Electric field analysis along pin-plane electrodes in SiR containing nanoparticle by using FEM

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Electric field analysis along pin-plane electrodes in SiR containing nanoparticle by using FEM

By:

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This dissertation is dedicated to everyone in the field of biomedical who embark in the journey of expanding tomb of knowledge and passion for saving life without any complaint. Most respect for these people for sacrificing their time and energy for their noble intention in making our life more convenient and safe.

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
FEA	Finite Element Analysis
FEM	Finite Element Method
HV	High Voltage
LV	Low Voltage
SiR	Silicon Rubber
TIV	Tree Inception Voltage
XLPE	Cross-Linked Polyethylene
ZnO	Zinc Oxide

LIST OF SYMBOLS

ε_r	Relative permittivity
p_n	Specific gravity for nanofiller
p_m	Specific gravity for polymer
vol%	Volume percent
wt%	Weight percent of nanofiller added

ABSTRAK

Silikon getah merupakan penebat polimer yang digunakan secara meluas dalam aplikasi voltan tinggi kerana ciri-ciri penebat elektrik yang baik dan boleh menahan suhu yang tinggi. Penebat polimer didapati mempunyai fenomena degradasi selepas penggunaan yang lama dan membawa kepada kerosakan. Pokok elektrik didapati merupakan salah satu punca kerosakan kabel. Nano-alumina didapati dapat menghalang pertumbuhan pokok elektrik. Namun, taburan medan elektrik dalam pokok elektrik masih tidak diketahui secara meluas. Oleh itu, projek ini akan mengkaji taburan medan elektrik dalam bahan-bahan penebat dengan menggunakan perisian “Finite Element Method” (FEM), Comsol Multiphysics. Penyiasatan mengenai taburan medan elektrik di dalam penebat Silicon getah yang mengandungi pelbagai kepekatan nano-alumina dikaji. Hasilnya, keamatan medan elektrik jatuh dalam nano-alumina itu. Keamatan medan elektrik pada antara muka semakin meningkat apabila kepekatan alumina menigkat disebabkan perubahan dalam jarak antara partikel. Akhir sekali, output projek ini dapat dibandingkan dengan eksperimen yang telah dilakukan oleh pengkaji-pengkaji terdahulu. Projek ini akan memberi pengetahuan dan pemahaman mengenai taburan medan elektrik di dalam pokok elektrik.

ABSTRACT

Silicon Rubber is a polymer insulator that is widely used in high voltage application due to its good electrical insulating properties and can withstand high temperature. Polymer insulators were found having degradation phenomena after long time usage and lead to breakdown. Electrical treeing is found as one of the causes of the cable breakdown. Nanofiller is found effective in inhibiting the electrical treeing growth during experiment setup. However, the electric field distribution in electrical treeing are still not well known. In this project, the simulation model of electrical treeing setup is developed and successfully executed. The electric field distribution containing various concentrations of nano-alumina in insulating materials is investigated using pin-plane electrodes model by using Finite Element Method (FEM) software, Comsol Multiphysics. As a result, the electric field intensity drops within the nanofiller. The electric field intensity at interface is increasing when concentration of nano-alumina increases due to changes in interparticle distance. Lastly, the output of this project can be compared with the experimental setup done by previous works. This project will give understandings about the electric field distribution in electrical treeing.

CHAPTER 1

INTRODUCTION

1.1 Background

Electricity delivered to the consumer has undergone three steps which are generation, transmission and distribution. During power generation division, electricity is generated and stepped up into high voltage (HV) for transmission to reduce losses. Power transmission division responsible for delivering the HV to specific areas of demands. Then, power distribution role is to step down high voltage to low voltage (LV) for varieties of consumers. Insulation plays an important role to make sure the electricity successfully delivered to consumers through conductors. There are many types of insulation available in the market such as polymers,ceramics, glass and etc. However, polymer insulation has replaced ceramics and glasses due to its popularity. Polymer insulator has some advantages such as able to minimize breakage, better breakdown voltage, lower installation cost. It is also lights in weight and smaller in size, higher tensile strength compared to inorganic materials such as ceramic and glass [1].

Silicone Rubber (SiR) is one of the polymers that is widely used in high voltage cable field because it has good electrical insulating properties and it can withstand high temperature. SiR normally used as a cable jointer in HV cable insulation. However, the insulators may facing the degradation of the insulation materials when exposed to high-stress voltage application and water moisture. Therefore, at the weakest point of the insulator, high electric field is formed and resulted in electrical treeing that lead to breakdown of the insulator [2]. A good insulator should inhibit the growth of electrical tree. Addition of nanofiller in the polymeric insulation could enhance the strength of the polymer insulator [3]. In addition, it is known that the Tree Inception Voltage (TIV) has increased with the addition of nanofiller [2]. The interparticle distance of the nanofiller was found affect the electric field distribution in polymeric insulator using Finite Element Method (FEM) [6]. A lot of experiment have been conducted to study about the electrical treeing but the understanding about the electric field distribution are still not well known.

Therefore, in this thesis, the electric field distribution in SiR will be investigated using modelled pin-plane electrode in Finite Element Method (FEM) software, Comsol. The permittivity of the insulating materials is the criteria required to represent the polymers used. The effect of nanofiller toward SiR is also analysed using FEM by changing the interparticle distance of nanofillers.

1.2 Problem Statement

Polymeric insulators are being used in current technology instead of traditional ceramic insulators due to better electrical, mechanical and thermal characteristics. However, polymer insulators were found having degradation phenomena after long time usage and lead to breakdown. Electrical treeing is found as one of the causes that lead to cable breakdown. Many researchers conducted an experiment to study the causes of electrical tree growth in polymer insulators [18]. Numerous factors were found affect the growth of electrical treeing such as the applied voltage, source frequency and temperature of the insulator. On the other hand, the researches about electric field distribution are still not well known. It is important to study about the electric field for improvement of insulator properties. Therefore, in this project, the electric field distribution along pin-plane electrodes is analysed by using Finite Element Analysis (FEA) software, Comsol Multiphysics. This project enhances understandings and provide knowledge for further studies.

1.3 Objectives

1. To develop simulation model of the electric field distribution along pin-plane electrodes by using FEM.
2. To investigate the electric field distribution of various concentration of nanofiller toward SiR.

1.4 Project Scope

The study of electric field distribution is modelled by pin-plane electrode using FEM software called COMSOL. ASTM 3756 standard [19] for evaluating electrical tree is used to model the pin-plane electrodes. Electric potential is assigned to the pin and ground to the plane. The parameters and variables used in this project are referred from standard and previous works.

The electric field distribution of SiR determined is analysed and compared with previous works. The electric field distribution in presence of nanofillers are analysed in this simulation by varying the interparticle distance of the nanofiller. The simulated result is used to gain better understandings for designers and researches in order to improve the current cable insulator.

