A STUDY ON DIFFERENT MODES OF TRIBOELECTRIC NANOGENERATORS

By
GEORGE SHERIF NASEEF GUIRGIS
A Thesis Submitted to the Faculty of Engineering,
The British University in Egypt, (**BUE**)

In Partial Fulfilment of the Requirements for
The **Master of Science (MSc)** Degree in

Renewable Energy Engineering
Electrical Engineering

June 2019
Cairo

Declaration of Originality

The signed declaration of originality is a component of the research dissertation and all other degree work undertaken during the course of studies of this academic year, including the respective electronic versions and all other written papers compiled for it.

I hereby confirm that I am the sole author of the written work and oral presentations here enclosed in the research dissertation and that I have compiled all the work submitted in my own words.

With my signature I confirm that

– I have committed none of the forms of plagiarism described in the 'GAR' bulletin.

– I have documented all methods, data and processes truthfully.

– I have not manipulated any data.

– I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Name: George Sherif Naseef Guirgis Bishay Maximous

Signature:

…………………………………………………………………………...

Date of signature(s): ……………………………………………..……

Acknowledgements

First and above all, I have to thank God providing me with the opportunity to meet such helpful and wonderful people who helped me from the start of the thesis.

I would like to express my deepest sense of gratitude to my respectable supervisors; **Dr. Ashraf Seleym** and **Dr. Hassan Mostafa**, who offered me the honour to be one of their students. I thank them for their continuous advice and encouragement, guidance, extreme caring, and great effort to provide me with an excellent atmosphere for doing this research.

I am indebted with great favour to **Dr. Tamer A. Ali** for his positive discussions, guidance, continuous support, and following me up through the study.

I would also like to express my appreciation to my parents, **Dr. Sherif Naseef** and **Mrs. Manal Fayez** for lots of support. It is their patience; unconditional love and support that help me get through the difficult periods of my life journey. I would like to thank my sister, **Dr. Mirella Sherif** for standing by my side through the thesis.

It gives me pleasure to thank **Eng. Mohamed Shehata**, **Eng. Ahmed Zaky**, **Eng. Ali M. Fathalla**, **Eng. Reem M. Abdel Sattar**, and **Eng. Endy A. Onsy** for their corporation during the research and I wish them all the best and further success in their professional and personal lives.

Finally, I would like to express my gratitude to all my friends and colleagues for supporting me and being by my side.

Abstract

Triboelectrification effect has been known since the ancient Greek time. Triboelectrification is the process of materials being charged through friction. In the past few years, electrical energy harvesting from the ambient environment has attracted much of the research interests due to the increasing need for energy resources that suit the rapid development of power electronic devices. Recently, a novel mechanical energy harvesting and transduction technology has been introduced called the triboelectric nanogenerators (TENGs), with many advantages over the other harvesters. A triboelectric nanogenerator (TENG) is used to convert the mechanical energy to electrical energy. TENG is a promising candidate for the new transducers generation recommended for energy harvesting. It is used to gather the mechanical energy from the surroundings with a great number of advantages such as ease in fabrication, cheap, and high efficiency.

In this research, a survey on the attached electrode TENG modes is studied and a new mode has been invented. There are 3 main modes named the attached electrode, single electrode, and freestanding TENG. For every mode, there is a certain structure and motion of the TENG. The attached electrode TENG has two types which are contact and sliding modes. A new mode in the attached electrode TENG named diagonal mode has been proposed and has been studied purposefully in attached electrode mode using Common Solution program (COMSOL) finite element analysis. The diagonal motion mode offers a new way of motion represented in the angle theta (ϴ)—between the left endpoint of the bottom dielectric and the left endpoint of the top dielectric—that ranges from 0 to 90 degrees, and allows for further energy optimization. A complete analytical model of the proposed TENG structure has been derived step by step, and its results were compared to COMSOL simulation results to validate its accuracy. The maximum error between the results is equal to 5.3%, 4.3% and 0.88% for the open circuit voltage (VOC), short circuit charge (QSC) and Capacitance (C) respectively.

Since COMSOL consumes a lot of time in solving the output parameters of the TENG, a new Computer Aided Design (CAD) tool is built based on the analytical equations derived from both COMSOL simulation results and theoretical framework. The tool optimizes the energy based on both the angle and the distance of motion in a few seconds which is very time-efficient compared to the time consuming COMSOL simulations. The tool results show great consistency with the data obtained from time consuming COMSOL results. The tool offers the user to calculate open circuit voltage, short circuit charge, capacitance, and output energy based on the inputs of the TENG parameters. Also, it plots the output TENG parameters versus the separation distance.

Effect of gap between two electrodes on the attached electrode sliding mode has been studied physically by using COMSOL Multi-physics and analytically using the MATLAB program. The gap has a great impact on the output TENG parameters as the open circuit voltage, the short circuit charge, the capacitance, and the output energy. The increase in the gap leads to the increase in the open circuit voltage and decrease in the capacitance. Effect of the metal thickness has been studied on the attached electrode sliding mode. The metal thickness has the same effect as the gap. The increase in the metal thickness leads to an increase in the open circuit voltage and the output energy but a decrease in the short circuit charge and capacitance.

A comparison between the simulation results of all different attached electrode TENG Modes is done. The results approve that the attached electrode diagonal mode results in a high capacitance, while the attached electrode contact mode results in a high open circuit voltage, high short circuit charge, and high output energy.

Table of Contents

List of Figures

List of Tables

Nomenclature

AE CM CD	Attached electrode Contact Mode Conductor to Dielectric
AE CM DD	Attached electrode Contact Mode Dielectric to Dielectric
AE SM CD	Attached electrode Sliding Mode Conductor to Dielectric
AE SM DD	Attached electrode Sliding Mode Dielectric to Dielectric
AE DM CD	Attached electrode Diagonal Mode Conductor to Dielectric
AE DM DD	Attached electrode Diagonal Mode Dielectric to Dielectric
CAD	Computer Aided Design
COMSOL	Computational Solution
GUI	Graphic User Interface
MATLAB	Matrix Laboratory
MACRS	Minimum Achievable Charge Reference State
NdFeB	Neodymium iron boron
PDMS	Polydimethylsiloxane
PTFE	Polytetrafluoroethylene
TENG	Triboelectric Nanogenerator

List of Symbols

C	Capacitance
d	Dielectric thickness
d0	Effective thickness
dm	Conductor thickness
E	Energy
ε0	Permittivity of vacuum
εr1	Relative dielectric constant of dielectric 1
εr2	Relative dielectric constant of dielectric 2
Qsc	Short circuit Charge
Voc	Open Circuit Voltage
x	Distance between the triboelectric surfaces
σ	Surface Charge density

Chapter 1

Introduction

1. Introduction

1.1 Background and Context

Energy harvesting has been regarded as a promising technology to compensate the lack of fuel sources. On the large scale, large amount of resources have been involved to find replaceable energy sources for fuel. The techniques of energy harvesting such as photovoltaic and mechanical energy harvesting can help in solving the huge energy demand of the modern society. The energy source problem for electronic devices can be solved by the energy harvesting when the traditional sources of energy are not reached [1-4].

Since the worldwide energy demand is growing quickly, looking for a new renewable energy source has a great role in the society [5-8]. From all different types of sources, mechanical energy is considered the best energy harvesting since it is clean and does not pollute the environment, and also, the mechanical energy is highly available [9]. Energy from the surrounding environment can be harvested by new technologies. Piezoelectric, electromagnetic, and electrostatic are the standard methods to harvest energy [10-12].

The electromagnetic generator has been developed by Beepy [1]. When the magnetic flux is changed due to an external motion, an electric current is induced in the copper coil. This is used in a great wide range of the power plants. Figure 1.1 shows the whole electromagnetic generator structure.

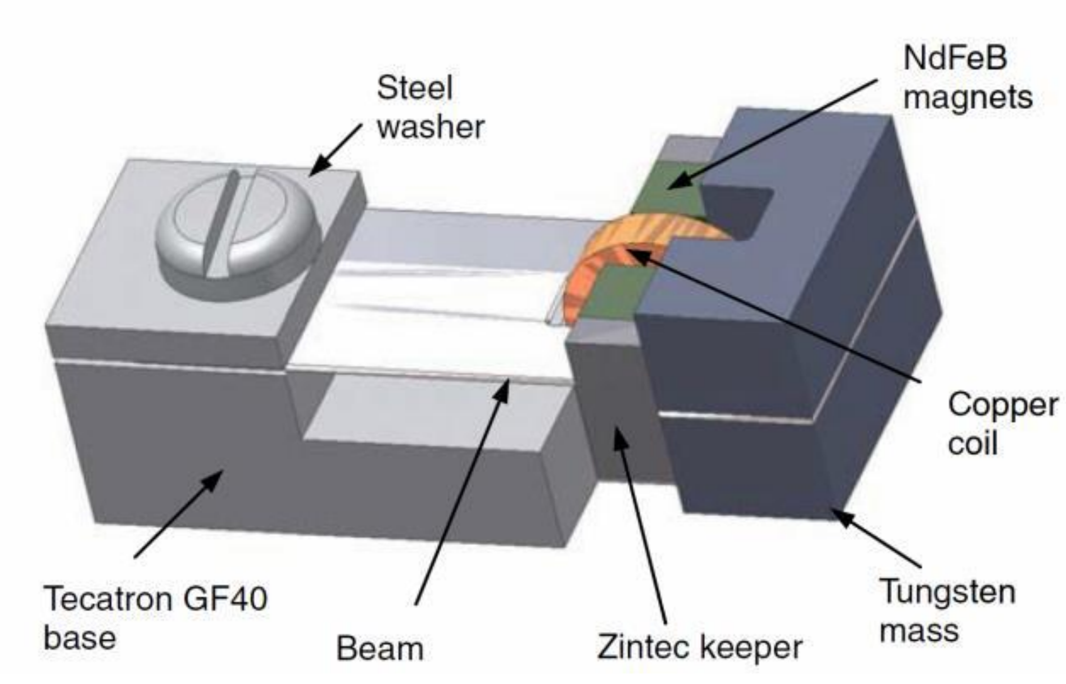


Figure 1.1 The whole structure of the electromagnetic generator [1]

This design has 4 energy density sintered magnets made of Neodymium iron boron (NdFeB) manually connected with Cyanoacrylate to all surfaces of the beam of the cantilever with the help of an alignment vibration.

The output peak power is equal to 46 µW from an acceleration of 60 mg across a certain load of 4000Ω and the energy efficiency is equal to 30% [1].

The main drawback of this electromagnetic generator is the size of the magnet which cannot be used in mobile applications that need low generators weight. Also, it cannot be used to harvest the blue energy (the energy harvested by sea oceans and waves) because it will sink due to the density of the permanent magnet.

Yu-Chong Tai et al. introduced a new energy harvester which is the electret generator. This basic principle of this generator is the electrostatic induction. In order to make the device work, the electret surface has to be charged with the electrostatic charges. The generator consists of certain polymers named as electrets. These polymers have the capability to preserve charges on their surfaces. Figure 1.2 shows the whole setup of the electret generator [10].

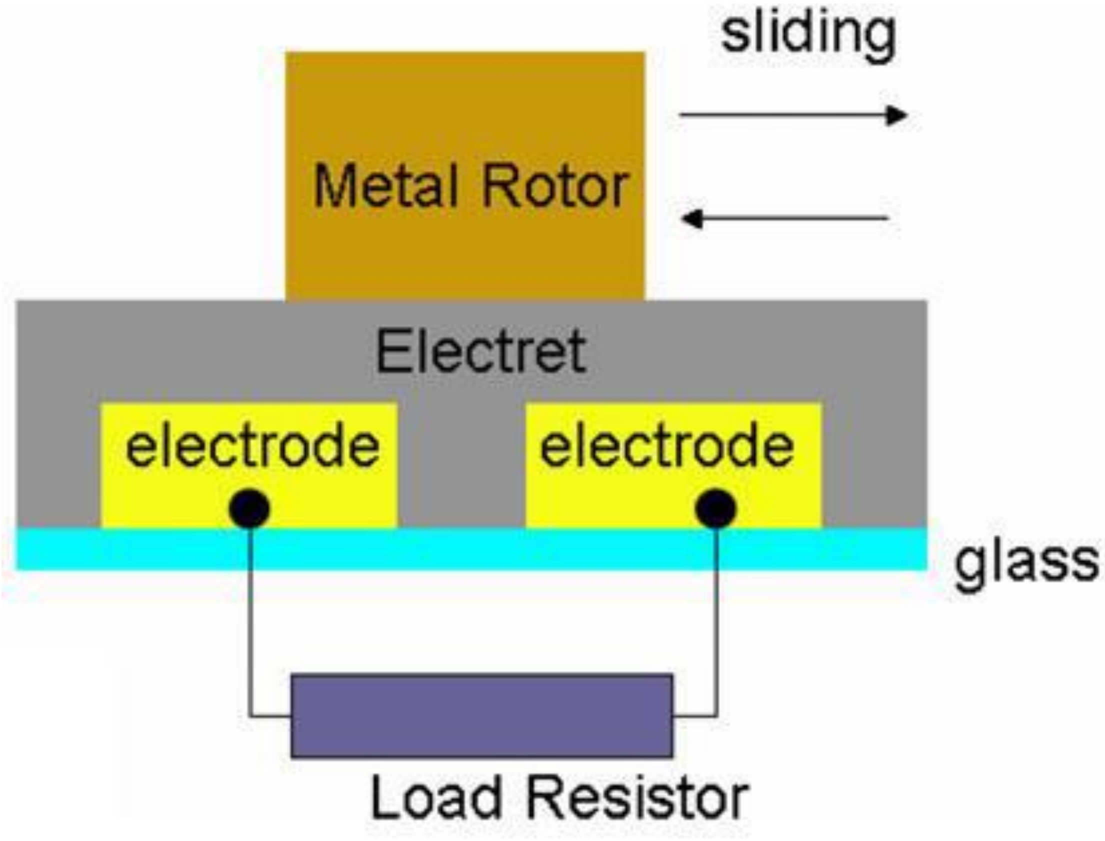


Figure 1.1 The electret generator setup [10]

The drawback of the electret generator is that it always requires being pre-charged. This is inapplicable in practical applications. Also, the output power is found to be very low. Figure 1.3 shows a complete schematic of the electret generator till the final product of electret generator [10].

Roundy proposed a new energy harvester which is the piezoelectric shown in Figure 1.3 [11].

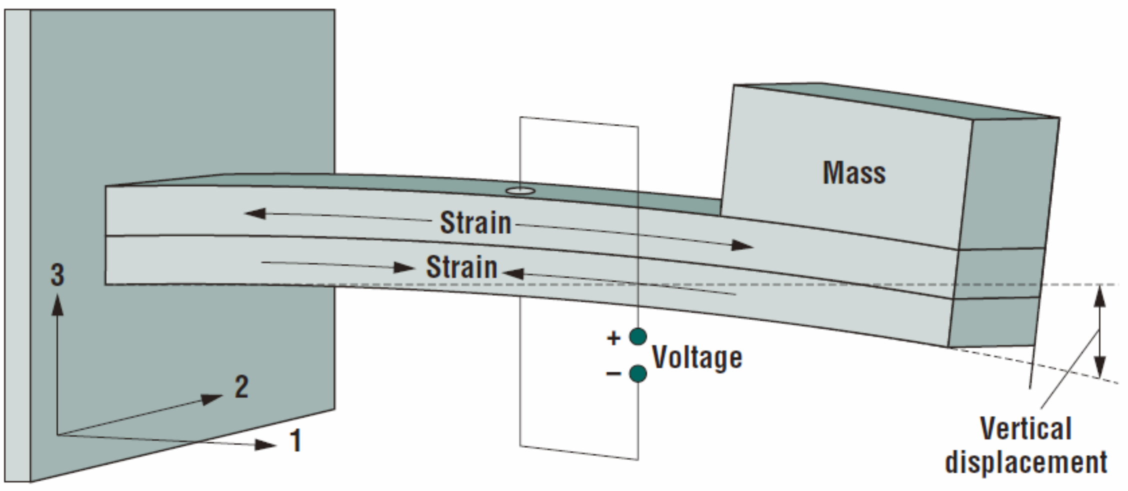


Figure 1.3 Piezoelectric setup [11]

The piezoelectric is based on conversion of mechanical energy to electrical energy. It consists of certain piezoelectric materials. During bending of the beam, the strain is generated in both of the top and bottom layers of the beam leading to a vibration. This vibration produces a low power of 0.1 mW.

