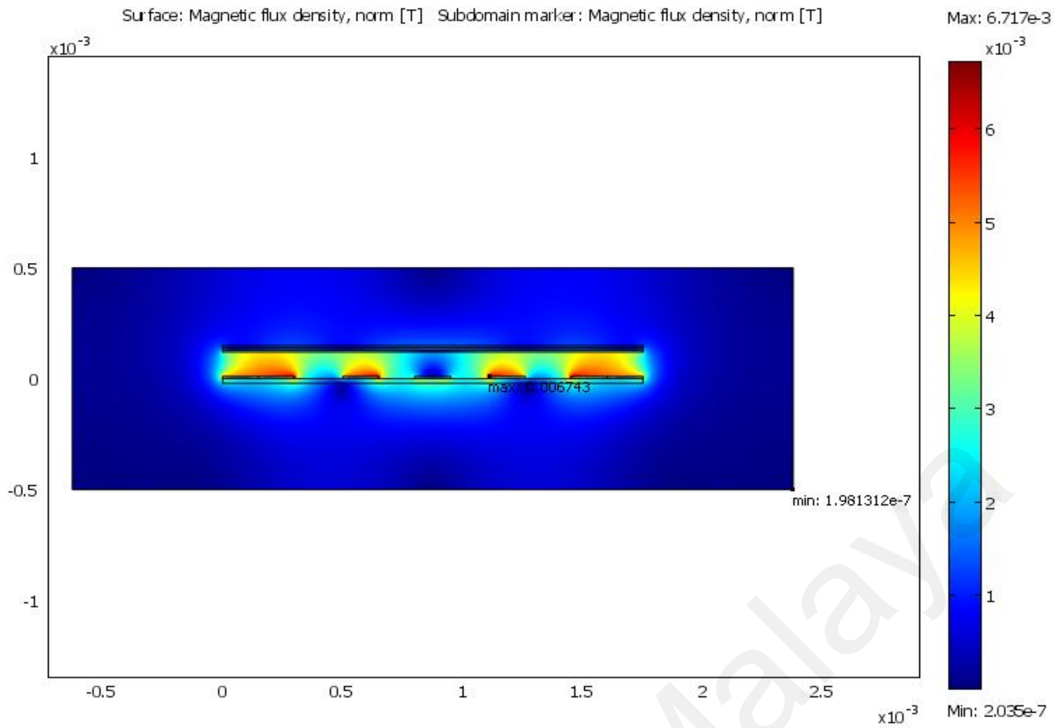
4.2.1 Effect of Conductivity and Permittivity on Electromagnetic Flux produced

Firstly, the model construct by using copper simulated in air medium with 1 atmosphere pressure. It was supplied with frequency of 50 Hz and 10 V of potential different, and then it was simulated. The surface graph plotted indicated the electromagnetic flux density produced by the electrode. This process has been repeated by using other two different conductive material which are gold and ITO.