1.5 Thesis Outline

This thesis consists of five chapters. The chapters are introduction, literature review and methodology, results & discussions and conclusion. The outline of the thesis can be composed as follows;

Chapter 2 discusses on literature review about electrical treeing process, factors that affect electrical treeing, the effect of nanofiller in insulator and the effect of interparticle distance toward permittivity.

Chapter 3 discusses methodology used in this project. The flow of the project is represented by the flowchart. It also includes the explanation about the method to model electric field distribution in electrical tree. The parameters used in the simulation is discussed in this chapter.

Chapter 4 presents the result of the simulated electric field. The characteristics of electric field distribution when various concentration of nano-alumina applied toward polymer insulators and the effect of interparticle distances in insulating material is analysed and discussed.

Lastly, Chapter 5 concludes the discussion of this project and includes the suggestions and improvements that can be done for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Previous researches about electrical treeing have been reviewed in this chapter. The breakdown process of polymer insulator, the factors affect electrical treeing and the influence of nanofiller toward polymeric material are discussed.

2.2 Current researches on investigating electrical treeing behavior.

Polymeric insulators used in current technology provide better insulator than traditional insulator such as ceramic and glass. It has better electrical, mechanical and thermal properties [7]. However, polymeric material experience aging and affect the long-term reliability of the insulator. One of the main causes of breakdown in polymer is electric treeing.

Electrical treeing occurred when localized electrical discharge phenomena took place. Fractal like network of channels will be formed called treeing and will lead to breakdown of the insulation. There is some type of treeing can be found in electrical treeing which are twig-like tree, branch-like tree, bush-like tree and pine-like tree as shown in Figure 2.1 [8]

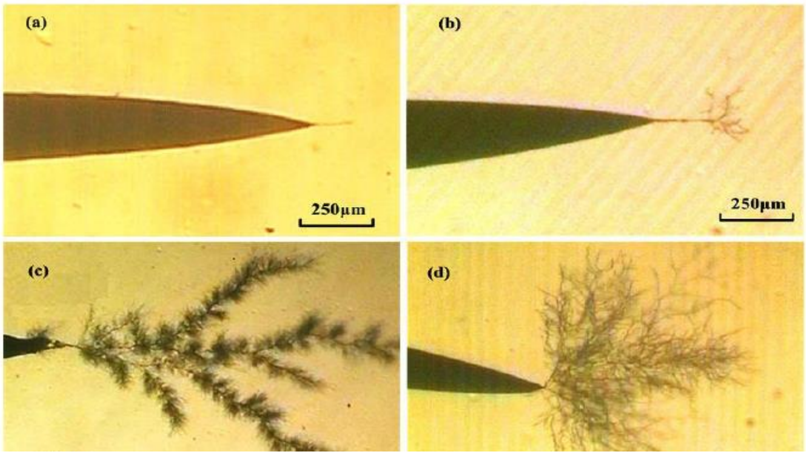


Figure 2.1: Different types of electrical trees in SIR: (a) twig-like trees; (b) branch-like trees; (c) bush-like trees; (d) pine-like trees [8]

According to Y. Zhang *et al*, electrical treeing has been divided into five stages, incubation, initiation, propagation, stagnation, and finally breakdown [8]. The arrangement of experiment setup by using pin-plane electrodes is as shown in Figure 2.2 and the behavior for every stage are briefly described in Table 2.1

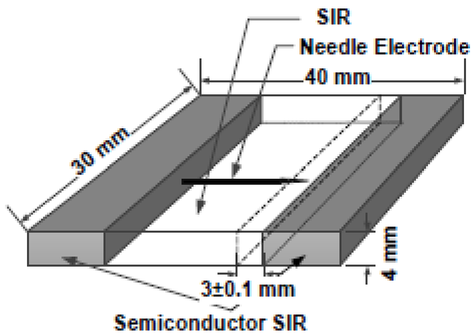


Figure 2.2 Schematic of experiment sample [8]

Table 2.1 : The growing process of electrical trees [8].

Stages	**Observation**
1. Incubation	No obvious electrical tree although high voltage has been applied.
2. Initiation	Visible treeing channel start to grow
3. Propagation	The tree start to transform into several types and has increased in length.
4. Stagnation	The electrical trees temporarily stop growing.
5. Breakdown	The final stage when the tree channel reach opposite side.

There are some factors reported affect electrical treeing. I. Iddrissu witnessed that the polarity of DC source affect the electrical treeing [9]. 67% of the samples breakdown when positive DC voltage supply while no breakdown of the sample when negative DC voltage supply was used.

Despite the polarity of the source, the shape of the tree also depends on the magnitude of the applied voltage [8]. As the voltage increases, the trees start to change its form. The density of the trees begins with twig-like, branch-like, bush-like and pine-like but somehow the researching about the shape of the trees are still on going to gain sufficient information about it. As shown in the Figure 2.3, when higher voltage applied, the shape of the treeing is different.

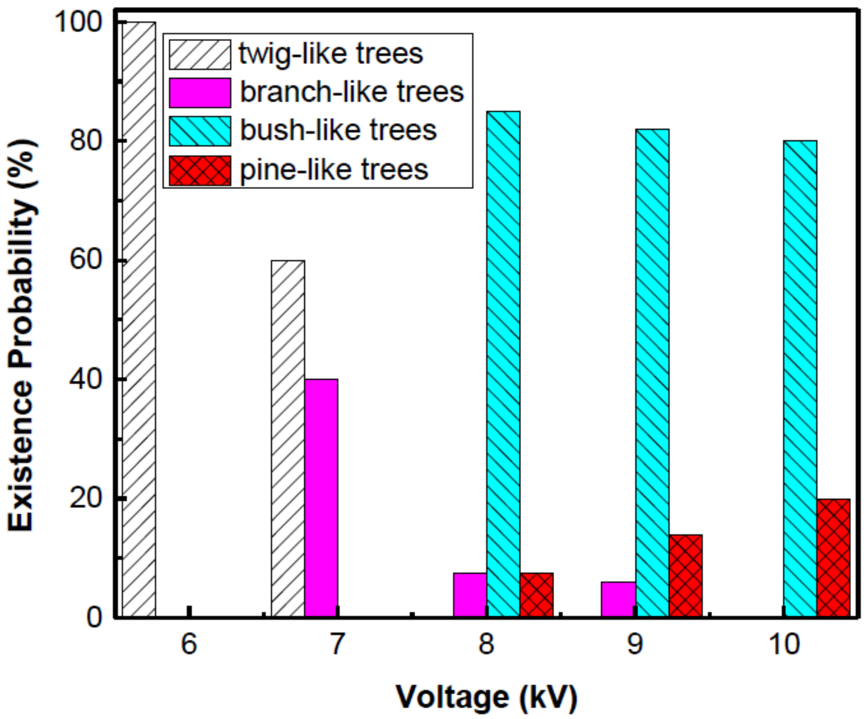


Figure 2.3 : Influence of voltage on electrical trees morphology [8]

In Y. Gao *et al* research, the investigation of electrical treeing behavior in XLPE polymer sample under different frequency of AC voltage was conducted [10]. The intensity of bush trees and the length of the trees increases as the frequency increases. They found that the frequency affect the electrical tree growth.