The main drawback of the piezoelectric is the extremely low power. Also, it is made of lead which is very toxic that has to be avoided in the environment for safety.

Since 2012, a new technology named nanogenerator to convert the mechanical energy into electrical energy in different scales. This technology is to solve the several drawbacks of the previous energy harvesters mentioned before. Two effects which are triboelectricity and piezoelectricity are the basic effects to develop the nanogenerators [13-29].

At a recent time, triboelectric nanogenerators (TENGs) developed by Zhong Lin Wang have become good technology to convert mechanical energy into electrical energy [23].

TENG can be applied in mechanical energy harvesting in life for example, motion, flowing water, wind, tire rotation and so on [24]. The advantages of the TENGs are that they are very cheap; they produce a high output power; they have high efficiency; and finally, they can be fabricated easily. TENG is based on triboelectrification and electrostatic induction

[25-28]. The triboelectrification is a kind of contact electrification such that specific materials are charged electrically after friction with a different material [29]. Electrostatic induction is the major mechanism to convert the mechanical energy into electrical energy [30].

There are three basic modes of operations which are attached electrode mode, single electrode mode and free standing mode. For every mode, there is a certain structure and choice of the materials and also, the triggering order. For example, in vertical contact mode, vertical force triggers the TENG causing a repeated contact separation of two different materials that are attached to electrodes on the bottom and top surfaces. Also, in horizontal sliding mode, the lateral separation triggers the TENG between two different materials in parallel. [31]

Sihong Wang and Long Lin fabricated the attached electrode contact mode [32] as shown in Figure 1.4.

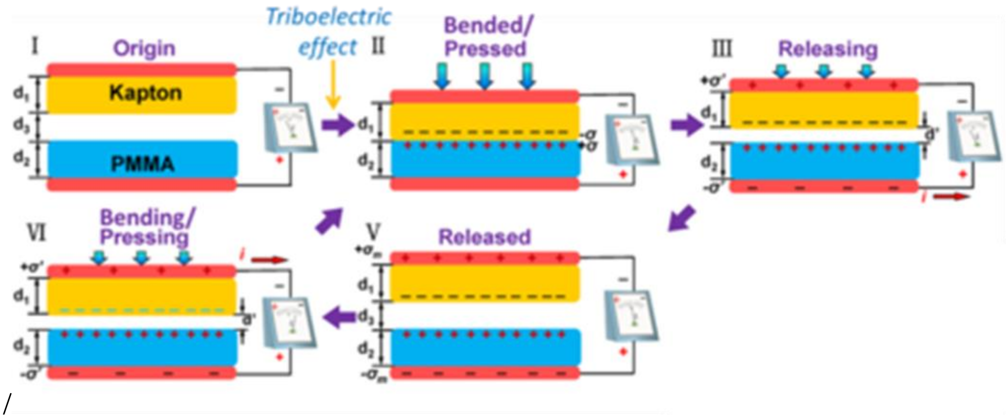


Figure 1.4 The attached electrode contact mode fabricated by Sihong Wang and Long Lin [32]

From Figure 1.4, when an external motor drives an external force, the electric potential of 200 V is generated and the optimal electric current of 0.1 mA is produced. These parameters can light an electric bulb. Also, the battery can be charged and the energy can be harvested from walking. Figure 1.5 shows a new way of harvesting energy from a shoe during walking.

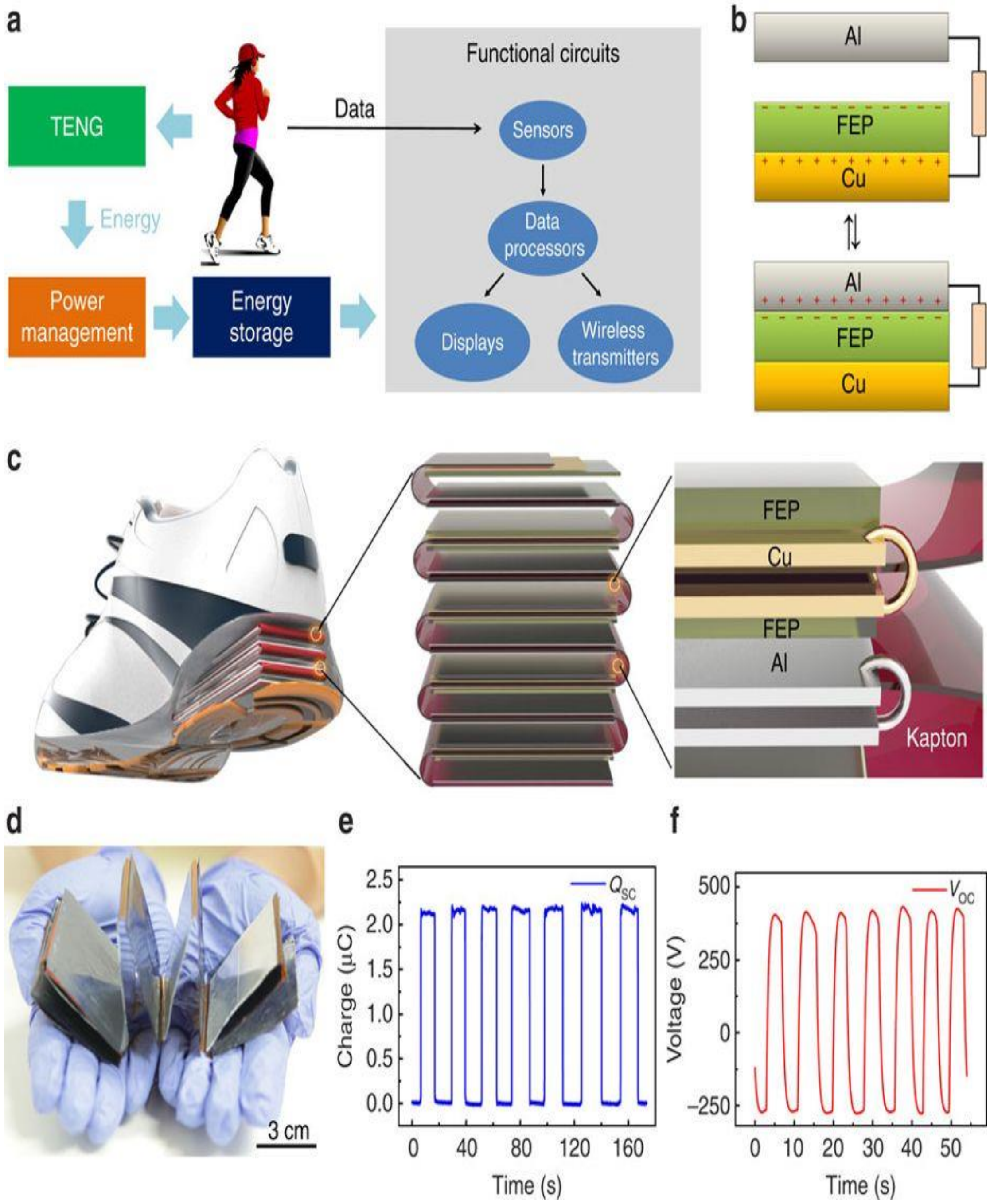


Figure 1.5 (a) TENG based self powered system (b) The mechanism of the attached electrode TENG Contact Mode (c) A complete structure of multilayer TENG (d) Photo of TENG fabrication (e) and (f) Output short circuit charge and open circuit voltage from the TENG fabrication [33]

Another category of the attached electrode is the sliding mode as shown in Figure 1.6 [34].

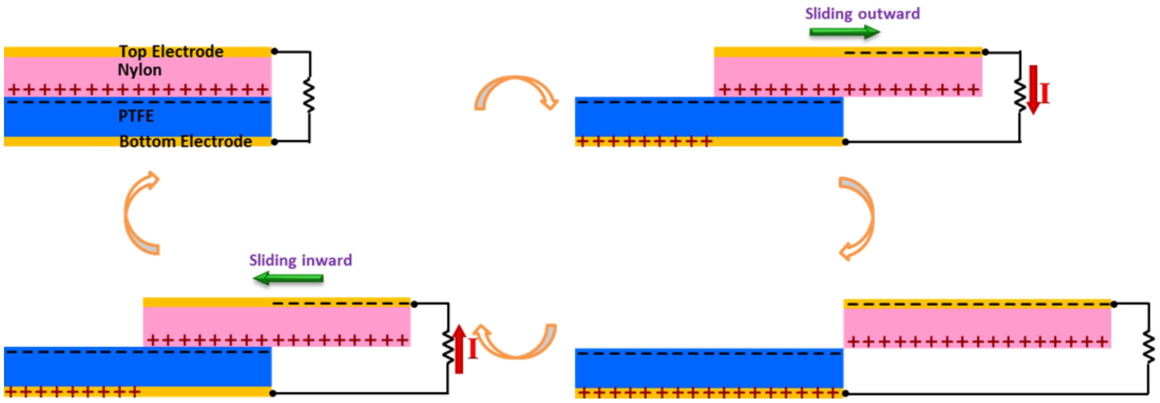


Figure 1.6 The fabricated attached electrode TENG and its output parameters [34]

The attached electrode sliding mode consists of nylon and polytetrafluorethylene (PTFE) which act as electric tribo pairs. The structure of the attached electrode TENG sliding mode is the same as in the attached electrode TENG Contact mode but the force is exerted in lateral direction instead of vertical direction. The attached electrode TENG sliding mode can light several LEDs as shown in Figure 1.7 [35].

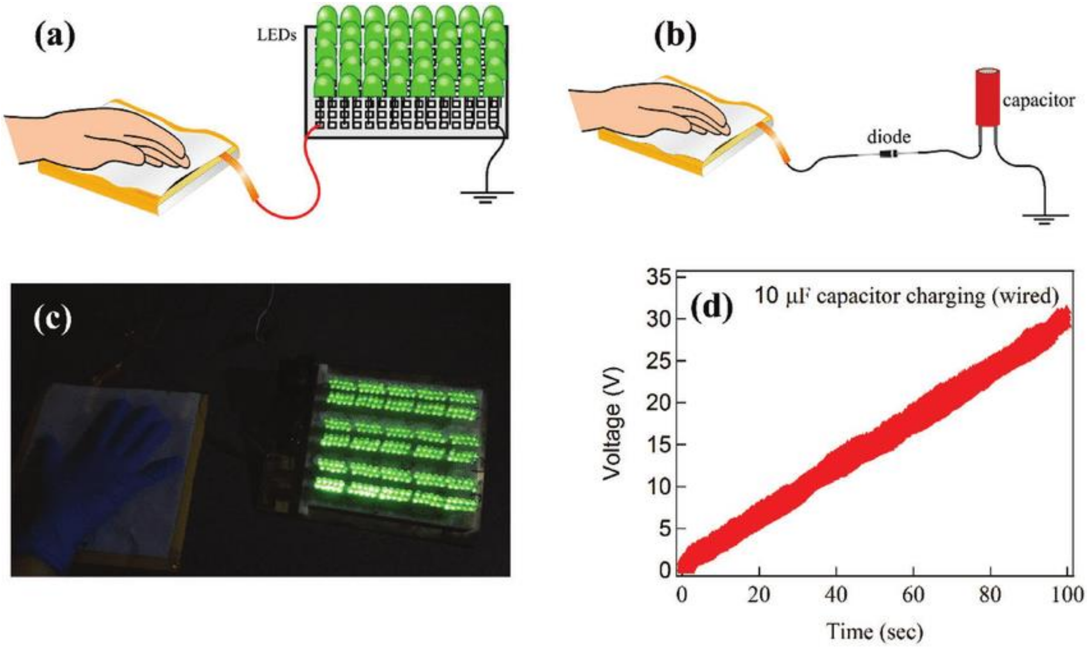


Figure 1.7 Applications of the TENG in (a) powering the leds (b) the capacitor charging (c)The led response (d) capacitor response [35]

The attached electrode needs wires in the upper and lower surfaces of the TENG. This leads to limitation in the TENG applications. In order to solve this problem, a new mode named as single electrode mode has been proposed as shown in Figure 1.8 [36].

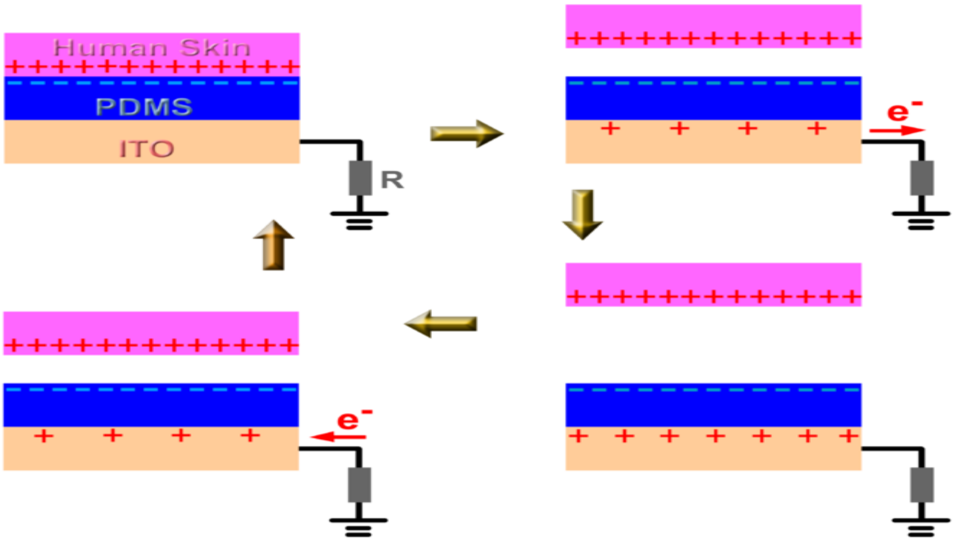


Figure 1.8 Single electrode mode TENG [36]

In the single electrode mode, one electrode which is the primary electrode can deal with the layer of the TENG while the reference electrode is fixed and placed anywhere. This device can be used in charging the mobile by only a single finger.

Another type of the TENG which is the freestanding TENG has been proposed as shown in Figure 1.9 [37]. In this type the electrodes are fixed and the triboelectric layer moves between them in both of vertical motion or in lateral motion.

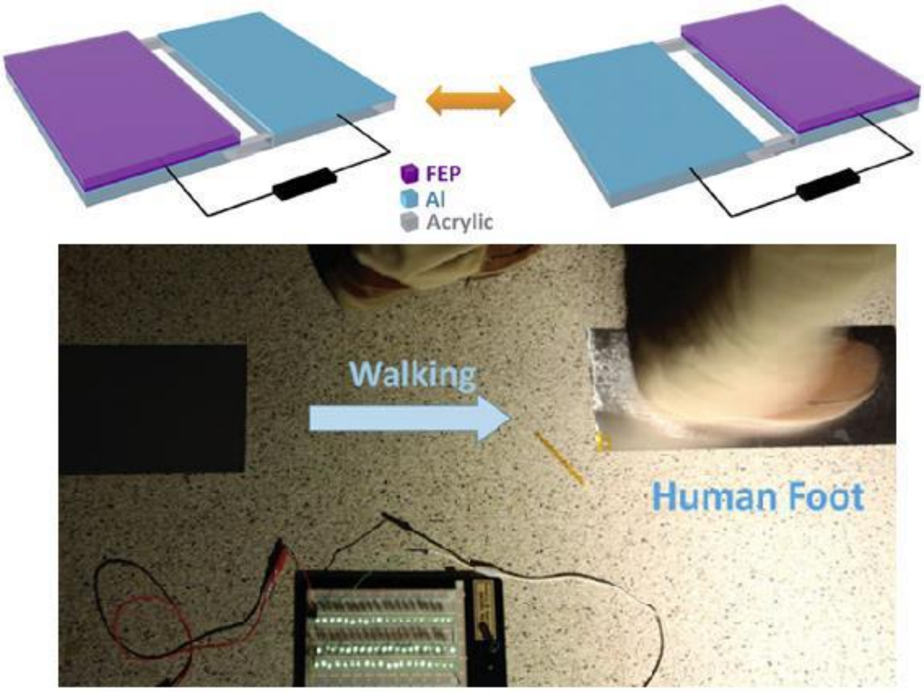


Figure 1.9 Freestanding TENG application [37]

Choosing the material is very important in the fabrication of the TENG since the dielectric material has two parameters which are relative permittivity and surface charge density affecting on the output of the TENG parameters. When the surface charge and relative permittivity of the material increase, the output energy increases as well. The triboelectric effect is found in almost all materials starting from the polymer to the silk to everything. So, all of these materials can be used to fabricate the TENG. There are a lot of varieties for choosing the material [38]

However, choosing the dependency of the material to lose or to gain electrons is on its polarity. The triboelectric series was published by John Carl Wilcke [39]. Figure 1.10 shows the triboelectric series. The material toward the bottom of the series, when rubbed with the material toward the top of the series will gain a more negative charge [40]. As a result, there are large numbers of ways in order to increase the performance of the TENG according to the point of view of materials. This gives an excellent opportunity for the material scientist and chemists to make an extensive study both in basic science and in practical studies.