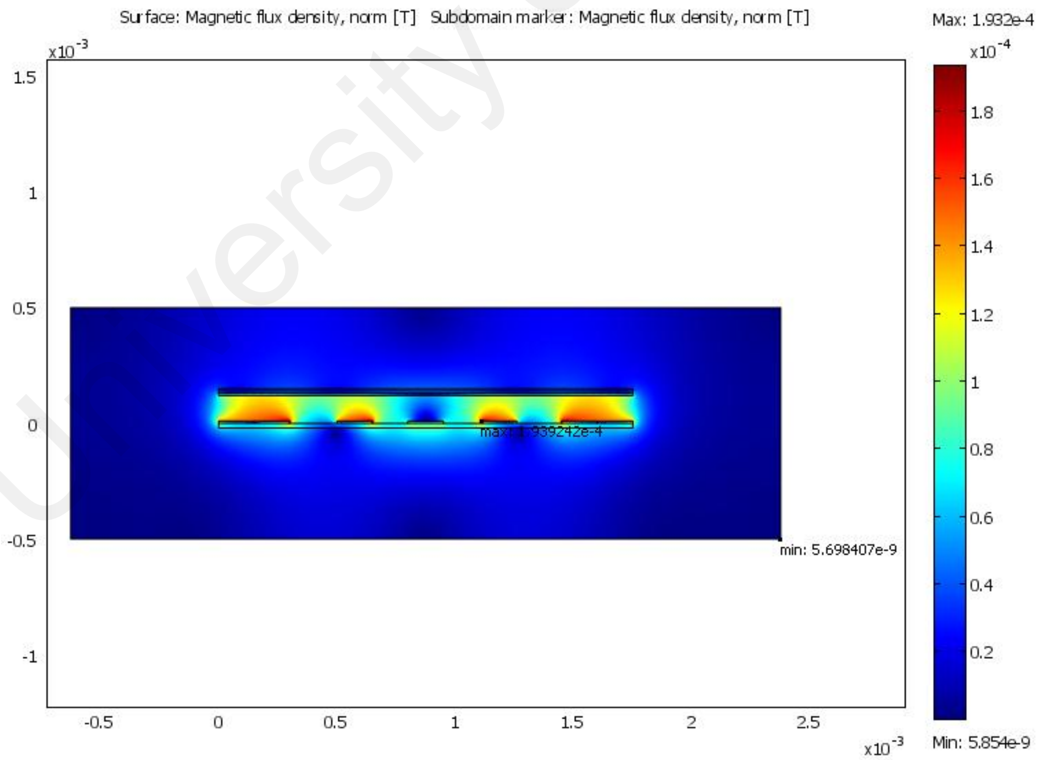
The result shows that copper which has higher value in electric conductivity and relative permittivity stated the highest maximum value of electromagnetic flux density produced which about 0.008891 Tesla compared to gold and ITO which stated 0.006743 Tesla and 0.0001939 Tesla respectively . Figure 4.1 shows electromagnetic flux density produces during the simulation process.



(a)


Surface: Magnetic flux density, norm [T] Subdomain marker: Magnetic flux density, norm [T]
Max: 6.717e-3
x10^-3
min: 1.981312e-7
Min: 2.035e-7
x10^-3
x10^-3
1
0.5
0
-0.5
-1
-0.5
0
0.5
1
1.5
2
2.5
6
5
4
3
2
1

(b)


Surface: Magnetic flux density, norm [T] Subdomain marker: Magnetic flux density, norm [T]
Max: 1.932e-4
x10^-3
x10^-4
min: 5.698407e-9
Min: 5.854e-9
x10^-3
1.5
1
0.5
0
-0.5
-1
-0.5
0
0.5
1
1.5
2
2.5
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2

(c)

Figure 4.1: Electromagnetic flux density produce when applied with 50Hz at air medium for 3 different materials which are a) copper, b) gold and c) ITO.

This finding have been approve according to Ampere's Law mentioned in equation 3.5 and 3.6 where the permittivity and conductivity of the material play an important role in the production of electromagnetic flux density.

Besides that, research done by R.N. Jadhav and V. Puri in 2010 have stated that copper as mentioned before has significant influence on electromagnetic properties. Besides, the result supported with research done by R. Kunanuruksapong and A. Sirivat in 2011 where permittivity or also known as dielectric constant affect the electric field produce. The electric field increased with increasing dielectric constant.

4.2.2 Effect of frequency toward the production of electromagnetic field.

After that, the model was simulated in different frequency supplies which are 50 Hz, 100 Hz, 1 KHz, 50 KHz and 500 KHz at the same medium to observe any changes in electromagnetic field produced. The graph in figure 4.2 shows the maximum and minimum value of electromagnetic flux density for each material for different frequency value.