J. G. Su *et al* reported that the shape electrical tree changed per temperature even though same pulse voltage was applied [11]. The tree structure was changed from branch to pine-branch tree when temperature is varied from 30^o to 90^o C. Bush trees visible when temperature at 150^oC.

SiR is widely used in power transmission and distribution due to their superior electrical properties such as high dielectric strength, high resistance to oxidation and can be used in wide range of temperature [1-2]. Despite light, easy to install and cheap, Rudi K *et al* mentioned that the silicon rubber showed self-healing property after the tree degraded [12].

2.3 Nanofiller inhibit electrical treeing

The occurrence of electrical treeing can be minimized by adding nanofiller. The presence of nanofiller in polymeric insulator increase the electrical strength of the insulator without alter the polymer material [2,4,5]. M.Hafiz et al have studied the effect of alumina nanofiller toward silicon rubber for electrical treeing investigation [2]. They have analyzed the nanofiller characteristics in SiR with different volume percent (vol%) of alumina is applied. They revealed that the concentration of alumina nanofiller in SiR was increased up to 2 vol%. On the other hand, the Tree Inception Voltage (TIV) dropped when 3 vol% of alumina nanofiller was added. They concluded that the addition of 1 vol% and 2 vol% alumina nanofiller reduce the electrical tree growth but when 3vol%, the tree growth increase.

There are two types of fillers used to inhibit the electrical treeing. There are microfiller and nanofiller. Nanofiller is better compared to microfiller, instead of using 50% microfiller, nanofiller only require 3%. These is because nanofiller has smaller particle size and thus, it has larger surface area [13-14]. Therefore, current researches were using nanofiller on their study.

T. Tanaka *et al* was studied about multi-core model to understand the properties and phenomenon in electrical insulation. They came with an equation about the interparticle distance, D in the fillers as shown in equation (2.1). From the equation, the wt% will affect the interparticle distance [15] and Figure 2.4 visualise the inter-filler distance.

$$D = \left\{\frac{\pi}{6}\left(\frac{p_n}{p_m}\right)\frac{100}{wt\%}\left[1 - \frac{wt\%}{100}\left(1 - \frac{p_m}{p_n}\right)\right]^{\frac{1}{3}} - 1\right\} d \qquad (2.1)$$

p_n	=	specific gravity for nanofiller
p_m	=	specific gravity for polymer
wt%	=	weight percent of nanofiller added
d	=	filler diameter

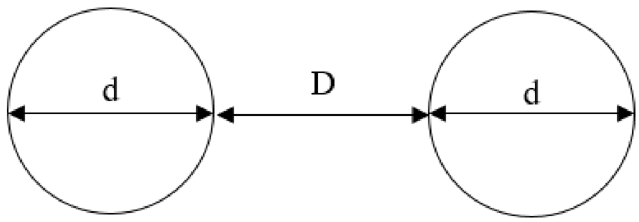


Figure 2.4 : Inter-filler distance [15]

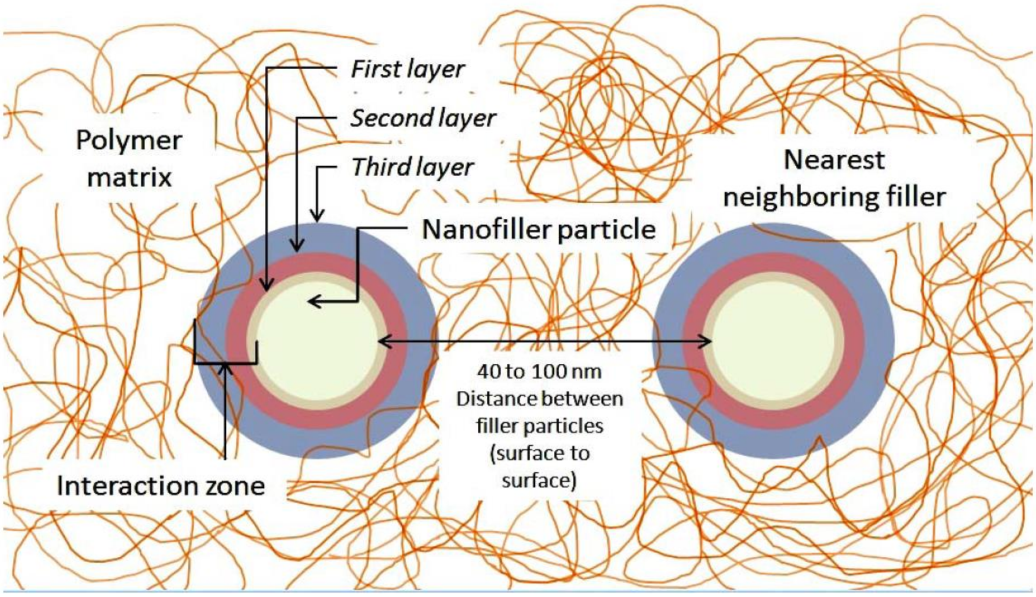


Figure 2.5 : Simplified diagram of polymer nanocomposites constituents [14]

A. I. Wan *et al* have discussed that nanocomposite consists of three major parts which are polymer matrix, three layer of interaction zones and nanofiller particle as shown in Figure 2.5. The zones between polymer and nanofiller called interaction zones or interface area plays important role in the material dielectric strength [14]. The size and type of the filler was found affect the insulation properties of the nanoparticles.

D.Pitsa *et al* has shown one of interesting presentation of relative permittivity model [16]. They reported that the permittivity is affected in the interface area of polymer matrix and nanofiller. The interfaces of nanofiller start overlapping when the distance between particle decreases. Based on their result, the relative permittivity was determined by the interfaces.

So far, it is understood that high stress of electric field can cause tree inception. However, the understanding on the electric field distribution in insulating material is not well known. Many researches have performed analysis on this method by simulating

Finite Element Analysis (FEA). M.Talaat have used FEA to analyse the effect of electric field toward electrical tree initiation [17].

2.4 Summary

Based on the literature review, the process of electrical treeing is understood and the factors that affect electrical treeing development in insulating material was explained. The properties of the insulating material also play an important role in preventing electrical treeing such as the self-healing properties. Instead of the materials characteristics only, the presence of nanofiller in the insulator was found can inhibit electrical tree. Many researches explain about the electrical treeing phenomena by doing the experiment while the analysis of electric field distribution in electrical treeing is not well known. Therefore, in this project, the electric field of pin-plane electrodes is analysed by using FEM software, Comsol Multiphysics. The effect of interparticle distance of the nanofiller on the electric field is also studied as it has great influence to stop electrical tree growth.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter mainly explains the method of developing simulation by using FEM software namely COMSOL Multiphysics. FEM is used to analyse the electric field distribution of SiR to understand on how the electric field affects the solid insulator.