Polyformaldehyde 1.3-1.4	(continued)
Etylcellulose	Polyester (Dacron)
Polyamide 11	Polyisobutylene
Polyamide 6-6	Polyuretane flexible sponge
Melanime formol	Polyethylene Terephthalate
Wool, knitted	Polyvinyl butyral
Silk, woven	Polychlorobutadiene
Aluminum	Natural rubber
Paper	Polyacrilonitrile
Cotton, woven	Acrylonitrite-vinyl chloride
Steel	Polybisphenol carbonate
Wood	Polychloroether
Hard rubber	Polyvinylidine chloride (Saran)
Nickel, Copper	Polystyrene
Sulfur	Polyethylene
Brass, silver	Polypropylene
Acetate, Rayon	Polyimide (Kapton)
Polymethyl methacrylate	Polyvinyl Chloride (PVC)
Polyvinyl alcohol	Polydimethylsiloxane (PDMS)
(continued)	Polytetrafluroethylene (PTFE)

Figure 1.10 Triboelectric Series

1.2 Scope and Objectives

In spite of several experiments demonstrated before [31], there are a lot of unsolved problems such as the effect of certain parameters on the output of the TENG that need to be solved. The main objective of this work is to assess different modes of the TENG and to demonstrate the same work in order to get the same results of the previous works and to develop a new mode named diagonal mode in the TENG to produce high TENG output parameter. Also, this study aims to find the effect of certain parameters of the TENG such as the effect of the thickness of both of the metal, and the dielectric as well as the effect of the gap between the metal and the dielectric and between the dielectric-to-dielectric in different modes of the TENG.

1.3 Achievements

A new mode named the diagonal mode is achieved in the attached electrode mode. In this mode, the motion is in a diagonal motion instead of vertical or lateral direction. Also, a CAD (Computer Aided Design) tool is developed instead of COMSOL Multiphysics for the simulation of the TENG. The work is based on two different modes of the attached electrode TENG. Open circuit voltage, capacitance, short circuit charge, and output energy of the TENG are discussed in details throughout the work. The results show that the gap between the two electrodes in the attached electrode TENG sliding mode has great effect in the output TENG parameters. The increase in the gap leads to increase in the open circuit voltage but decrease in the capacitance. Also, the effect of the metal thickness has the same effect of the gap. The results show that the optimal open circuit voltage, short circuit charge, and energy are yielded from the attached electrode TENG Contact mode Conductor to Dielectric while the optimal capacitance is yielded from the new mode (Diagonal mode).

1.4 Overview of dissertation

The organization of this work is as follows. Chapter 2 presents the different materials used in the fabrication of the TENG and the different modes of the TENG which are the attached electrode, single electrode, and freestanding electrode. A new mode of the attached electrode which is the diagonal mode as well as the simulation results are presented in Chapter 3. Finally, the conclusion and the future work are drawn in Chapter 4.

Chapter 2

Modes of the TENG

2. Modes of the TENG

2.1 Introduction

This chapter presents the different modes of the TENG and the material used in the fabrication of the TENG.

2.2 Modes of the TENG

As mentioned before, there are three basic modes which are Attached electrode mode with two types (Contact and sliding mode), single electrode mode, and freestanding mode of operations of the TENG which are shown in Figure 2.1 [22]. The attached electrode TENG has one electrode fixed and the other electrode moves with the TENG material. The single electrode TENG has the two electrodes fixed and the TENG deals with the upper electrode. The freestanding TENG has the two electrodes fixed and the TENG moves between them.

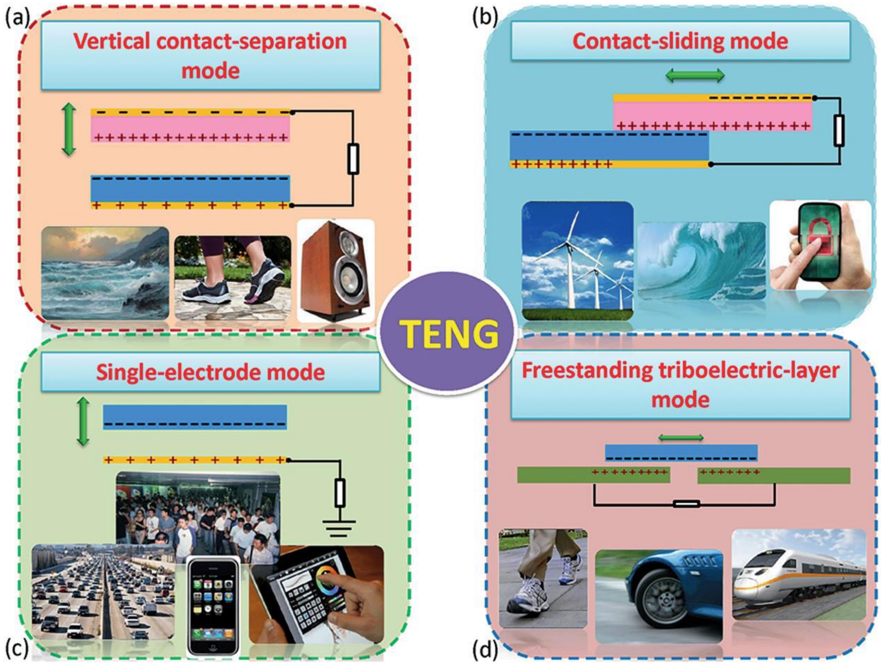
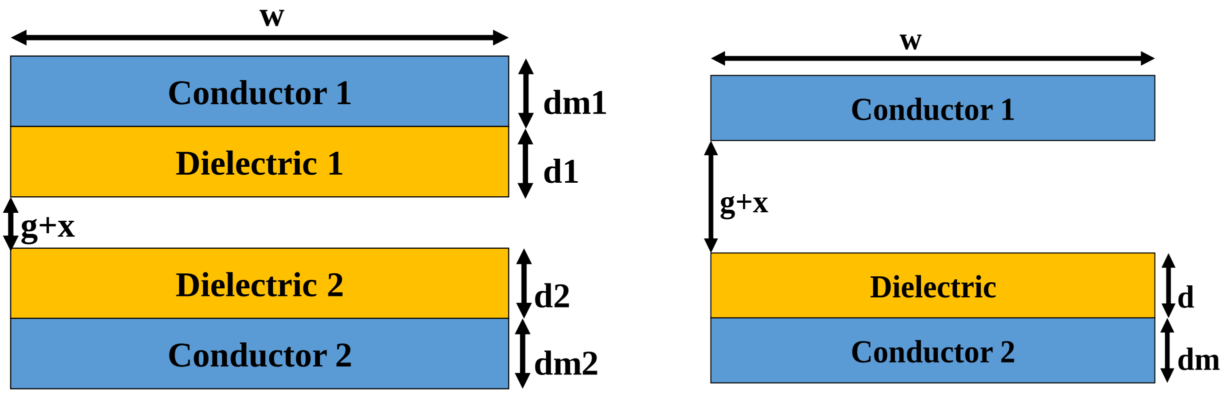


Figure 2.1 Four modes of TENG operations (a)Attached electrode Contact mode (b) Attached electrode sliding mode (c) Single electrode mode (d) Freestanding mode [22]

2.2.1 Attached Electrode Contact Mode

The contact mode was first proposed in [41]. The contact mode can be classified into two categories which are conductor-to-dielectric and dielectric-to-dielectric. Figure 2.2 shows the setup for both categories of the contact mode.



(a) (b)

Figure 2.2 The contact mode for (a) Dielectric-to-dielectric (b) Conductor-to-dielectric

Each dielectric has a thickness d and dielectric constant εr. The two dielectrics are separated by the vertical distance (x) which can be changed by the effect of the mechanical force. Each triboelectric layer is attached to conductor electrodes. The two layers surfaces have the same surface charge density but with different signs. The tribo-charges are supposed to be distributed uniformly. When the two layers are pushed away from each other (i.e. the distance x increases), the electrical potential difference is induced between the two electrodes due to the effect of Gauss theorem which states that the sum of the electric flux in the closed surface is equal to the charge divided by the permittivity [42]

The open circuit voltage is given by the following equation [41]:

$$V_{oc} = \frac{\sigma x}{\varepsilon_0} \tag{2.1}$$

where σ is the surface charge density,

x is the vertical separation distance,

ε_0 is the permittivity of the air and is equal to $8.854*10^{-12}$ F/m,

It can be seen that the separation between the two TENG layers is directly proportional with the open circuit voltage. The separation can be chosen depending on the application used. However, for convenience, the separation distance is chosen such that w<x<l. [41]

The short circuit charge is given by (2.2). [41]

$$Q_{sc} = \frac{wl\sigma x}{d_0 + x} \tag{2.2}$$

where w is the width of the dielectric,

l is the length of the dielectric

ε_0 is the permittivity of the air and is equal to $8.854*10^{-12}$ F/m, and

ε_r is the relative permittivity

d_0 is the effective distance and is given by:

$$d_0 = \frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} \tag{2.3}$$

where d_1 is the thickness of dielectric 1,

and d_2 is the thickness of dielectric 2.

The capacitance (C) is given by [43]:

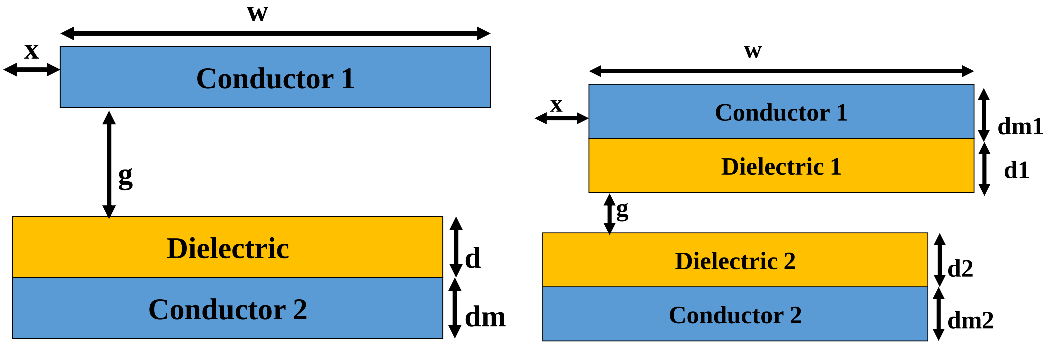
$$C = \frac{wl\varepsilon_0}{d_0 + x} \tag{2.4}$$

Finally, the output energy (E) can be derived by [43]:

$$E = 0.5 * Q_{sc} * V_{oc} \tag{2.5}$$

2.2.2 Attached Electrode Sliding Mode

The sliding mode was first proposed in [45]. The sliding mode can be classified into two categories which are conductor-to-dielectric and dielectric-to-dielectric. Figure 2.4 shows the setup for the sliding mode.



(a) (b)

Figure 2.3 The attached electrode sliding mode for (a) conductor-to-dielectric (b) dielectric-to-dielectric

In Dielectric-to-Dielectric type, two metal electrodes are attached to two dielectric layers. The lower part is fixed while the upper part slides through the lateral direction. During the separation, the two dielectrics have charges but with different signs at the non-overlapped zones due to the tribo-electric effect [32]. By induction, the metal electrodes are polarized during separation and accordingly, the charges are transferred between the electrodes. In Conductor-to-Dielectric type, the geometrical structure is the same as in the Dielectric-to-Dielectric type. The only difference is that there is no upper dielectric and the metal layer has two roles which are the upper triboelectric layer and the top electrode.

The V-Q-x relation can be obtained by Gauss' theorem. The strength of the electric field can be given by [45]:

$$V_{oc} = E_1 d_1 + E_2 d_2 = \frac{\sigma x}{\varepsilon_0 (w - x)} * \left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}\right) = \frac{\sigma x d_0}{\varepsilon_0 (w - x)} \qquad (2.6)$$

From (2.6), it is clear that when x is close to w, the open circuit voltage approaches to infinity. So, the lateral separation should be less than the width, roughly 90% of the width. The capacitance can be considered as a parallel plate form:

$$Cap = \frac{\varepsilon_0 l (w - x)}{\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}} = \frac{\varepsilon_0 l (w - x)}{d_0} \qquad (2.7)$$

According to (2.6) and (2.7), the V-Q-x relation can be derived:

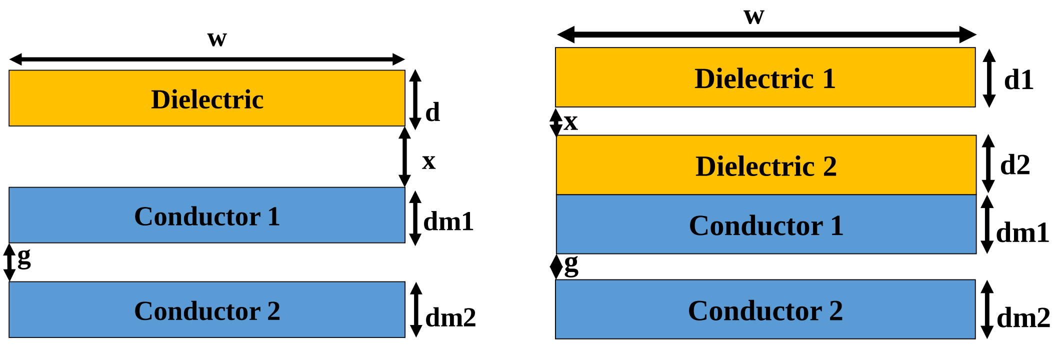
$$V = -\frac{Q}{Cap} + V_{oc} = -\frac{Q d_0}{\varepsilon_0 l (w - x)} + \frac{\sigma x d_0}{\varepsilon_0 (w - x)} \qquad (2.8)$$

The short circuit charge can be obtained by putting V=0. The transferred charges are:

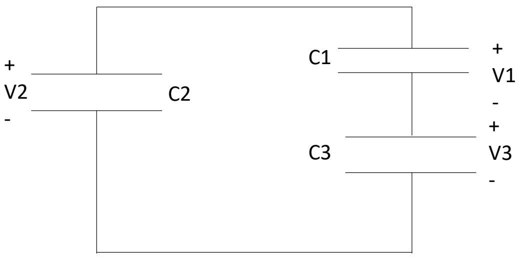
$$Q_{sc} = \sigma w x \qquad (2.9)$$

2.2.3 Single Electrode Contact Mode

Both of the contact and sliding mode TENGs need two electrodes, one for the moving part of the TENG and the other is fixed. In order to solve this problem, a new structure has been established to eliminate the moving part so that there will be only one electrode. This is called single electrode mode. In this mode, only one electrode is attached to the triboelectric mode and the other electrode acts as electric potential reference that can be placed anywhere [46-48].The two electrodes are fixed and the dielectric moves upwards. Figure 2.5 shows the setup of the single electrode mode.