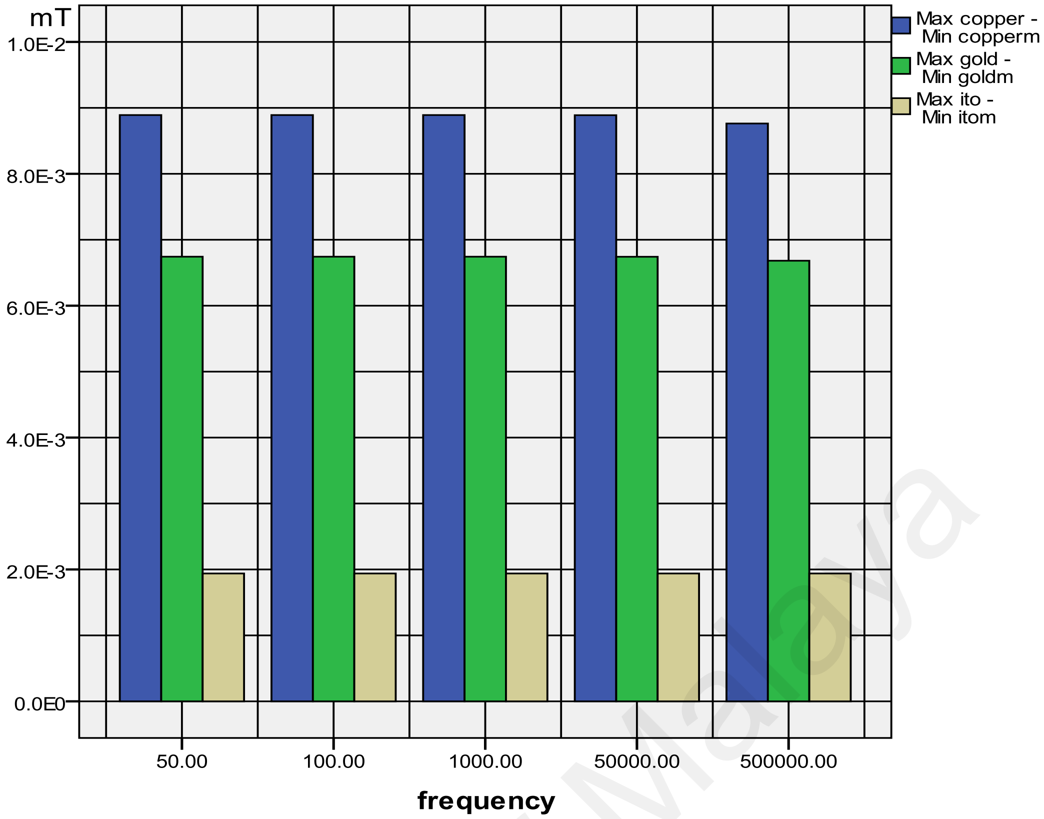


Figure 4.2: The value of electromagnetic flux for each material against frequency applied.

Here, electromagnetic flux density is higher above materials with higher electrical conductivity and permittivity as expected like copper. Based on figure above, each material experienced the changes in electromagnetic flux density value after 50 KHz frequency and above was applied. The simulation results show all materials stated a very small decrement in the maximum and minimum value of electromagnetic flux density after 50 KHz was supplied. This condition was reversed compared to results mentioned by Muller *et al.* (1996) where the strength of electric field increased at higher frequency range up to MHz.

In order to prove the decrement of electromagnetic field value due to increasing of frequency, the simulation was done at 5MHz. The results shows that value for copper and gold decreased for about 0.002 from previous value meanwhile value for ITO remain the same. These have been shows in Ampere's law equation where electromagnetic field actually did not affect much by the frequencies. As mentioned before, frequency plays an important role in determination of Clausius-Masotti factor which affect the dielectophoresis force, F_{DEP} as shown in figure below;