3.2 Project Implementation Flow

Figure 3.1 shows the flowchart of this project. The project is started by researching the relevant reading materials such as journals and conferences. By collecting the information, the method of the simulation model is performed. The simulation model is performed in Comsol Multiphysics. All the parameters and boundary condition are set into the software before running the simulation. If there are any errors occurs during computing the simulation, the parameters and boundary conditions such as such as the material used, assignation of voltage and drawing defects are revised. The results obtained about the electric field distribution is analysed and verified.

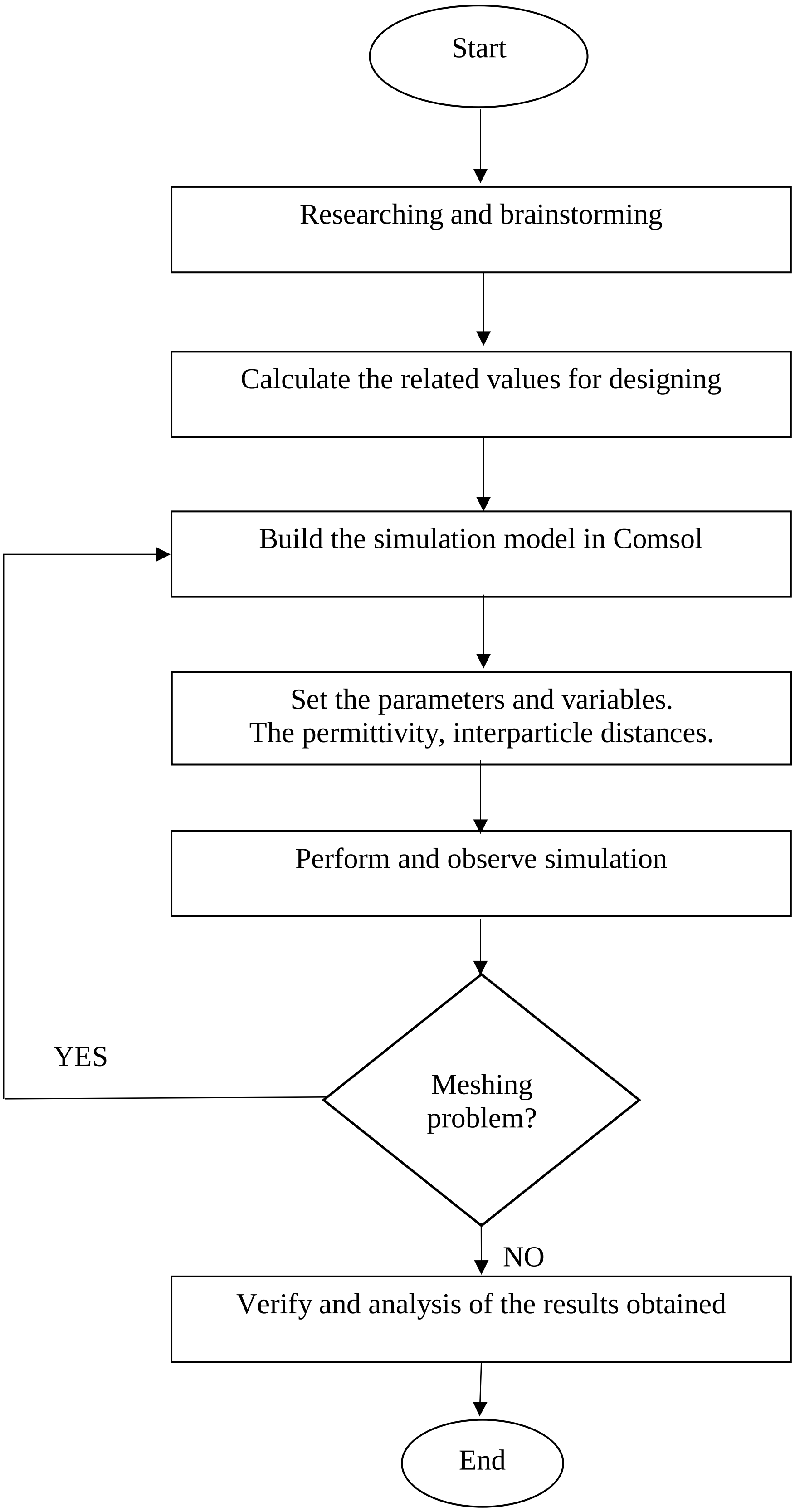


Figure 3.1: Flowchart of this project

3.3 Project Requirement

In this project, the electrical tree simulation is modeled according to ASTM 3756 standard which explains the test method for evaluating resistance to electrical treeing [19]. The investigation about the electric field distribution is simulated using 2-dimensional Finite Element Analysis (FEA) software called Comsol Multiphysics 5.2a. The electric field distribution is observed and determined.

3.4 Process Modelling

The dimension of the pin-plane electrodes and the insulating material are obtained from the standard. The dimension of the pin electrode is shown in Table 3.1. Figure 3.2 shows the simple diagram of the pin electrode.

Table 3.1: The dimension of the pin electrode

Pin Electrode dimension	**Values**
Diameter, ϕ	1mm
Tip radius,r	$5 \pm 1\mu m$
Tip angle, Θ	30 ± 1^{o}

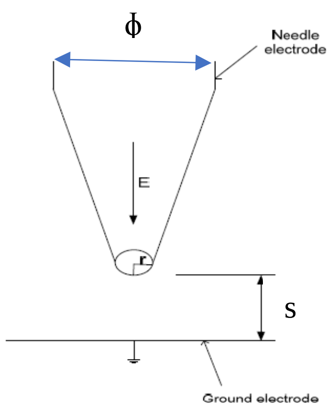


Figure 3.2: Simple diagram of pin electrode [18]