(a) (b)



(c)

Figure 2.4 The single electrode contact mode for (a) conductor-to-dielectric (b) dielectric-to-dielectric (c) The equivalent circuit model

In order to understand the V-Q-x relation, a theoretical circuit needs to be built as shown in Figure 2.5c. The concept of nodes needs to be used. Each node represents a surface or a volume or a surface in the system. The whole surface of the Dielectric in conductor-to-dielectric mode can be taken as Node 1. Similarly, the primary electrode which is the conductor 1 can be taken as Node 2, and the reference electrode which is the conductor 2 can be taken as Node 3. Since the electric field lines connect the two nodes, there is an equivalent capacitance between each of them. Thus, the whole system can be shown as virtual capacitances (C_1, C_2, and C_3) [49].

C_1, C_2, and C_3 are not actual capacitances reflecting the connection of electric line. The real capacitance is the combination of the virtual capacitances. They are expressed by [49]:

$$C_a = C_1 + \frac{C_2 C_3}{C_2 + C_3} \tag{2.10}$$

$$C_b = C_2 + \frac{C_1 C_3}{C_1 + C_3} \tag{2.11}$$

$$C_0 = C_3 + \frac{C_1 C_2}{C_1 + C_2} \tag{2.12}$$

From (2.10), (2.11), and (2.12) by substitution:

$$C_1 = \frac{2C_a C_b C_0 (C_a C_b - C_b C_0 + C_a C_0)}{2C_a C_b C_0 (C_a + C_b + C_0) - C_a^2 C_b^2 - C_a^2 C_0^2 - C_b^2 C_0^2} \tag{2.13}$$

$$C_2 = \frac{2C_a C_b C_0 (C_a C_b + C_b C_0 - C_a C_0)}{2C_a C_b C_0 (C_a + C_b + C_0) - C_a^2 C_b^2 - C_a^2 C_0^2 - C_b^2 C_0^2} \tag{2.14}$$

$$C_3 = \frac{2C_a C_b C_0 (-C_a C_b + C_b C_0 + C_a C_0)}{2C_a C_b C_0 (C_a + C_b + C_0) - C_a^2 C_b^2 - C_a^2 C_0^2 - C_b^2 C_0^2} \tag{2.15}$$

So, the open circuit voltage is given by V3 (Appendix 1)

$$V_3 = \frac{C_2 \sigma w l}{C_3 C_1 + C_2 C_1 + C_3 C_2} \tag{2.16}$$

The short circuit charge is expressed by:

$$Q_{sc} = V_{oc} * C_3 \tag{2.17}$$

Since the capacitance is not ideal due to the edge effect which affects the capacitance value, the capacitance can be derived by the following equation [47]:

$$C = \frac{\varepsilon_0 w l}{d} (1 + \mathrm{alpha}(\frac{d}{l})) \tag{2.18}$$

where alpha(x) is the edge effect parameter and is expressed by [48]:

$$\mathrm{alpha}(x) = \frac{x}{\pi}(1 + \ln(1 + \frac{2\pi}{x} + \ln(1 + \frac{2\pi}{x}))) \tag{2.19}$$

Therefore, the following capacitances (C_a, C_b, and C_0) can be written as:

$$\mathrm{C}_a = \frac{\varepsilon_0 \mathrm{*l.*w}}{\mathrm{d0+x+dm1}} \mathrm{*(1+alpha(} \frac{d0 + x + dm1}{l} \mathrm{))} \tag{2.20}$$

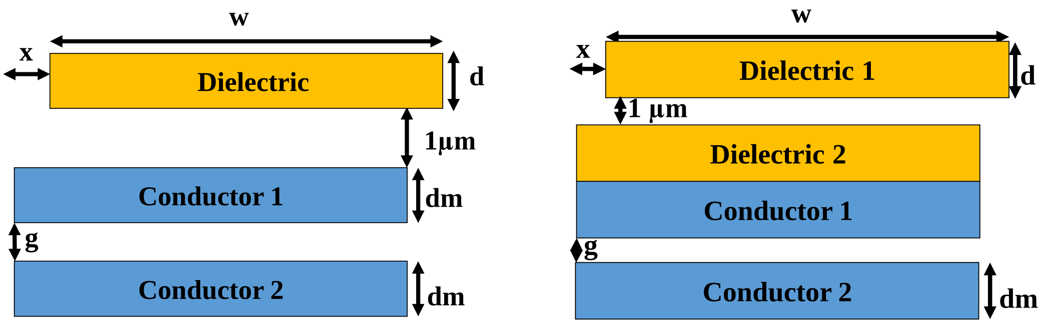
$$\mathrm{C}_b = \frac{\varepsilon_0 \mathrm{*l*w}}{\mathrm{d0+g+x+dm1+dm2}} \mathrm{*(1+alpha(} \frac{\mathrm{d0+g+x+dm1+dm2}}{l} \mathrm{))} \tag{2.21}$$

$$\mathrm{C}_0 = \frac{\varepsilon_0 \mathrm{*l*w}}{g} \mathrm{*(1+alpha(} \frac{g}{l} \mathrm{))} \tag{2.22}$$

There is a shield effect of electrostatic field in the single electrode mode. This shield effect is due to the edge effect and the gap effect. The single electrode is different from the attached electrode since the single electrode has a fixed gap not like the attached electrode. The gap in the single electrode is directly proportional with the open circuit voltage, but it is inversely proportional with the short circuit charge i.e. as the gap between the electrodes increases, the open circuit voltage increases exponentially but the short circuit charge decreases till it reaches 0. Also, the open circuit voltage saturates when g is very large [46].

2.2.4 Single Electrode Sliding Mode

There is another mode of the single electrode mode TENG, which is called sliding mode. The setup of the sliding mode Single electrode TENG is similar to that of the contact mode Single electrode TENG, but instead of moving the dielectric upwards, the dielectric moves in the lateral direction as shown in Figure 2.5.



(a) (b)

Figure 2.5 Setup of sliding mode Single electrode TENG (a) Conductor-to-dielectric (b) Dielectric-to-dielectric

The calculation of the capacitances is the same as that in the contact mode except the calculation of C_b. It can be derived by the following equation due to the fringing effect [48-52].

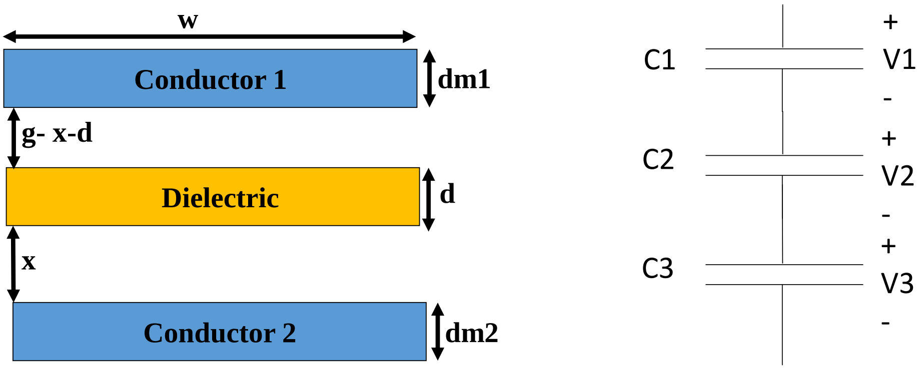
$$C_b = (\frac{\varepsilon_0 * l * (w-x)}{d0+g+dm} * (1+2*(\frac{d0+g+dm}{\Pi l})+(\frac{2*(d0+g+dm)}{\Pi l} * \log(\frac{\Pi l}{(d0+g+dm)}))) \qquad (2.23)$$

The open circuit voltage can be derived by:

$$Voc = \frac{\sigma * (x-w) * l * ((\frac{1}{C0})+(\frac{1}{Ca})-(\frac{1}{Cb}))}{2} \qquad (2.24)$$

2.2.5 Free Standing Mode

The shield effect is a great problem in single electrode. So, a new mode has been proposed which is the freestanding mode [53-57]. In this mode, the dielectric moves between the two electrodes as shown in Figure 2.6.



(a) (b)

Figure 2.6 The freestanding electrode contact mode for (a) Conductor-to-dielectric (b) The equivalent circuit model

From Figure 2.7, there is a gap between the 2 metal conductors in which the dielectric moves up and down between them. The dielectric has to be in contact with the two metals, the two dielectric surfaces will have a negative surface charge density, and the two metals surfaces will have the same surface charge density, but with a positive sign. The concept of nodes has to be understood as in single electrode mode [46]. The edge effect is ignored since the area size of the freestanding mode is observed as infinitely large. Due to the large area, the connection of electrical line between 2 non-adjacent nodes is completely blocked by the dielectric.

The open circuit voltage is calculated by the following equation under Minimum Achievable Charge Reference State (MACRS) [53]:

$$V_{oc} = \frac{2\sigma x}{\varepsilon_0} \tag{2.25}$$

The V-Q-x can be derived by [53]:

$$V = -\frac{Q(d_0 + g)}{\varepsilon_0 wl} + \frac{2\sigma x}{\varepsilon_0} \tag{2.26}$$

The short circuit charge can be calculated from (2.26) by putting V equal to 0 and Qsc can be calculated from the following equation

$$Q_{sc} = \frac{2\sigma wlx}{d_0 + g} \tag{2.27}$$

From (2.25) and (2.27), the open circuit voltage and the short circuit charge have a linear relation with the separation distance x. Unlike the attached electrode, the Voc and Qsc have a saturation trend with separation distance. The freestanding mode can drive about 600 LEDS [58].

Chapter 3

Attached Electrode TENG Simulation Survey and Results

3. Attached Electrode TENG Simulation Survey and Results

3.1 Introduction

This chapter presents a survey on different modes of the attached electrode TENG which are contact mode, sliding mode, and a new mode which is the diagonal mode. In the attached electrode contact mode, the motion of the TENG is vertically upwards, while in the attached electrode sliding mode, the motion is in lateral direction. A new mode named diagonal mode is proposed with the motion is in the diagonal direction. Also, this chapter presents the effect of both of the gap and the conductor thickness in the attached electrode sliding mode on the output effective TENG parameters which are the open circuit voltage, short circuit charge, capacitance, and the output energy. The work of the three modes of the TENG was carried out by using COMSOL Multi-physics program. This program simulates the electrostatic and electromechanical changes. The relation between the voltages (V) between the two copper electrodes, the distance (x) separating between the two triboelectric layers and the transferred charges (Q) in between is considered the most important equation to represent the real-time power generation of the triboelectric nanogenerators. The triboelectric layer material used in the fabrication of the TENG is poly-tetra-fluoro-ethylene (PTFE) since it have the ability to gain/lose electrons easily as shown in the triboelectric series. Moreover, the equations developed in the tool can be further used to develop circuit model for attached electrode TENG working in the diagonal mode using Verilog-A [59]. A CAD tool has been proposed using the MATLAB GUI (Appendix 16). The MATLAB GUI is then converted to an executable file. The CAD tool is used to carry out the analytical part of the simulations

3.2 Simulation results of the attached electrode contact mode conductor-to-dielectric

The setup of the vertical contact mode setup is shown in Figure 3.1, with the terminal denoted as V.

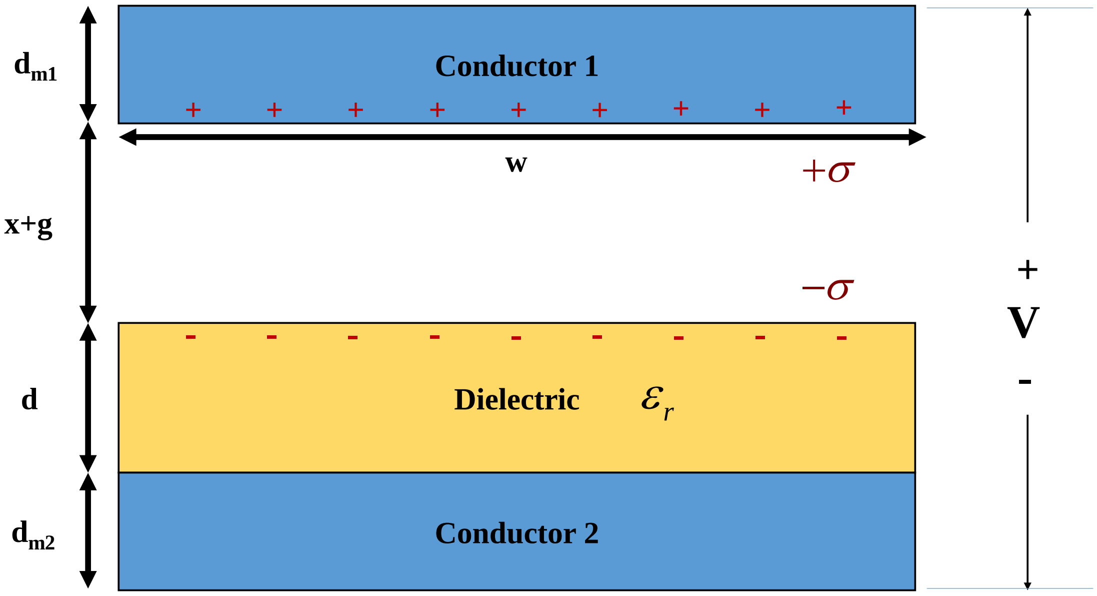


Figure 3.1 The attached electrode contact mode Conductor-to-dielectric used in COMSOL

The parameters used in COMSOL Multi-physics are shown in Table 3.1 as follows [41].

Table 3.1 Parameters used for COMSOL simulation in attached electrode contact mode conductor-to-dielectric

Parameter	Value
Width (w)	0.1 m
Length (l)	0.1 m
Thickness of the metal (d_{m1})	220 μm
Dielectric (d)	220 μm, ε_r=2
Thickness of the metal (d_{m2})	220 μm
Surface charge density (σ)	7μC/m^2
Gap (g)	100 μm
Separation vertical distance (x)	1 mm:1 mm:10 mm

The open circuit voltage and capacitance are evaluated at different separation distances (x) for both of the vertical contact mode and the lateral sliding mode. As mentioned before, the simulations are carried out by COMSOL Multi-physics (version 5.3a).

3.2.1 The relation between the open circuit voltage and the vertical separation in the attached electrode contact mode conductor-to-dielectric

Figure 3.2 shows the output open circuit voltage distribution from the COMSOL between when x=1360μm

Figure 3.2 Calculated potential distributions at the attached electrode contact mode conductor-to-dielectric when x=1360μm

Figure 3.3 shows the relation between the open circuit voltage and the vertical separation distance.

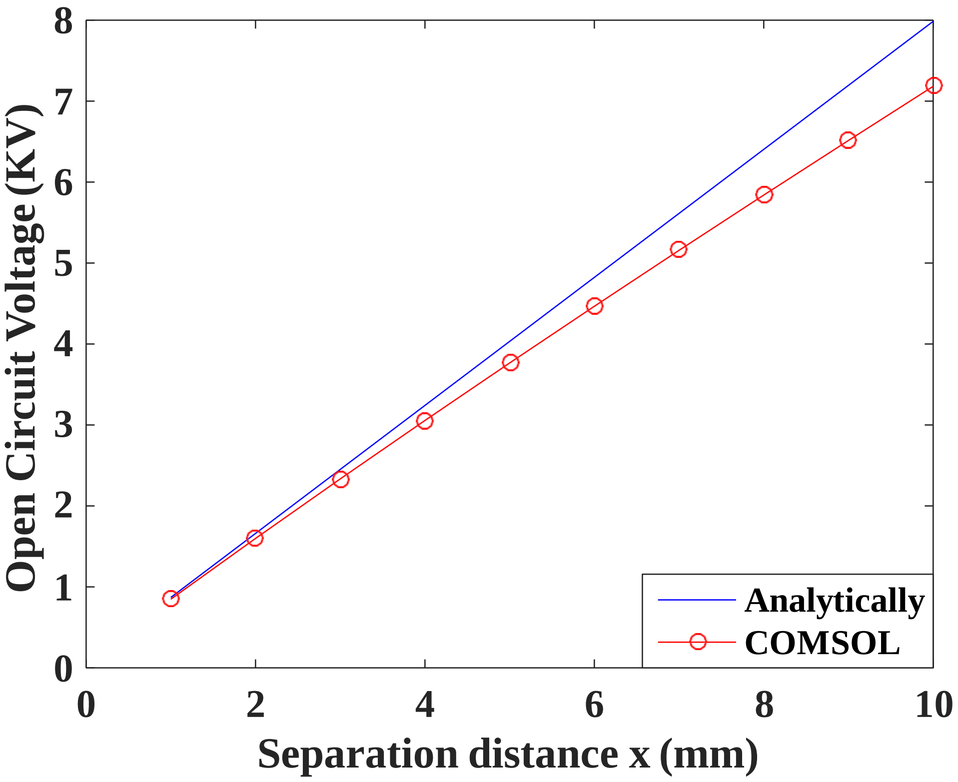


Figure 3.3 Calculated open circuit voltage at different separation distance in the Attached Electrode Contact Mode Conductor-to-dielectric

From Figure 3.3, it is clear that the open circuit voltage is directly proportional with the vertical separation distance and the average error is found to be equal to 7.27%. However, the open circuit voltage saturates at a very large separation distance in practical [41].