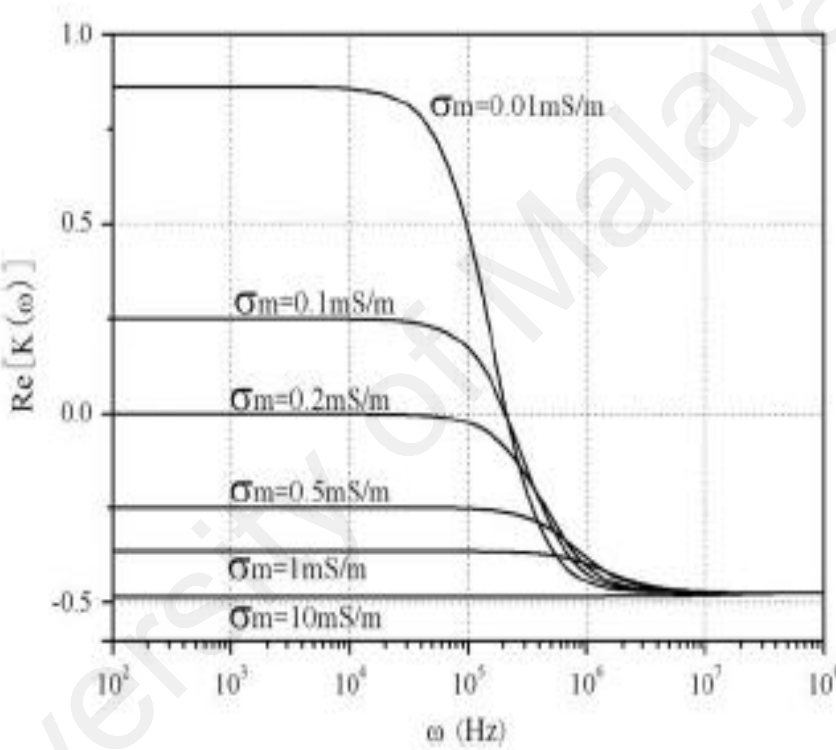


Figure 4.3: The variation of Clausius-Masotti factor with frequency at different electrolyte solution conductivities by J. Cao *et al.* (2008).

Besides, this phenomenon can be explained by research conducted by R.N. Jadhav and V. Puri in 2010 where conductive material which applied with AC electric field tend to produce less stronger of electric field over higher frequency. This happens due to decrease in polarization of that material with increase in frequency.

By comparing these 3 materials at varies frequency, copper offers a very wide range of electromagnetic field compare to other two materials with mean of 0.008865 mT at with standard deviation of 0.00005. Meanwhile, ITO become the most stable material where the electromagnetic flux density remain the same at all 5 different frequency but unfortunately its produces a very small range of electromagnetic field.

Besides, figure 4.3 shows the statistical analysis for these 3 materials against different frequencies. This graph indicates that there is no significant different in the mean of electromagnetic flux density over frequency. Overall, copper represented higher mean value of electromagnetic flux density with standard deviation of 0.000057026. Meanwhile, gold and ITO stated mean of 0.00673060 and 0.00193900 respectively with standard deviation of almost zero.