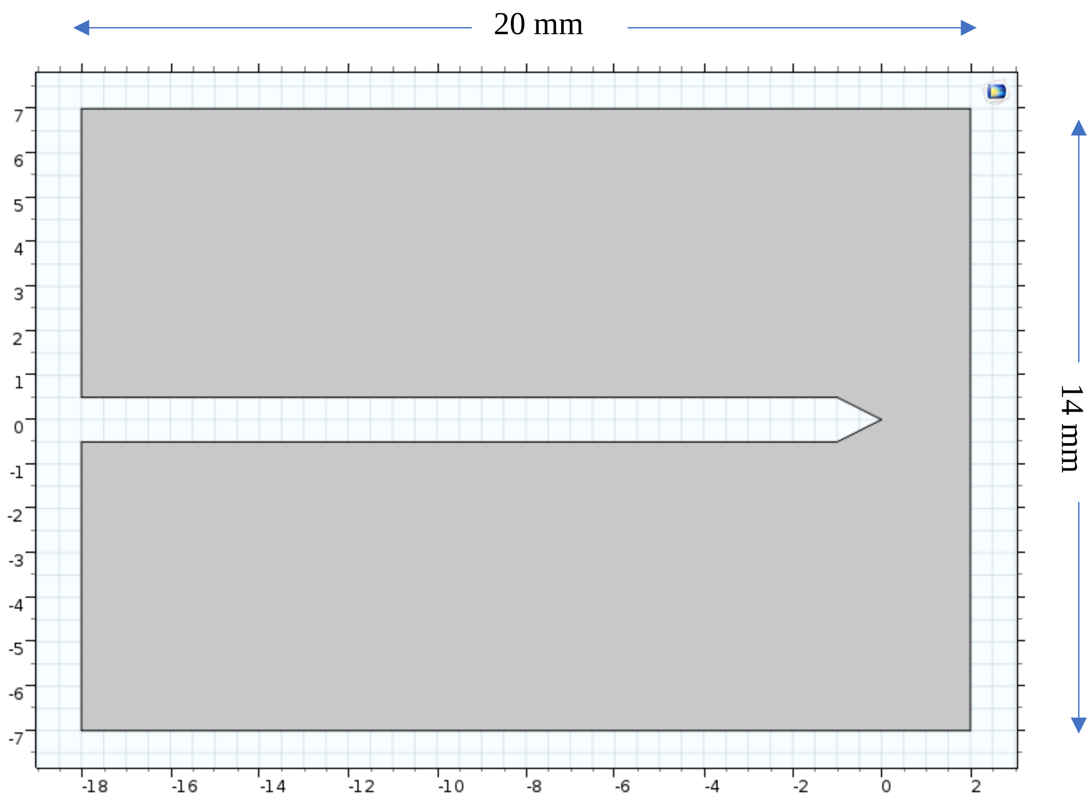


Figure 3.3 : Model of pin-plane electrodes with gap of 2mm

The dimension of the insulating material is 20mm X 14mm. The voltage assigned to the pin and plane electrodes are 11kV and 0V (ground) respectively. The distance between the electrodes is 2 mm. The distance is chosen by referring previous work in order to compare the result of this simulation with the experiment [1]. However, smaller model with 0.1mm gap has been developed to see clearer image of electric field distribution of nanofiller. The electric field distribution for both model is quite the same because instead of applying 0 V (ground) at plane electrode, electric potential is assigned by referring the electric potential distribution from 2mm model. Figure 3.4 shows the model near the pin electrode while Figure 3.5 shows the model in between pin and plane electrodes and near the plane electrode with the same gap of 0.1mm. The voltage at electrodes are assigned according to the voltage distribution of 2mm gap model.