3.2.2 The relation between short circuit charge and the vertical separation in the Attached Electrode Contact Mode Conductor-to-dielectric

The relation between the short circuit charge and the vertical separation distance is shown in Figure 3.4.

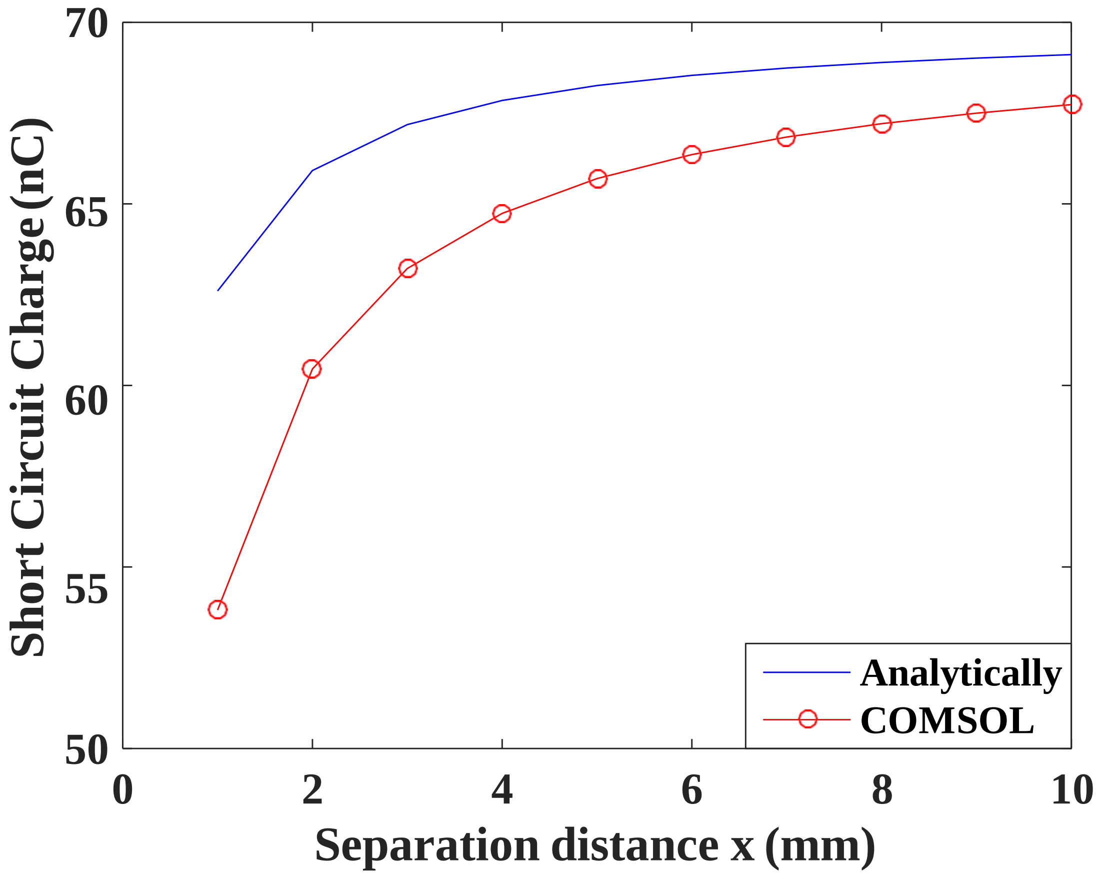


Figure 3.4 Calculated short circuit charge at different separation distance in the Attached Electrode Contact Mode Conductor-to-dielectric

From Figure 3.4, the short circuit charge is directly proportional with the vertical separation distance. The average error is found to be equal to 5.33%. However, there is saturation in the short circuit charge at a very large separation distance [41].

3.2.3 The relation between the capacitance and the vertical separation in the Attached Electrode Contact Mode Conductor-to-dielectric

Figure 3.5 shows the relation between the capacitance and the vertical separation distance.

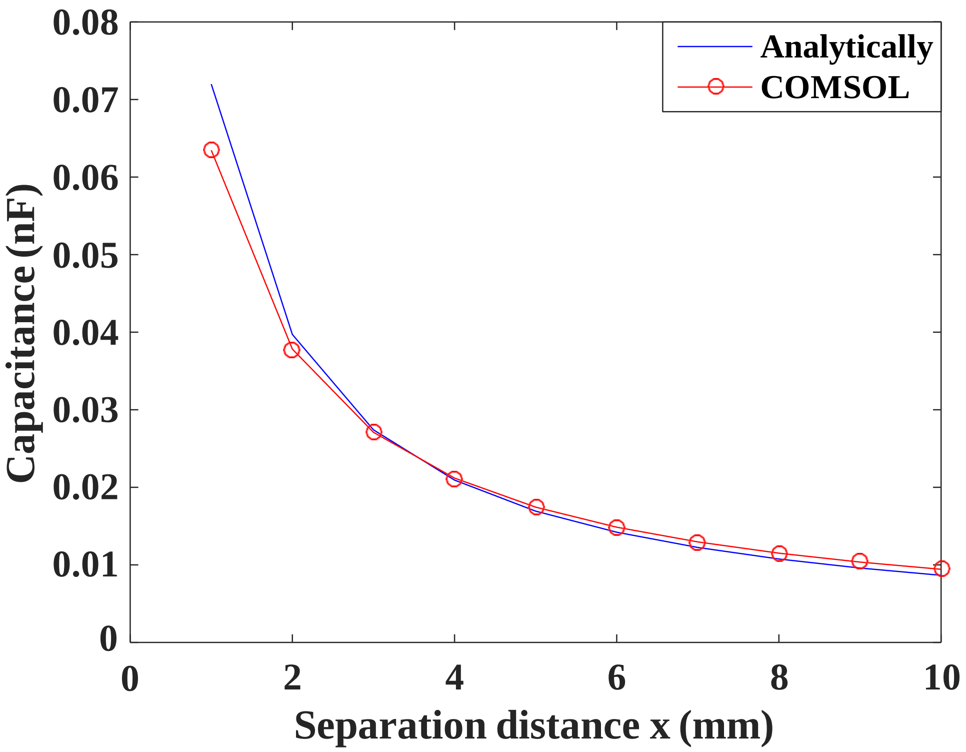


Figure 3.5 Calculated capacitance at every vertical separation distance in the Attached Electrode Contact Mode Conductor-to-dielectric

From Figure 3.5, there is a tradeoff between the capacitance and the separation distance. The greater the vertical distance, the smaller capacitance is. The mean error between the analytical and the COMSOL is found to be equal to 5.58%. Also, from Figures 3.3 and 3.5, the capacitance is inversely proportional with the open circuit voltage.

3.2.4 The relation between the energy and the vertical separation in the Attached Electrode Contact Mode Conductor-to-dielectric

Figure 3.6 shows the relation between the energy and the vertical distance.

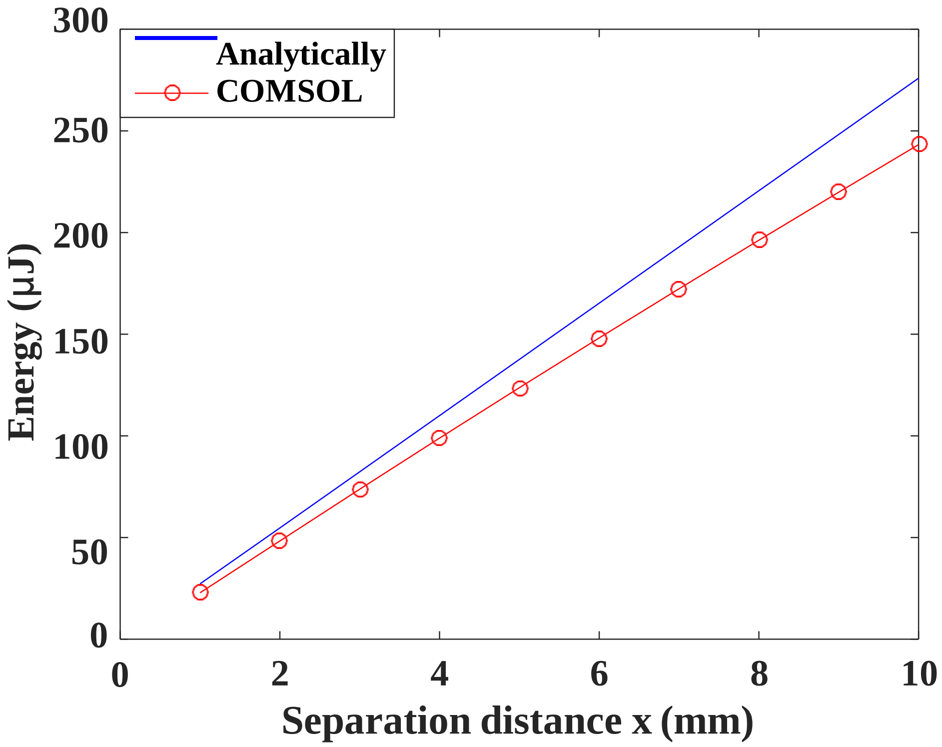


Figure 3.6 The calculated energy at different vertical separation distance in the Attached Electrode Contact Mode Conductor-to-dielectric

From Figure 3.6, the energy is directly proportional with the vertical separation distance. The average error from the analytical equation and the COMSOL is found to be 4%.

From Figures 3.3-3.6, the maximum open circuit voltage obtained from COMSOL is found to be equal to 7.2 KV, the maximum short circuit charge is found to be equal to 67 nC, the maximum capacitance is found to be equal to 63 pF, and the maximum output energy is found to be equal to 243 μJ.

3.3 Simulation results of the attached electrode contact mode dielectric-to-dielectric

The setup of the attached electrode contact mode dielectric-to-dielectric is shown in Figure 3.7.

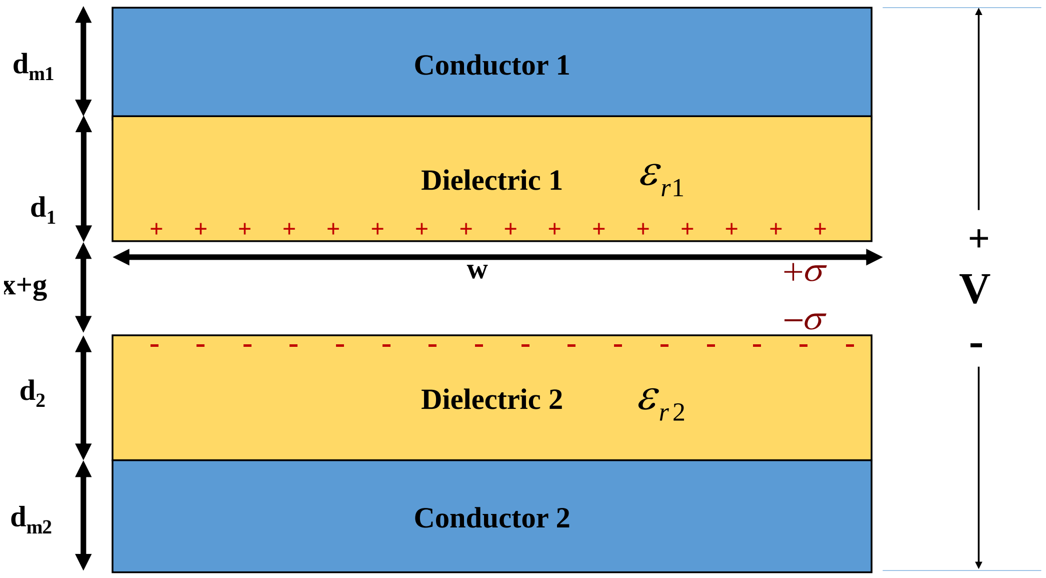


Figure 3.7 The attached electrode contact mode Dielectric-to-dielectric used in COMSOL

The open circuit voltage, short circuit charge, capacitance, and energy are calculated by MATLAB (version R2015b) and COMSOL Multiphysics with the following parameters in the Table 3.2.

Table 3.2 Parameters used for COMSOL simulation in attached electrode Contact Mode Dielectric-to-dielectric

Parameter	Value
Width (w)	0.1 m
Length (l)	0.1 m
Thickness of the metal (d_{m1})	220 µm
Dielectric 1 (d1)	220 µm, ε_{r1}=2
Dielectric 2 (d2)	220 µm, ε_{r2}=4
Thickness of the metal (d_{m2})	220 µm
Surface charge density (σ)	7µC/m^2
Gap (g)	100 µm
Separation vertical distance (x)	1mm:1mm:10mm

3.3.1 The relation between open circuit voltage and the vertical separation in the Attached Electrode Contact Mode Dielectric-to-dielectric

Figure 3.8 shows the distribution of the open circuit voltage from COMSOL.

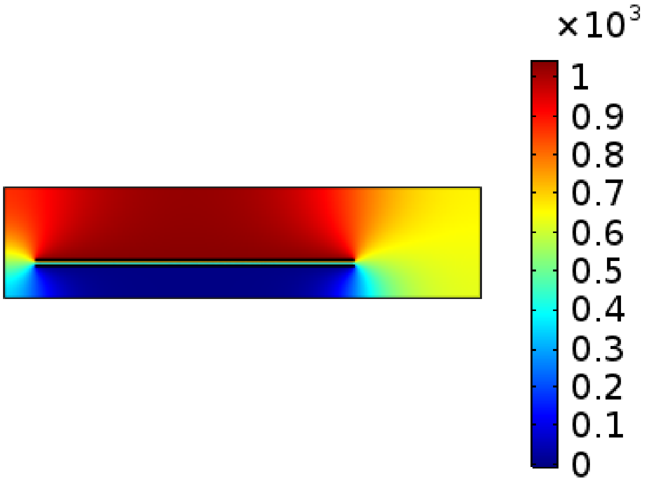


Figure 3.8 Calculated potential distributions at the attached electrode contact mode dielectric-to-dielectric when x=1360µm

Figure 3.9 shows the calculated open circuit voltages at different separation vertical distances.