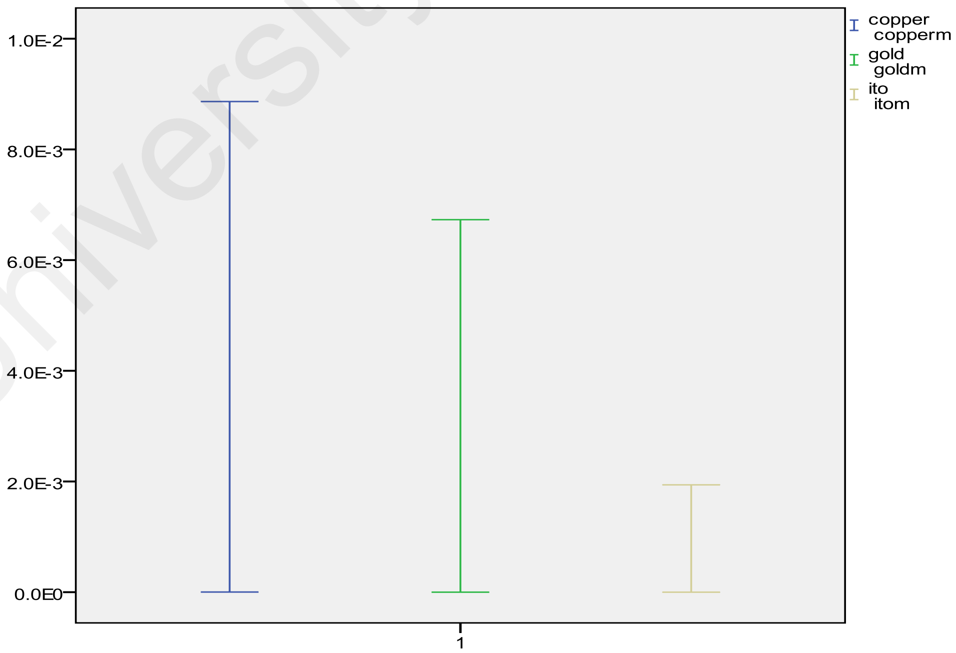


Figure 4.4: Mean of electromagnetic flux density against different materials.

4.2.3 Effects of Conductive Medium

The final setting for the simulation test was to include the different conductive medium to the electrode model. Besides in air environment at 1 atm, this model has been simulated in distilled water and yeast concentration medium. Distilled water was stated to have conductivity of 1.5 $x10^{-4}$ S/m and relative permittivity of 78.57 while yeast solution that dispersed in KCL concentration was stated to have $5.5x10^{-4}$ S/m conductivity and 50.6 for its relative permittivity as mention before.

The simulation result from both different environments shows the same result as stated in air environment. Figure 4.5 indicates that there is no significant change on electromagnetic flux density under different conductivity. This situation might happen due to assumption made earlier where continuity conditions are applied for internal boundaries of the model.

The electromagnetic flux is expected to experience some changes in real world due to dielectric properties of the medium. According to J. Cao *et al.* (2008), the conductivity of electrolyte or conductive medium influenced the Clausius-Masotti factor and thus affects force experienced by the particles as shown in figure 4.3. Besides, based on research done by D. A. Pavlov and Michael S. Zhdanov in 2001 have shown that conductivity play an important role in electromagnetic field production where the combination of anomalous conductivity and permeability within the same body could increase significantly the anomalous time domain electromagnetic response. Thus, some parameter or other approaches should be introduced, so that a more reliable result can be obtained.

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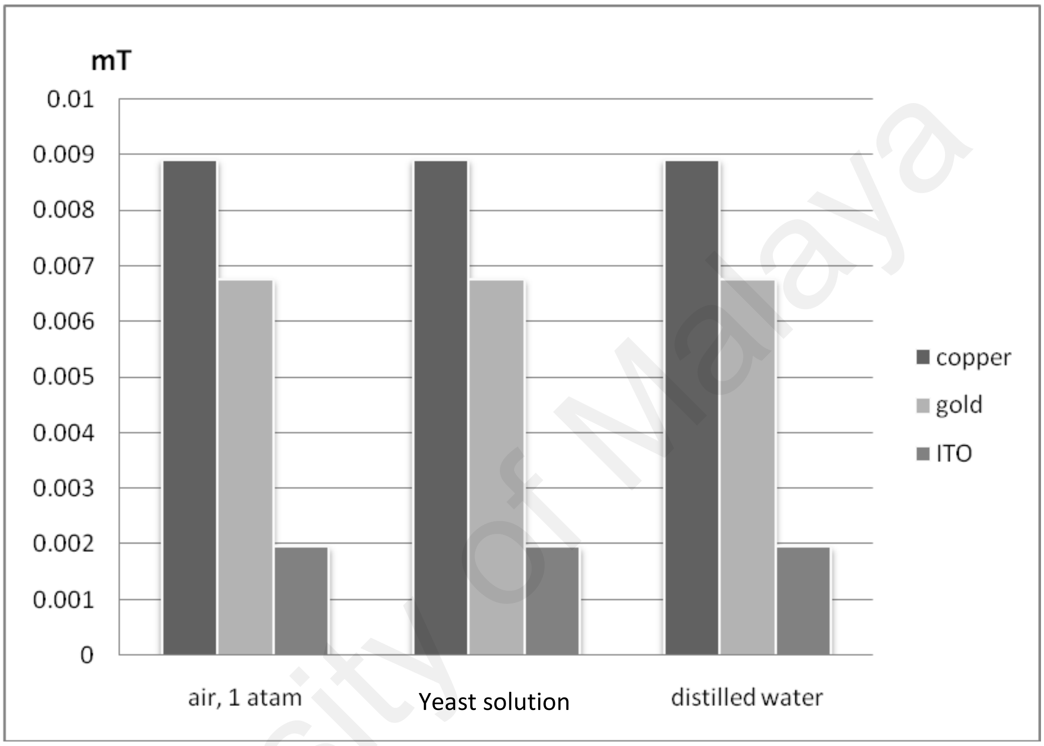