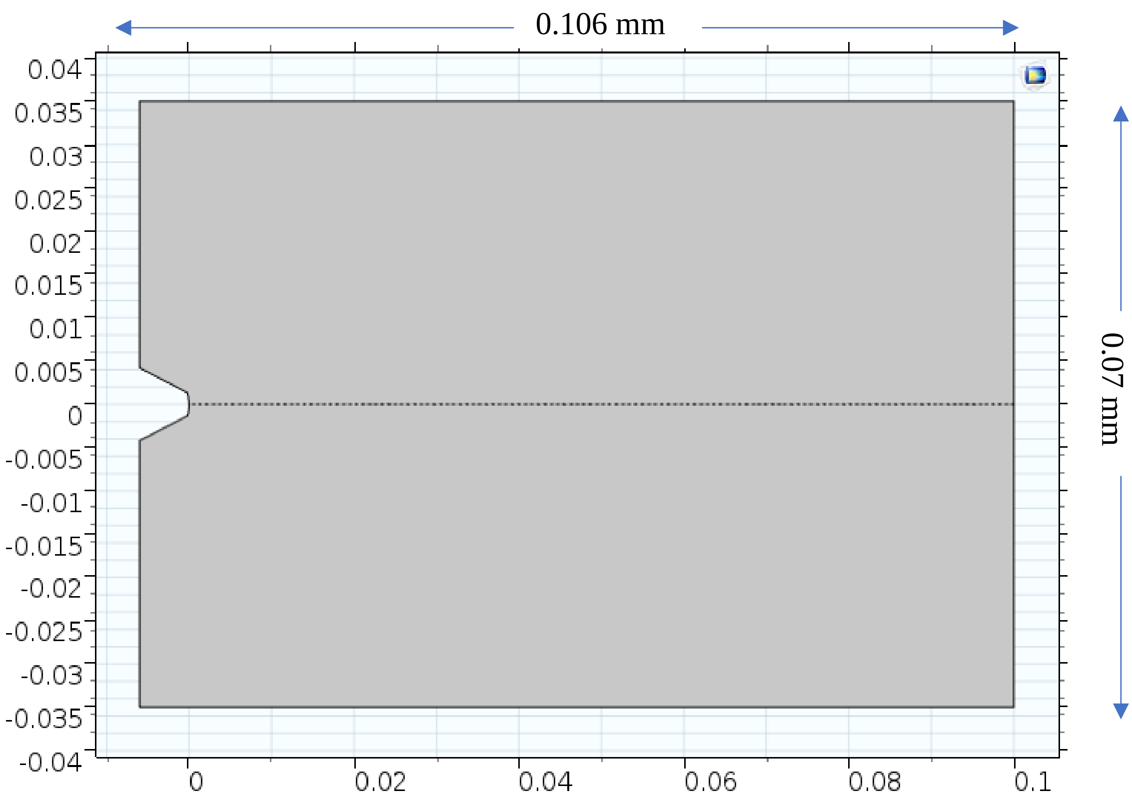


Figure 3.4 : Model of pin-plane electrodes with gap of 0.1mm near pin electrode

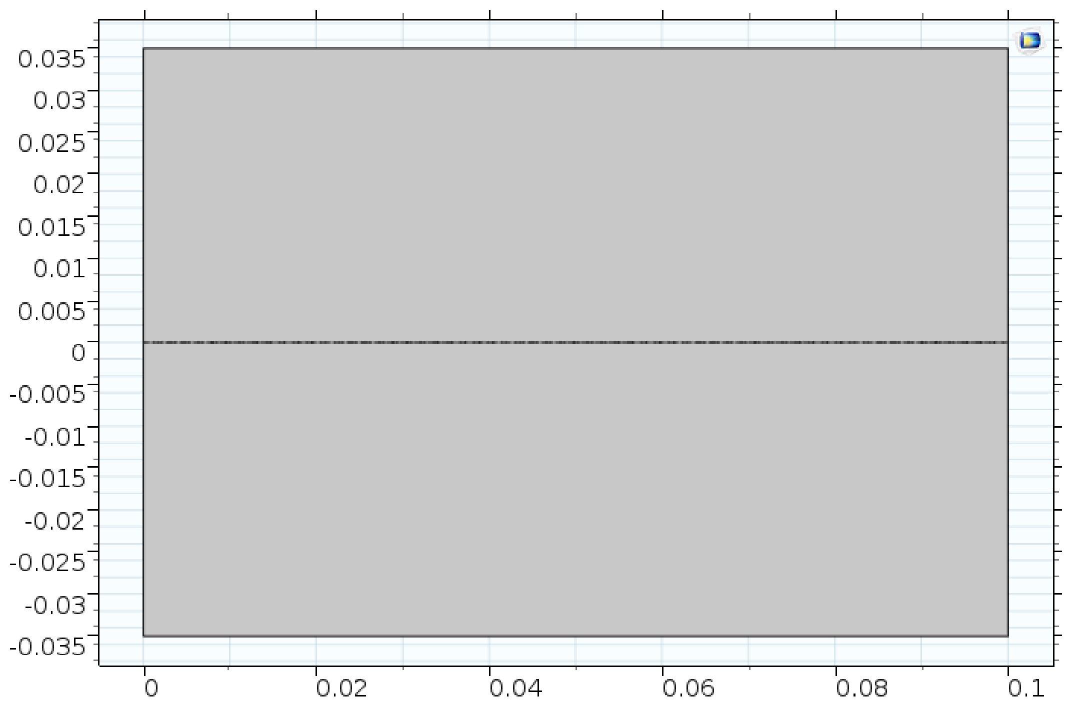


Figure 3.5 : Model of pin-plane electrodes with gap of 0.1mm in between electrodes and near plane electrode.

In this simulation, the relative permittivity is varied, which representing type of insulating material and nanofiller used. The interparticle distance, D is calculated using Tanaka's equation as shown in (3.1) [17].

$$. D = \left\{ \frac{\pi}{6} \left(\frac{p_n}{p_m}\right) \frac{100}{wt\%} \left[1 - \frac{wt\%}{100} \left(1 - \frac{p_m}{p_n}\right)\right]^{\frac{1}{3}} - 1 \right\} d \qquad (3.1)$$

p_n	=	specific gravity for nanofiller
p_m	=	specific gravity for polymer
wt%	=	weight percent of nanofiller added
d	=	filler diameter

3.5 Physics, Boundary Conditions and Parameters

The physics used in Comsol is Electrostatics physics. Two boundaries are used in this simulation. The boundaries are high voltage potential and ground. The electric potential of 11kV is assigned to the pin electrode and 0V is assigned to plane electrode but only for 2mm model. For 0.1mm model, electric potential is assigned according to the electric potential distribution of 2mm model. The parameters used in the simulation is shown in Table 3.2. The weight percent, wt% are used in equation (3.1) to calculate the interparticle distance, D and the result is shown in Table 3.3.

Table 3.2 : Parameters values for the simulation model.

Parameters	**Values**
Voltage, V	11 kV
Permittivity of the materials, ε_r : a) SiR a) Alumina	 3.15 9.1
Specific gravity,p a) SiR b) Alumina	 1.230 kg/m^3 4.000 kg/m^3
Nanofiller Particle diameter, d	13 nm
Weight Percent, wt%	0%, 1% ,3% ,5%

Table 3.3 : Interparticle distance in SiR/Alumina nanocomposite

Weight percent, wt%	**Interparticle distance, nm**
0	-
1	58.89
3	36.61
5	28.65

CHAPTER 4
RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the modelling result of electric field distribution in SiR/alumina are discussed. The developed specimen model is simulated and the electric field distribution is analysed. The electric field distribution of interparticle distance of nanofiller is discussed in this chapter.

4.2 Electric field distribution in Silicon Rubber

Figure 4.1 shows the contour structure of electric field distribution in SiR material that is obtained by using Comsol Multiphysics. The electric field intensity is identified by observing the colour differences in specific region.

The intensity of electric field is increasing from dark blue, light blue, green, yellow, orange, red and dark red. The color scale is provided at the right side of the figure to specify the intensity of electric field. Based on the figure, the electric field is highest at pin electrode or high voltage electrode especially at the tip of the pin. The electric field is decreased and become almost uniform over the gap from point A to B.

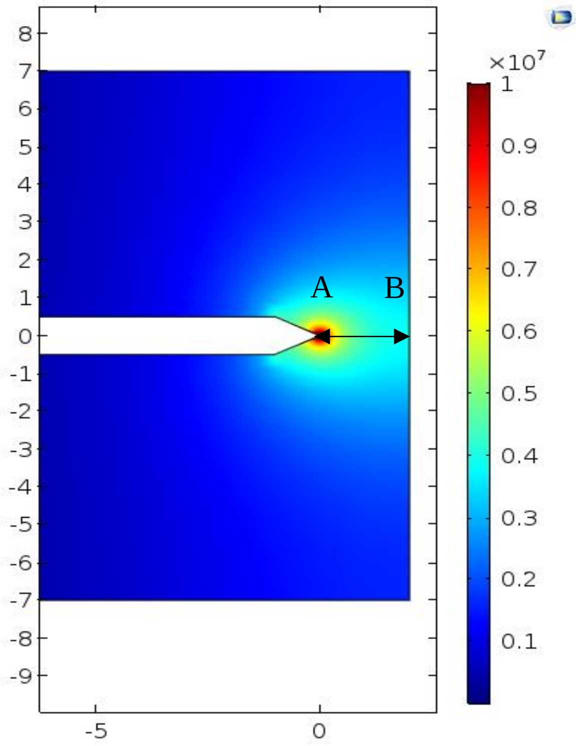


Figure 4.1 : The contour structure of electric field in SiR.

Figure 4.2 shows the line graph of electric field intensity for the pin tip to the ground electrode. The electric field near the pin electrode at 0mm is 83.2739 MV/m while the electric field near plane electrode at 2mm is 3.8265 MV/m. The simulation model is validated with uniform electric field applied for 2mm gap and 11kV applied voltage. The uniform electric field produced is 5.5 MV/m as shown as green line in Figure 4.2. The electric field is much higher than critical electric field, E_{cr} which mean there is possibility of ionisation occur in this condition due to high electric field exerted.

When insulator is subjected to high electric field which is above critical field, E_{cr}, the ionization process may occur and the atom of the molecule will gain sufficient energy to liberate electrons. The liberation of electrons due to the ionization process may initiate to the development of electrical treeing in the solid insulator and eventually lead to the breakdown of the insulator.