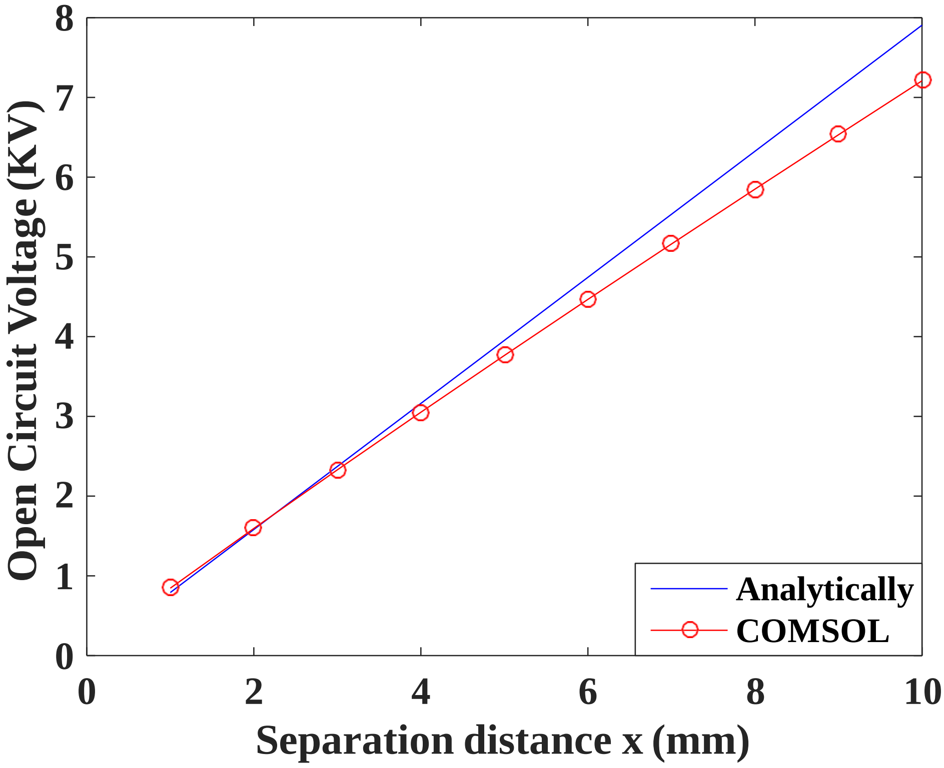


Figure 3.9 The calculated open circuit voltage at different separation vertical distances in the attached electrode contact mode dielectric-to-dielectric

From Figures 3.3 and 3.9, the open circuit voltage in the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric is the same because the open circuit voltage does not depend on the thickness of the dielectric.

3.3.2 The relation between short circuit charge and the vertical separation in the Attached Electrode Contact Mode Dielectric-to-dielectric

The relation between the short circuit charge and the vertical separation distance is shown in Figure 3.10.

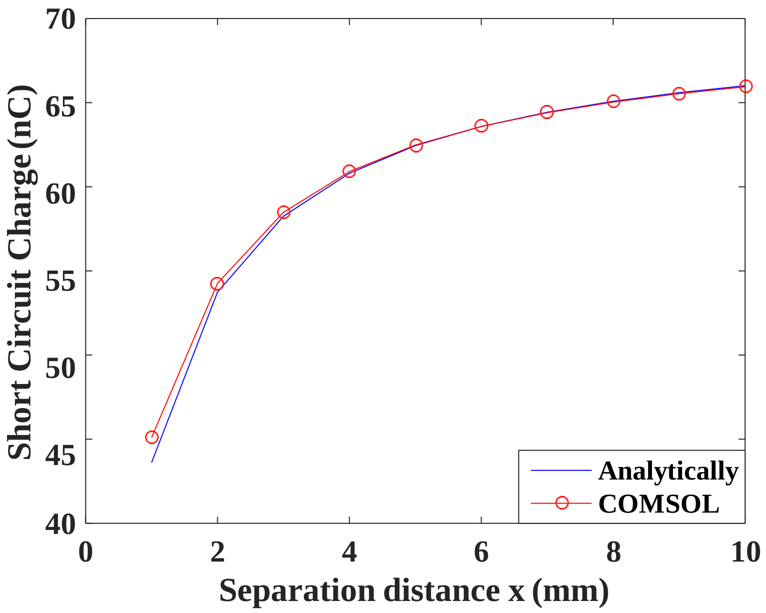


Figure 3.10 The calculated short circuit charge at different separation vertical distances at the attached electrode contact mode dielectric-to-dielectric

From Figure 3.10, it is obvious that the short circuit charge is directly proportional with the separation distance in the attached electrode dielectric-to-dielectric. From Figures 3.4 and 3.10, the short circuit charge in case of dielectric-to-dielectric is less than that in case of conductor-to-dielectric due to the effect of the 2 dielectric thicknesses.

3.3.3 The relation between capacitance and the Vertical Separation in the Attached Electrode Contact Mode Dielectric-to-dielectric

Figure 3.11 shows the relation between the calculated capacitance and the vertical separation distance.

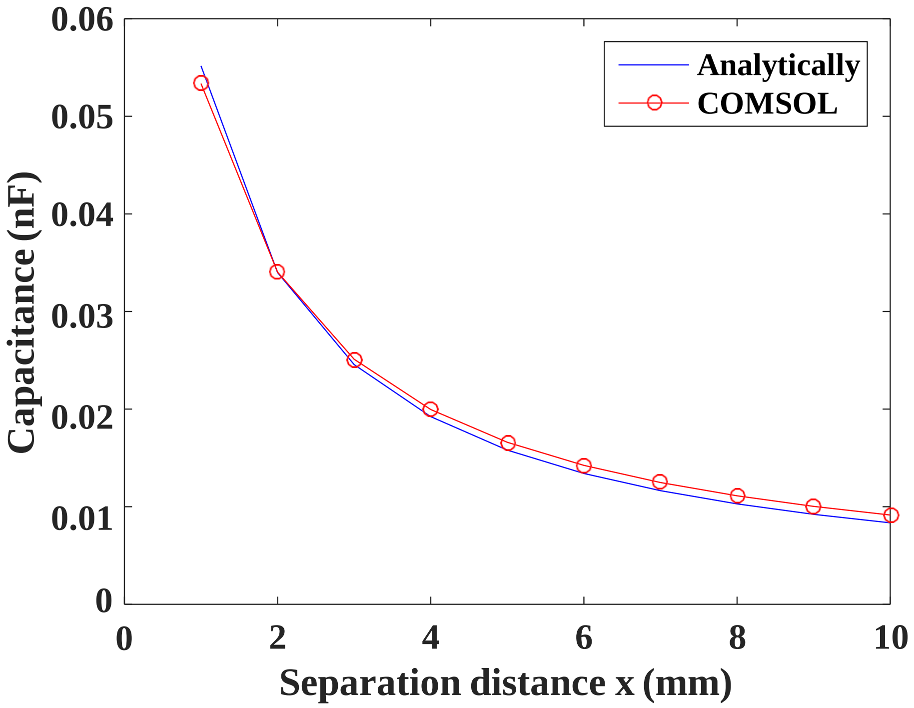


Figure 3.11 The calculated capacitance at every vertical separation vertical distances at the attached electrode contact mode dielectric-to-dielectric

The capacitance in case of the attached electrode dielectric-to-dielectric is less than that in case of the attached electrode conductor-to-dielectric since due to the dielectric thickness (i.e. the larger the dielectric thickness (d), the smaller the capacitance value).

3.3.4 The relation between the energy and the Vertical separation in the Attached Electrode Contact Mode Dielectric-to-dielectric

Figure 3.12 shows the relation between the output energy from the TENG and the vertical separation distance in the attached electrode contact mode dielectric-to-dielectric.

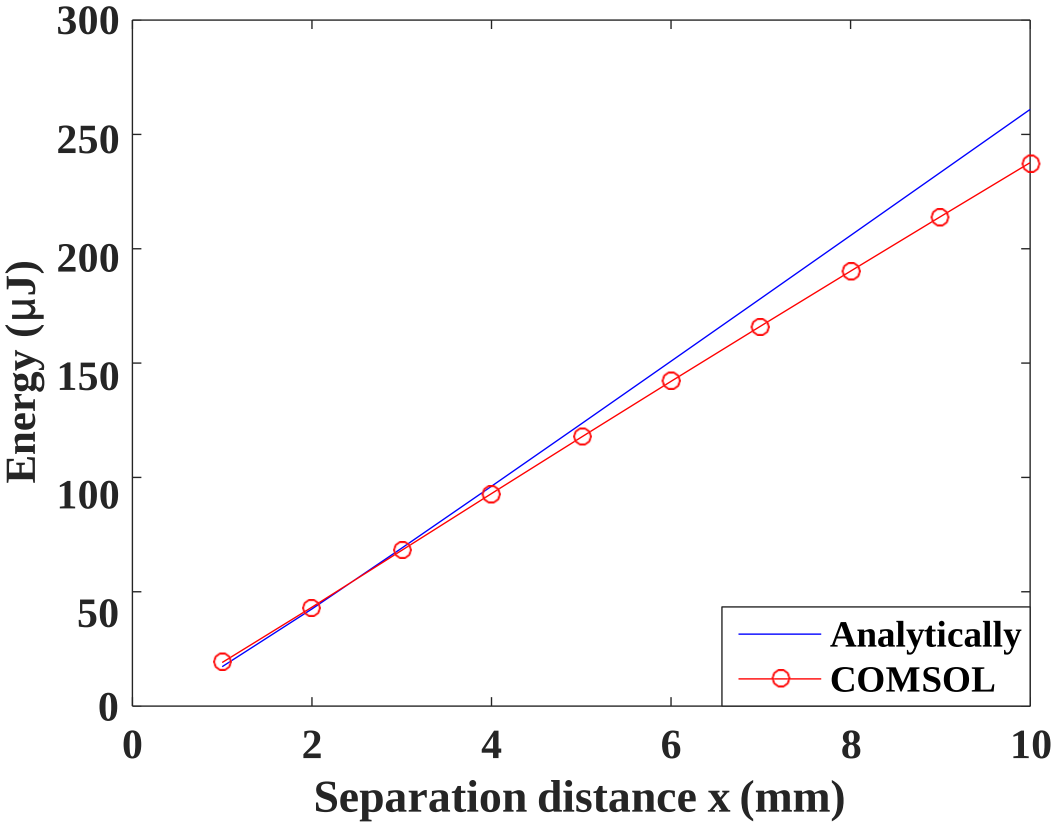


Figure 3.12 The calculated output energies at different vertical separation distance in the attached electrode contact mode dielectric-to-dielectric

From Figures 3.9-3.12, the maximum open circuit voltage obtained from COMSOL is found to be equal to 7.2 kV, the maximum short circuit charge is found to be equal to 66 nC, the maximum capacitance is found to be equal to 53 pF, and the maximum output energy is found to be equal to 238 µJ.

3.3.5 Effect of certain parameters on the output of the attached electrode contact mode

To summarize the difference between the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric, the following parameters effects have to be investigated. These parameters are the effect of the dielectric thickness (d), the conductor thickness (dm), and the relative permittivity of the material (εr).These parameters are studied from the equations of the attached electrode contact mode and from the previous Figures. The effect of the parameters on the output of the TENG (the open circuit voltage, the short circuit charge, the capacitance, and the energy) is shown in Table 3.3.

Table 3.3 Effect of parameters on the TENG output

Parameter	Open Circuit voltage	Short circuit charge	Capacitance	Energy
d	Independent	Inversely proportional	Inversely proportional	Inversely proportional
d_m	Independent	Inversely proportional	Inversely proportional	Inversely proportional
ε_r	Independent	Directly proportional	Directly proportional	Directly proportional

3.4. Comparison between the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric

In this study, a comparison between the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric has been conducted. A complete comparison between the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric regarding to the open circuit voltage, short circuit charge, capacitance, and energy is shown in Table 3.4.

Table 3.4 Comparison between the maximum output paramters of the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric

Point of comparison	Attached electrode contact mode Conductor-to-dielectric	Attached electrode contact mode Dielectric-to-dielectric
Open Circuit voltage	7.2 KV	7.2 KV
Short Circuit Charge	67 nC	66 nC
Capacitance	63 pF	53 pF
Energy	243 µJ	238 µJ

3.5. Simulation results of the attached electrode sliding mode conductor-to-dielectric

The setup of the lateral sliding mode TENG conductor-to-dielectric setup is shown in Figure 3.13, with the terminal denoted as V.

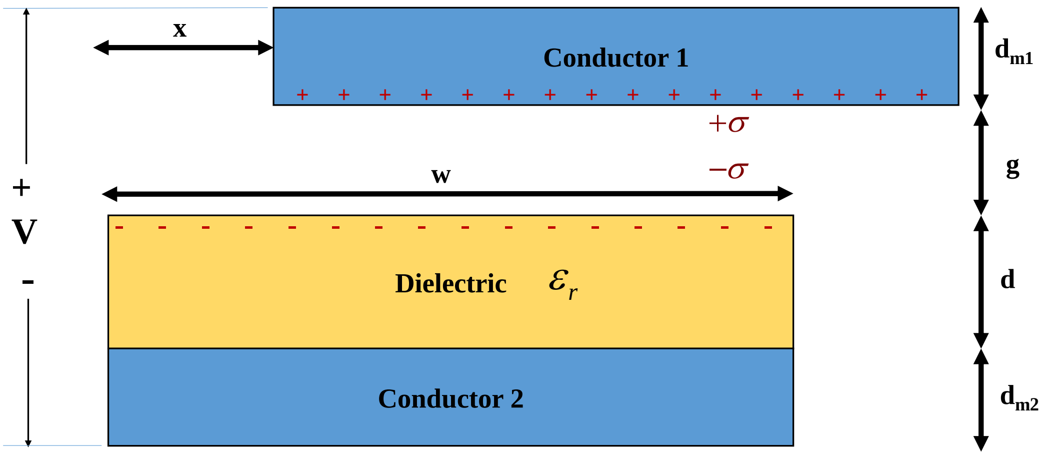


Figure 3.13 The attached electrode sliding mode conductor-to-dielectric used in COMSOL

The FEM calculation used in COMSOL is shown in Table 3.5. The parameters used in the attached electrode TENG sliding mode are the same at that in the attached electrode TENG contact mode. An open circuit voltage, short circuit charge, capacitance and output energy are calculated with change in the lateral separation (x) in the attached electrode sliding mode conductor-to-dielectric. The open circuit voltage, the short circuit charge, the capacitance, and the energy are calculated as before.

Table 3.5 Parameters used in COMSOL in the attached electrode sliding mode conductor-to-dielectric

Parameter	Value
Width (w)	0.1 m
Length (l)	0.1 m
Conductor thickness (d_m)	220 µm
Dielectric thickness (d)	220 µm
Gap (g)	100 µm
Surface charge density (σ)	7 µC/m^2
Lateral distance (x)	1mm:1mm:10mm

3.5.1 The relation between the open circuit voltage and the lateral separation in the attached electrode sliding mode conductor-to-dielectric

Figure 3.14 shows the relation between the lateral separation and the open circuit voltage.

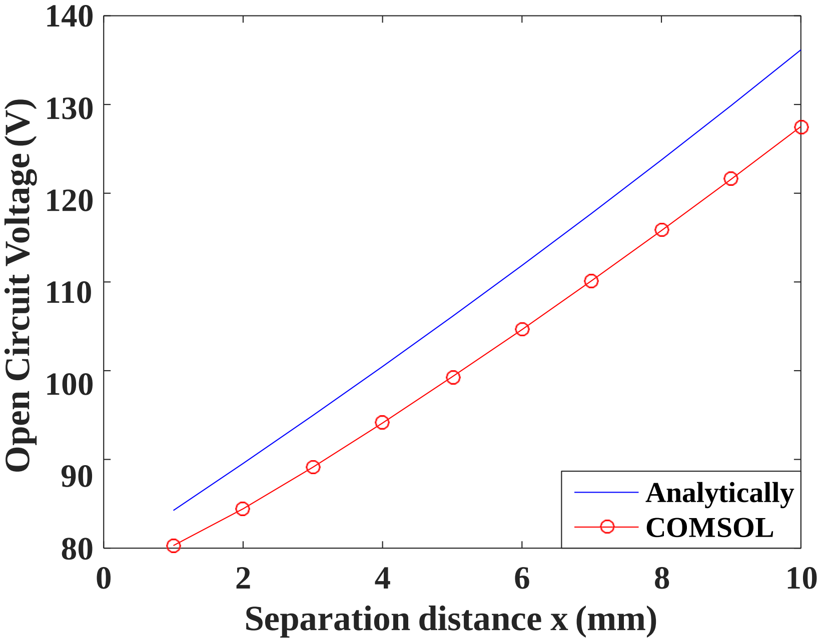


Figure 3.14 The calculated open circuit voltages at different lateral separation distances in the attached electrode sliding mode conductor-to-dielectric

3.5.2 The relation between the short circuit charge and the lateral separation in the attached electrode sliding mode conductor-to-dielectric

Figure 3.15 shows the relation between the lateral separation and the short circuit charge.