Figure 4.5: The comparison of electromagnetic flux density produced by 3 different materials in 3 different conductive medium.

CHAPTER 5: CONCLUSION

Simulation model develop using Comsol Multiphysics software have been shown to be capable in modelling electromagnetic field for dielectrophoresis experiment. Although the electromagnetic flux model has been simulated previously for a single dot electrode by Fatoyinbo *et al* (2008), similar model is yet to be studied for multiple dots arranged in an array that has been shown to be capable of conducting DEP experiments (Fatoyinbo *et al.*, 2011).

This simulation model has provided a clear figure on the production of electromagnetic field by the electrode. Simulation in different condition have shown that copper offer a wide range of electromagnetic field strength meanwhile supplying a higher frequency effect not only polarisability of particles but also the strength of electromagnetic field.

5.1 Limitation

Some limitations when conducting this project have been recognised. Mostly limitations come from the simulation setting. There are some parameters was ignored due to limitation of information on how it works. Besides, the low specification of computer used to run this simulation also affected the results. This software required a big space in computer memory to allow it to process more data. This limitation has lead to only 2-dimensional simulation.

5.2 Future Development

These are a list of desirable improvements to be incorporated into the current developed system.

5.2.1 Improving the frequency setting

As mentioned before, frequency plays an important role in DEP as described in Clausius-Mossotti factor. But here, the frequency used for the simulation process was based on assumption where the main purpose was to observe the electromagnetic field produce. This process can be improved by using a suitable frequency range where DEP phenomenon occurs on particles which in kHz to MHz range.

Besides, by using Comsol Multipysics 3.3 package, to use simultaneously application of alternating current electrical signal to independent addressable dot microelectrode seem to be impossible. This is because it's only allowing to set only one electrical signal at a time. Thus, some modification and upgrading on the software will be beneficial to the continuity of this research.

Besides, in order to seek for the best and reliable approaches in developing simulation model, other finite element method software like ANSYS or FEM CAD can be consider and comparison between approaches can be made.

5.2.2 Improving Model Dimension

For this project, the microarray electrode has been modelled in 2-dimension due to small capacity of RAM. The modelling process will be more effective if it can be done in 3-dimensional view. 3D modelling will allow more specific analysis which can lead to better and reliable result.

There are a few solution suggested to overcome the problem related to out of memory space. Firstly, the geometry size must be reducing at least half to make the modelling process successful. Besides, this can be achieved upgrading the hardware capacity as suggested by Comsol Multiphysics as mention below;

- A 64-bit operating system is highly recommended.
- For a given hardware, the choice between Windows, Mac OS, or Linux will not significantly affect performance.
- 4-8 GB physical RAM per core of the computer is recommended.
- Dual-socket or if possible four-socket nodes are recommended.
- A CPU with as fast a memory bus as possible is beneficial (QPI or Hyper Transport bus). The numbers are often measured in Giga Transfers/Seconds (GT/s) and can be found on manufacturers' web pages or Wikipedia.
- As high memory bandwidth as possible is beneficial.

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