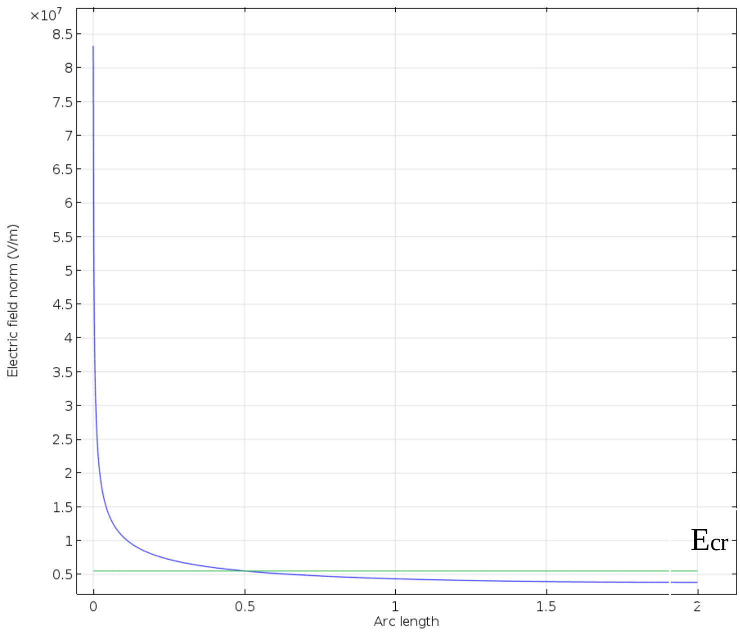
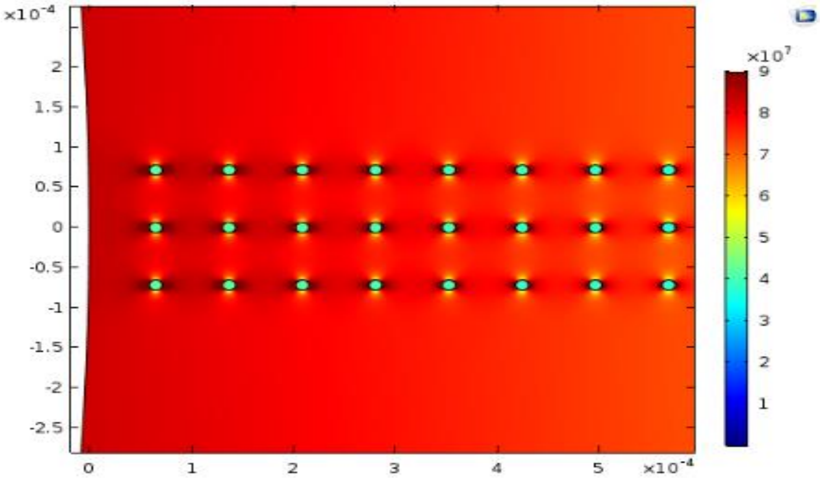


Figure 4.2 : Electric field distribution along the line of A to B

4.3 Effect of interparticle distances toward electric field distribution in insulator.

Figure 4.3 shows the magnification of contour structure of electric field for 1wt%, Figure 4.4 shows the magnification of contour structure of electric field for 3wt% and Figure 4.5 shows the magnification of contour structure of electric field 5wt% of nanofiller concentration in SiR. The contour structure shows the intensity of electric field by various color range. The electric field intensity is lowest inside the nanofiller while highest in between the nanofillers. In addition, the electric field intensity for the region in between the electrodes and near to the plane electrode are both lower than critical field. So, the possibility of electrical treeing growth is low in this region.



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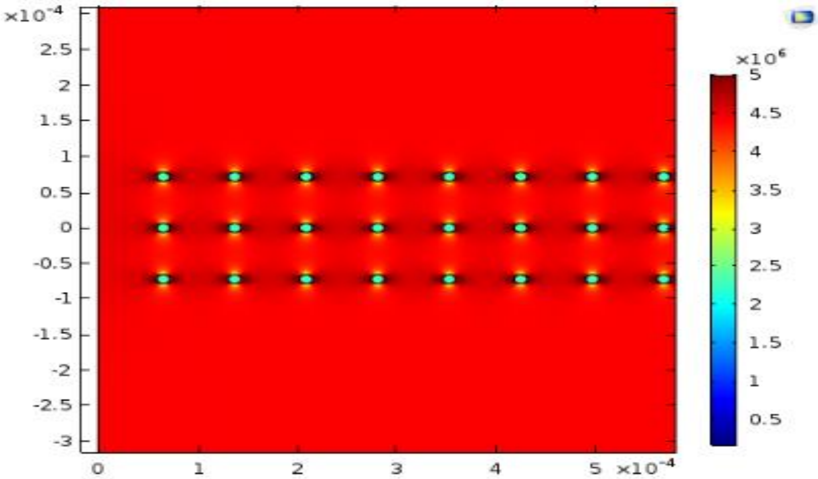

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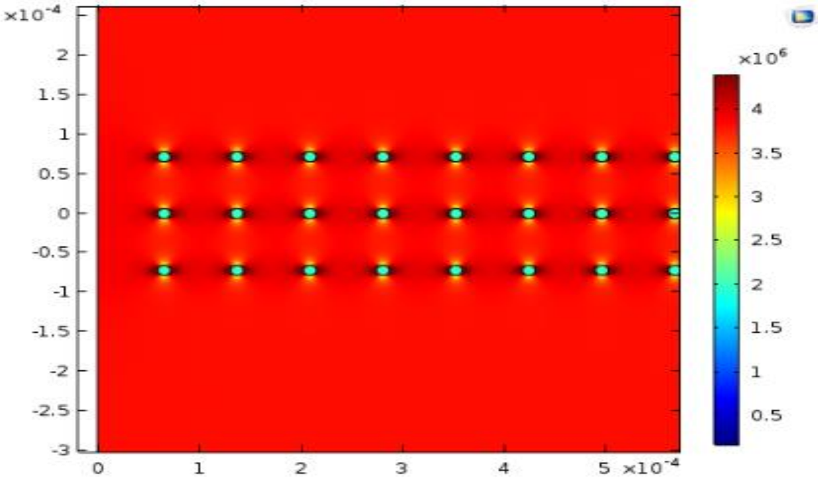
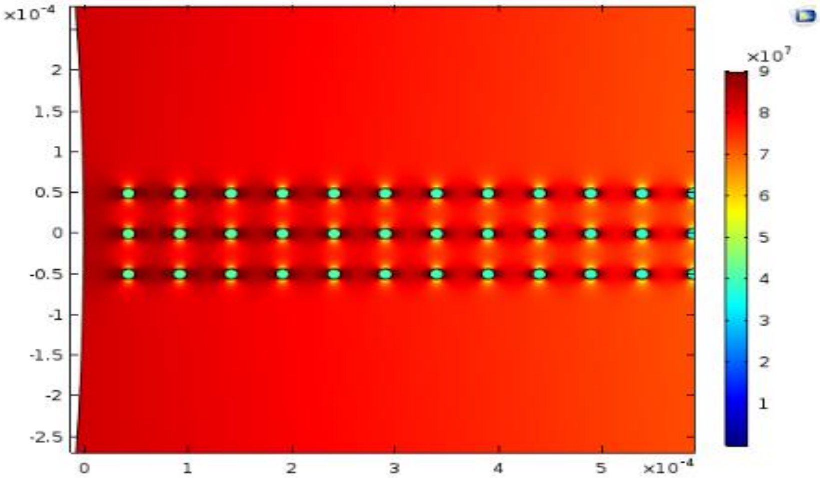


c)

Figure 4.3: The contour structure of electric field in nanocomposite SiR/Alumina with alumina concentration of 1wt% a) near pin electrode b) in between electrodes c) near plane electrode