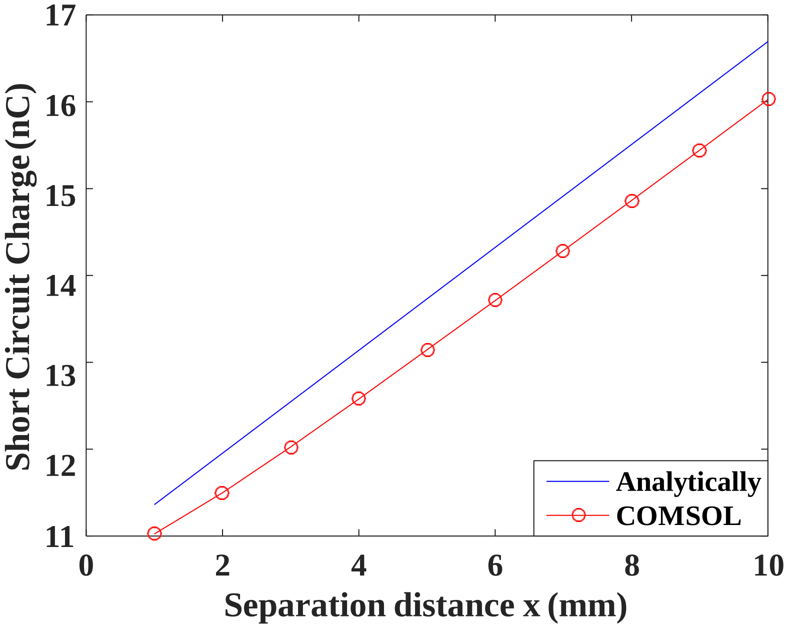


Figure 3.15 The calculated short circuit charges at different lateral separation distances in the attached electrode sliding mode conductor-to-dielectric

3.5.3 The relation between capacitance and the lateral separation in the attached electrode sliding mode conductor-to-dielectric

Figure 3.16 shows the relation between the lateral separation and the capacitance.

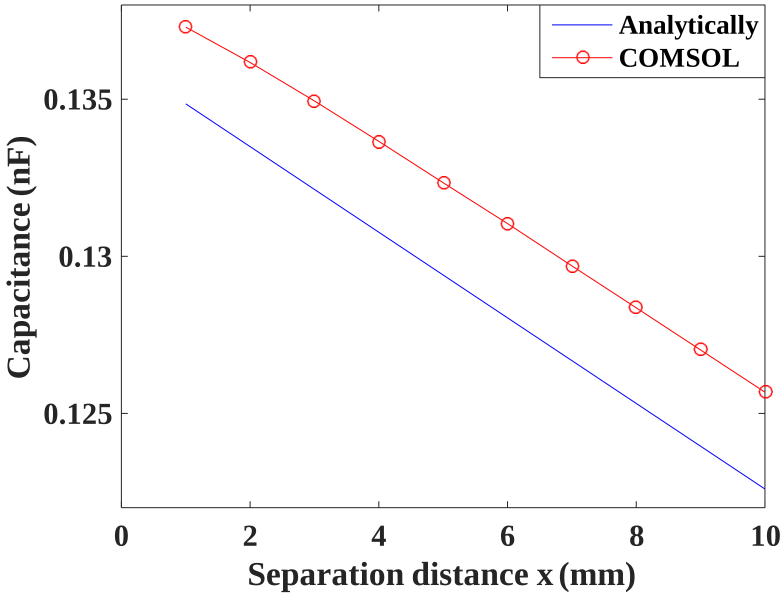


Figure 3.16 The calculated capacitances at different lateral separation distances in the attached electrode sliding mode conductor-to-dielectric

3.5.4 The relation between the energy and the lateral separation in the attached electrode sliding mode conductor-to-dielectric

Figure 3.17 shows the relation between the lateral separation and the output energy.

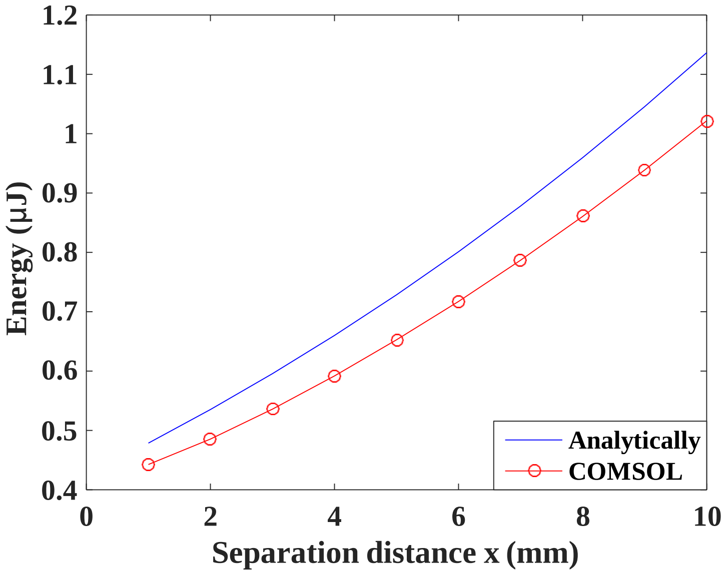


Figure 3.17 The calculated output energies at different lateral separation distances in the attached electrode sliding mode conductor-to-dielectric

From Figures 3.14-3.17, the maximum open circuit voltage obtained from COMSOL is found to be equal to 127.5 V, the maximum short circuit charge is found to be equal to 16 nC, the maximum capacitance is found to be equal to 137 pF, and the maximum output energy is found to be equal to 1.02 µJ.

3.6. Simulation results of the attached electrode sliding mode dielectric-to-dielectric

The setup of the lateral sliding mode TENG dielectric-to-dielectric setup is shown in Figure 3.18, with the terminal denoted as V.

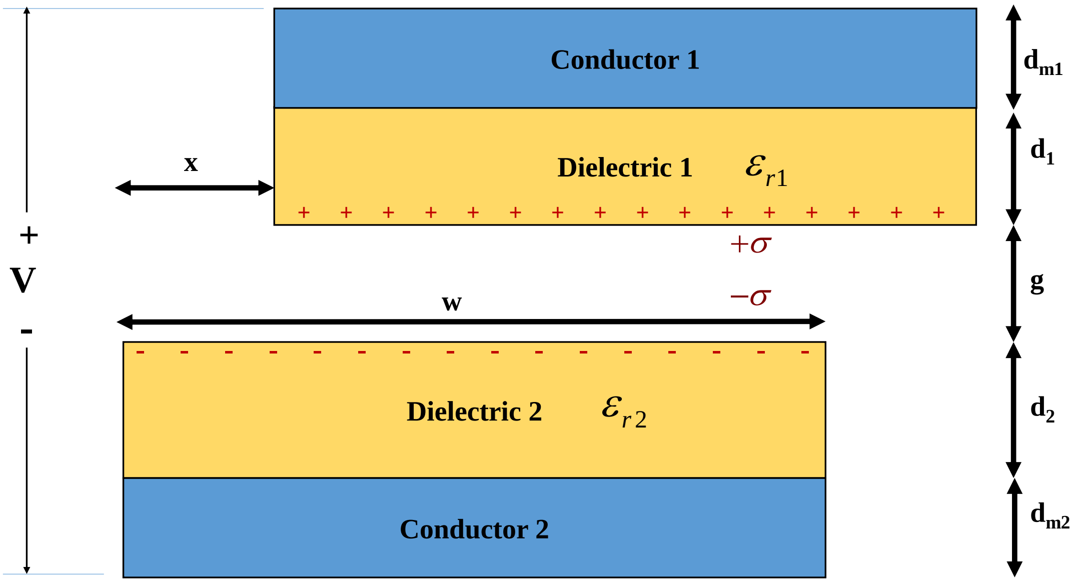


Figure 3.18 The attached electrode sliding mode dielectric-to-dielectric used in COMSOL

The parameters used in the attached electrode sliding mode dielectric-to-dielectric for COMSOL simulation are shown in Table 3.6 to calculate the open circuit voltage, short circuit charge, capacitance, and output energy.

Table 3.6 Parameters used in COMSOL in the attached electrode sliding mode conductor-to-dielectric

Parameter	Value
Width (w)	0.1 m
Length (l)	0.1 m
Conductor thickness (d_m)	220 µm
Dielectric thickness (d_1)	220 µm
Dielectric thickness (d_2)	220 µm
Gap (g)	100 µm
Surface charge density (σ)	7 $\mu C/m^2$
Lateral distance (x)	1mm:1mm:10 mm

3.6.1 The relation between the open circuit voltage and the lateral separation in the attached electrode sliding mode dielectric-to-dielectric

Figure 3.19 shows the relation between the lateral separation and the open circuit voltage analytically using the MATLAB and COMSOL.

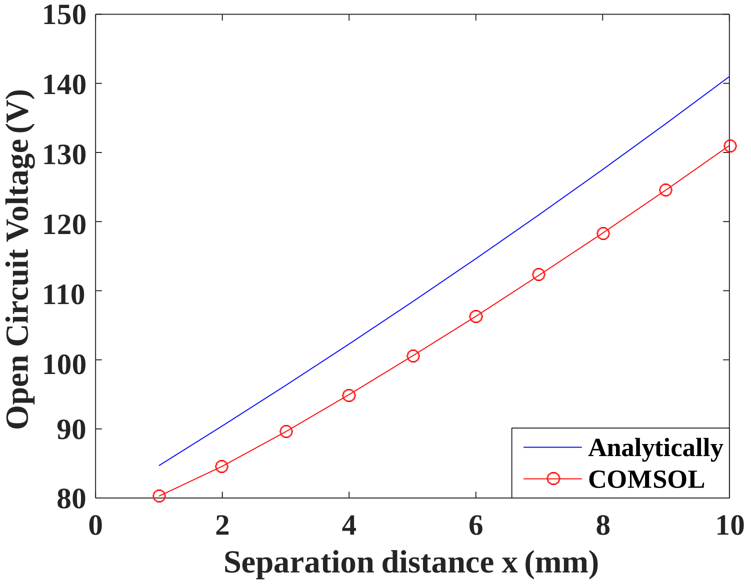


Figure 3.19 Calculated open circuit voltages at different lateral separation distances in the attached electrode sliding mode Dielectric-to-dielectric

3.6.2 The relation between the short circuit charge and the lateral separation in the attached electrode sliding mode dielectric-to-dielectric

Figure 3.20 shows the relation between the lateral separation and the short circuit charge analytically using the MATLAB and COMSOL.

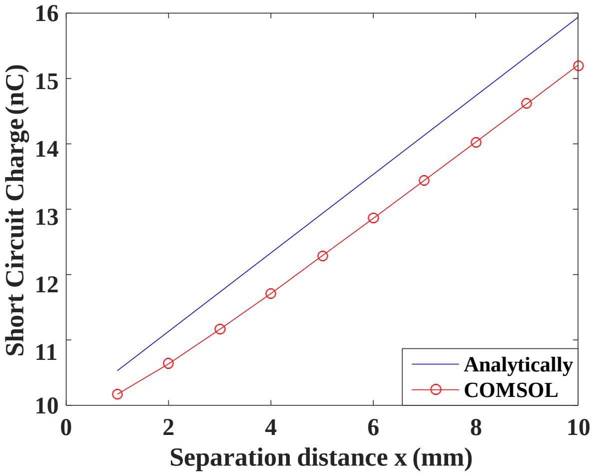


Figure 3.20 The calculated short circuit charges at different lateral separation distances in the attached electrode sliding mode dielectric-to-dielectric

3.6.3 The relation between the capacitance and the lateral separation in the attached electrode sliding mode dielectric-to-dielectric

Figure 3.21 shows the relation between the lateral separation and the capacitance analytically using the MATLAB and COMSOL.

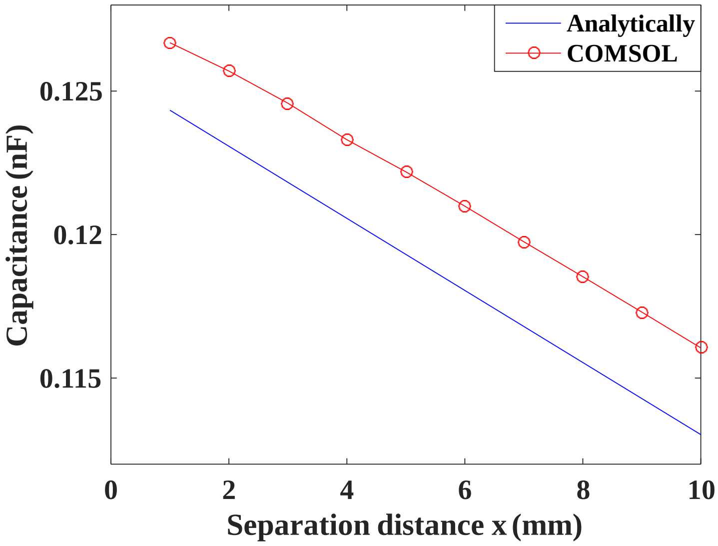


Figure 3.21 The calculated capacitances at different lateral separation distances at the attached electrode sliding mode dielectric-to-dielectric

3.6.4 The relation between the energy and the lateral separation in the attached electrode sliding mode dielectric-to-dielectric

Figure 3.22 shows the relation between the lateral separation and the output energy analytically using the MATLAB and COMSOL.

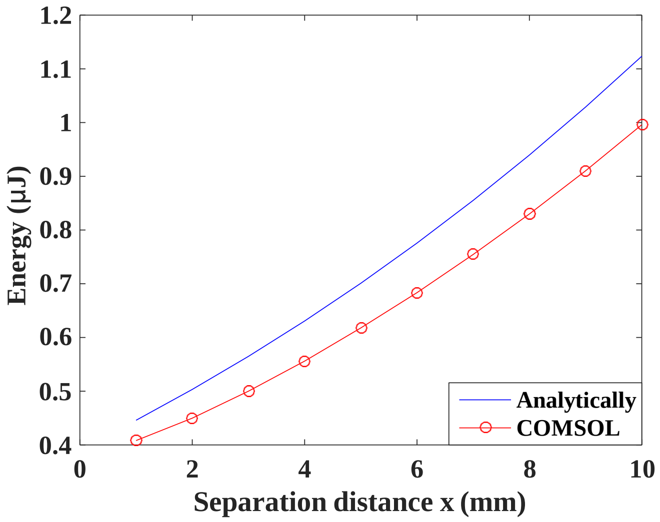


Figure 3.22 The calculated output energies at different lateral separation distances at the attached electrode sliding mode dielectric-to-dielectric

From Figures 3.19-3.22, the maximum open circuit voltage obtained from COMSOL is found to be equal to 131.5 V, the maximum short circuit charge is found to be equal to 15 nC, the maximum capacitance is found to be equal to 13 pF, and the maximum output energy is found to be equal to 0.99µJ.

3.7. Effect of the air gap on the attached electrode sliding mode

The sliding mode proposed in [38] is assumed to have zero gap. The gap between the 2 electrodes has been studied physically by using COMSOL Multiphysics and analytically using the MATLAB. The increase in the gap leads to the increase in the open circuit voltage and decrease in the short circuit charge. Also, the equation of the open circuit voltage of the attached electrode sliding mode (2.6) can be modified by the following equation:

$$V_{oc} = \frac{\sigma x (d_0 + g)}{\varepsilon_0 (w - x)} + \frac{\sigma g}{\varepsilon_0} \tag{3.1}$$

The capacitance equation (2.7) can by modified by the following equation:

$$Cap = \frac{\varepsilon_0 l (w - x)}{d_0 + g} \tag{3.2}$$

From (3.1) and (3.2), it is clear that the gap (g) is directly proportional with the open circuit voltage but inversely proportional with the capacitance.