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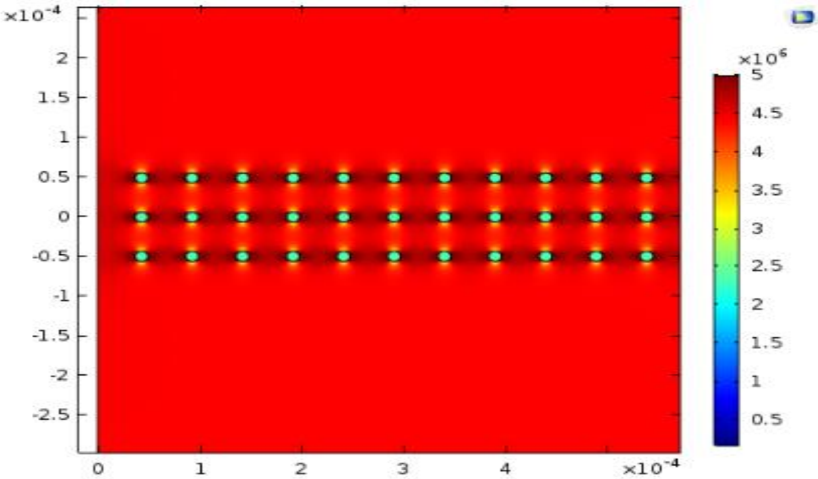

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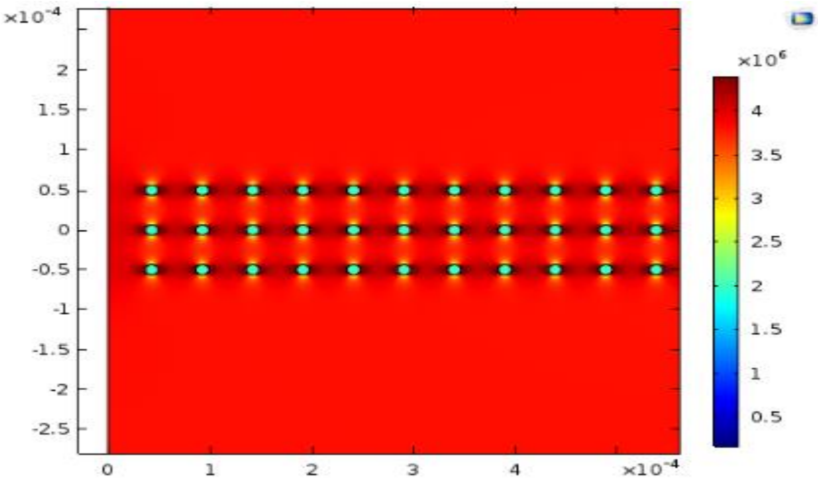

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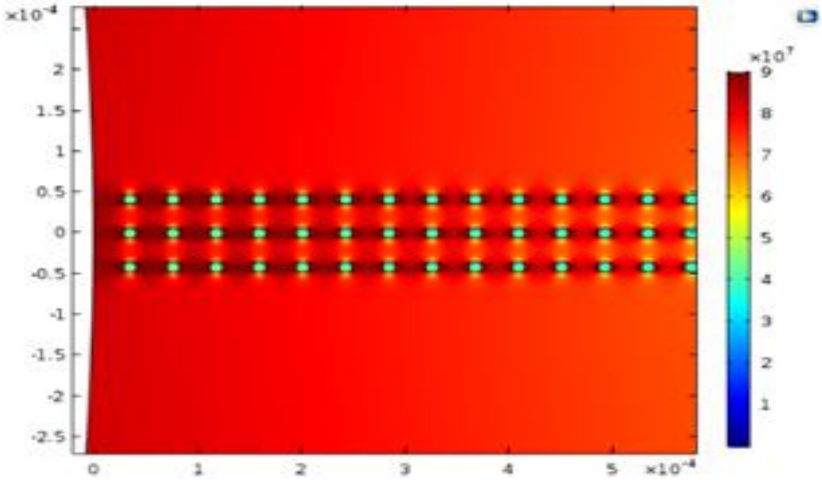
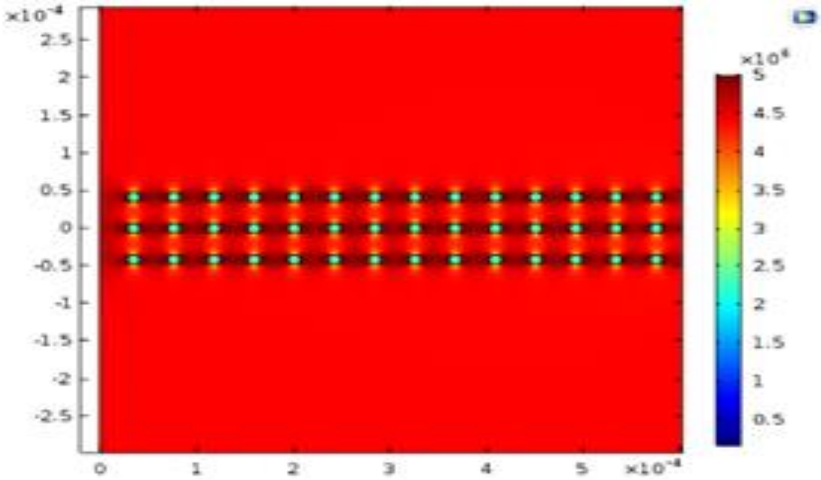
Figure 4.4: The contour structure of electric field in nanocomposite SiR/Alumina with alumina concentration of 3wt% a) near pin electrode b) in between electrodes c) near plane electrode



a)



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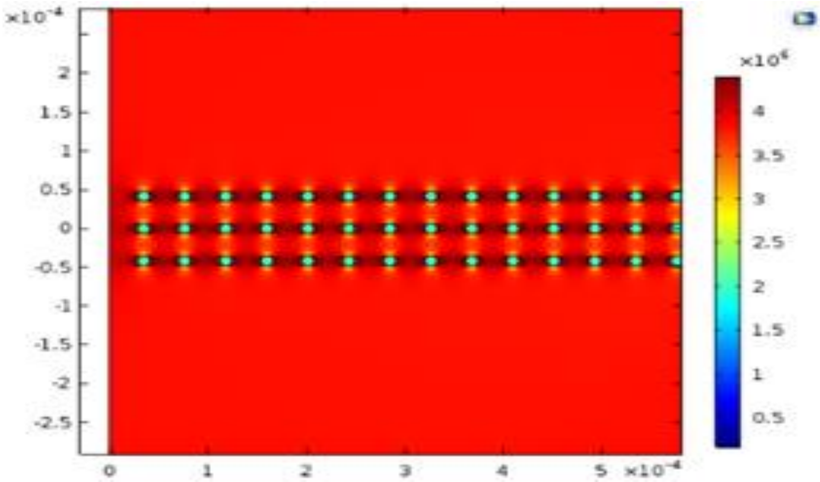

c)

Figure 4.5: The contour structure of electric field in nanocomposite SiR/Alumina with alumina concentration of 5wt% a) near pin electrode b) in between electrodes c) near plane electrode