3.7.1 Effect of air gap on the attached electrode sliding mode conductor-to-dielectric output parameters

The gap has a great effect on the attached electrode sliding mode since the increase in the gap leads to an increase in the open circuit voltage (i.e. the gap is directly proportional to the open circuit voltage). From (3.1) and (3.2), the gap is inversely proportional to the capacitance. Figures 3.23-3.26 show the relation between the effect of gap on the open circuit voltage, short circuit charge, capacitance, and output energy respectively at the attached electrode sliding mode conductor-to-dielectric.

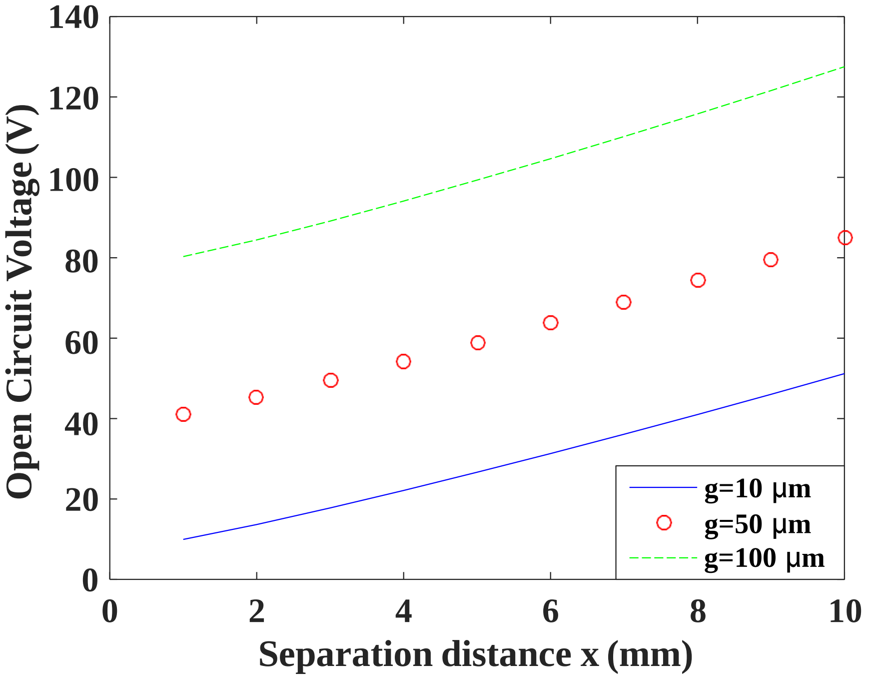


Figure 3.23 Impact of gap on the open circuit voltage in the attached electrode sliding mode conductor to dielectric

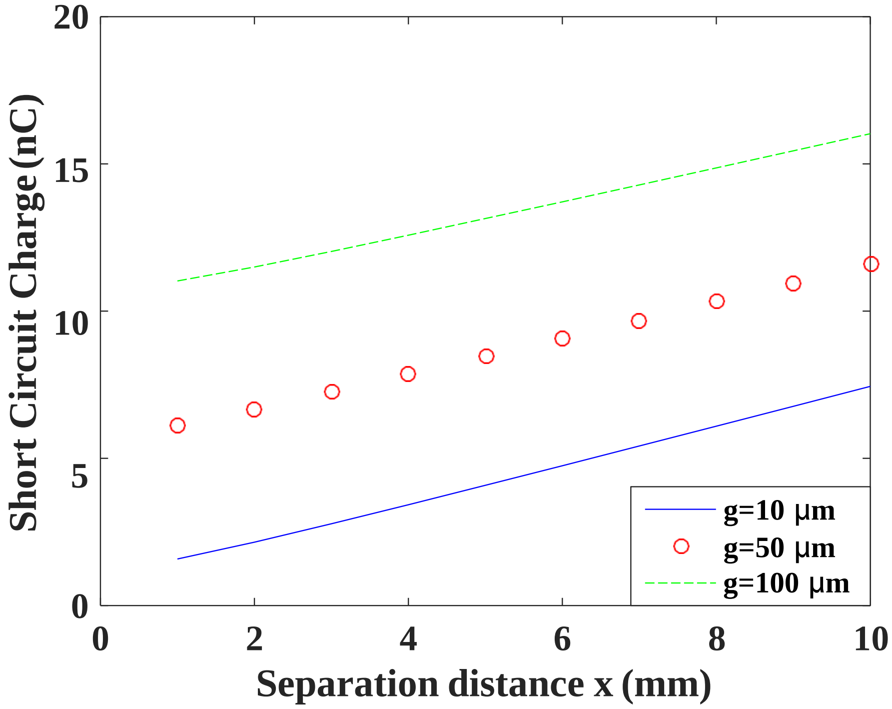


Figure 3.24 Impact of gap on the short circuit charge in the attached electrode sliding mode conductor-to-dielectric

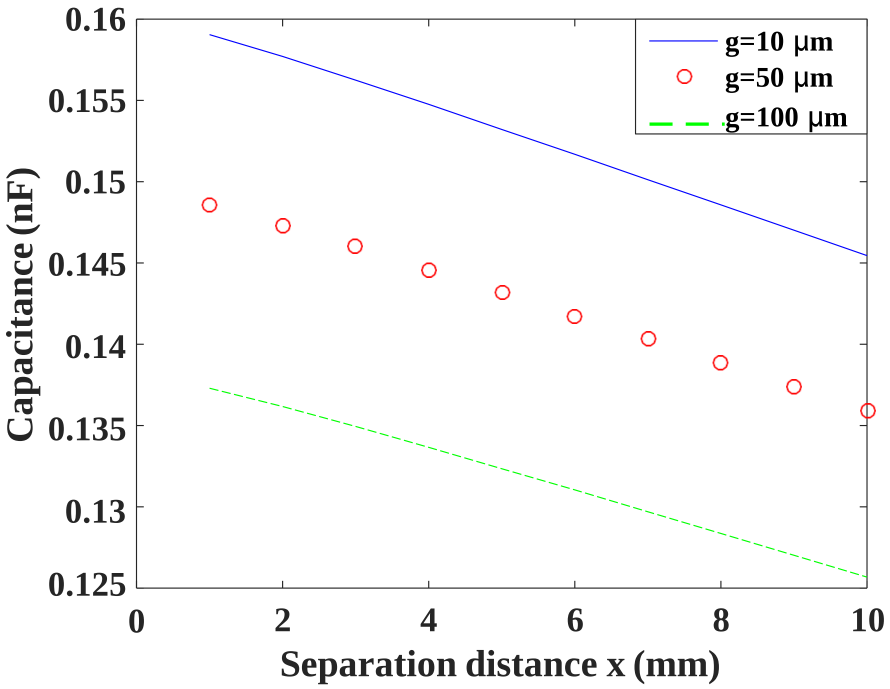


Figure 3.25 Impact of gap on the capacitance in the attached electrode sliding mode conductor to dielectric

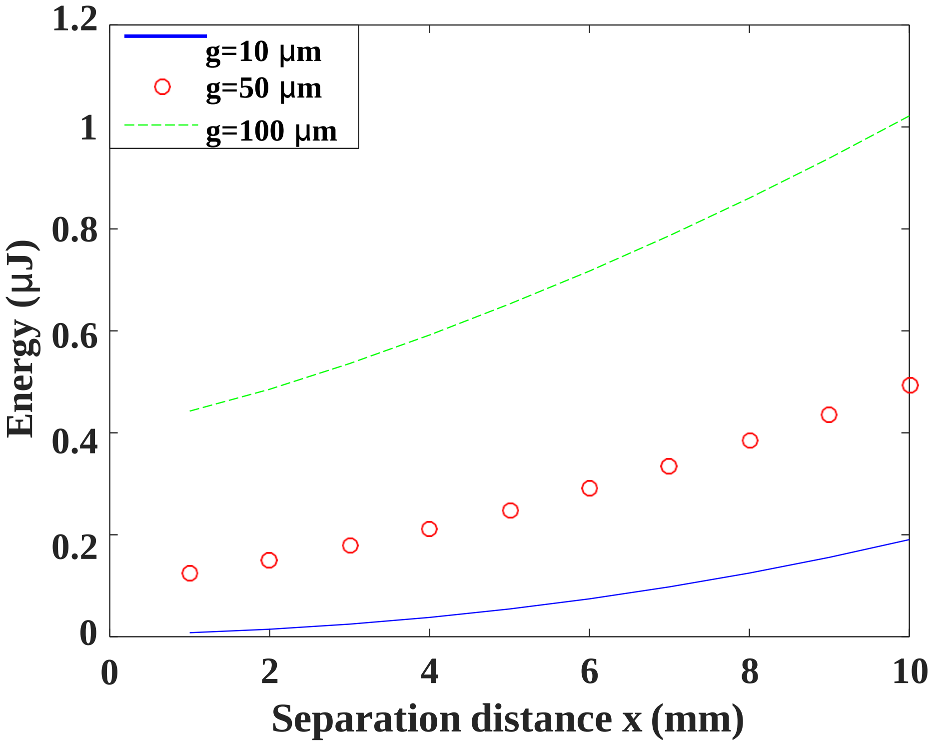


Figure 3.26 Impact of gap on the output energy in the attached electrode sliding mode conductor to dielectric

3.7.2 Effect of air gap on the attached electrode sliding mode dielectric-to-dielectric output parameters

The gap in the sliding mode dielectric-to-dielectric has the same effect as in the sliding mode conductor-to-dielectric. However, in dielectric-to-dielectric, when the gap increases, the open circuit voltage increases significantly due to the effect of the dielectric thickness. Figures 3.27-3.30 show the effect of the gap on the TENG outputs.

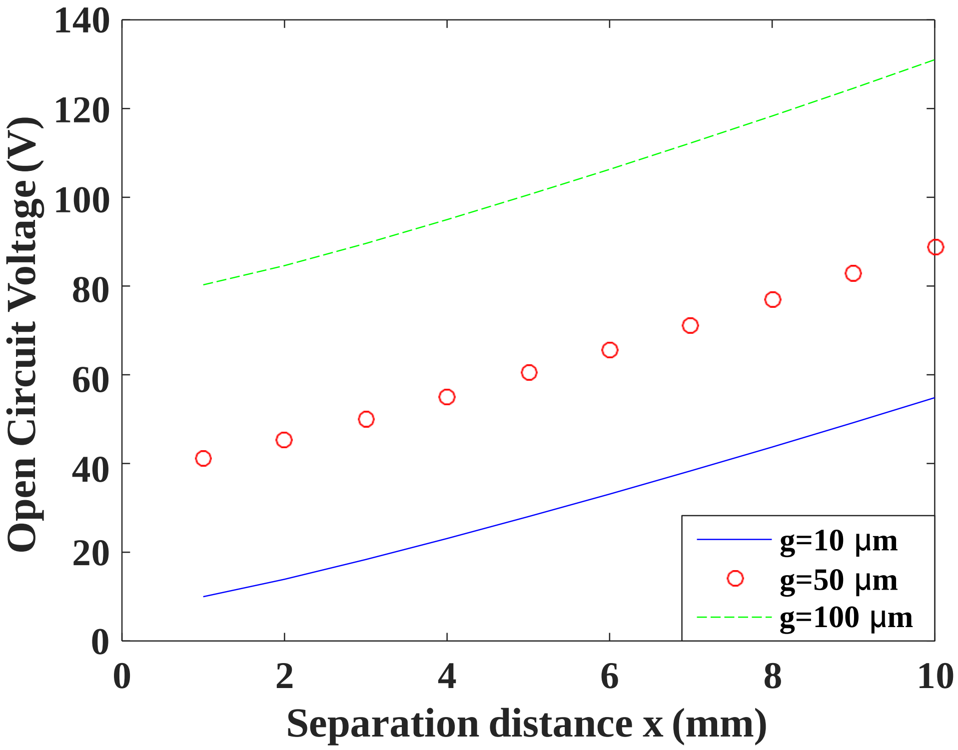


Figure 3.27 Impact of gap on the open circuit voltage in the attached electrode sliding mode dielectric to dielectric

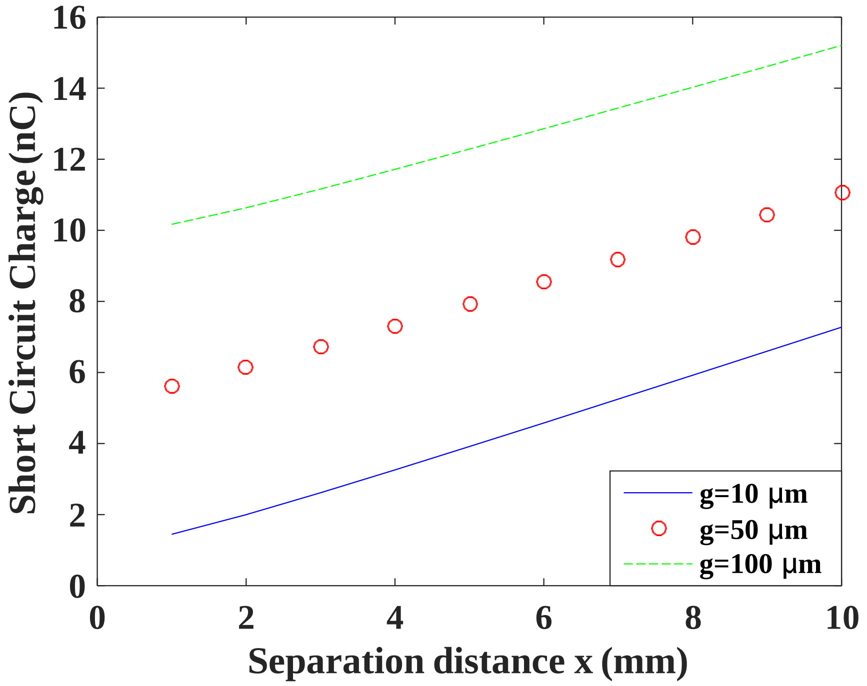


Figure 3.28 Impact of gap on the short circuit charge in the attached electrode sliding mode dielectric to dielectric

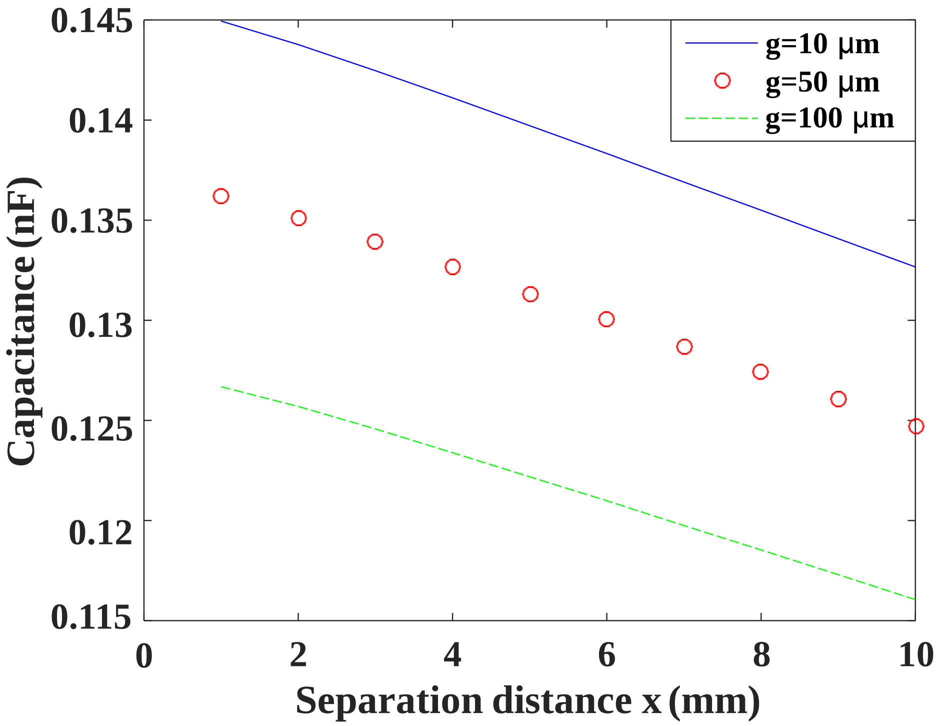


Figure 3.29 Impact of gap on the capacitance in the attached electrode sliding mode dielectric to dielectric

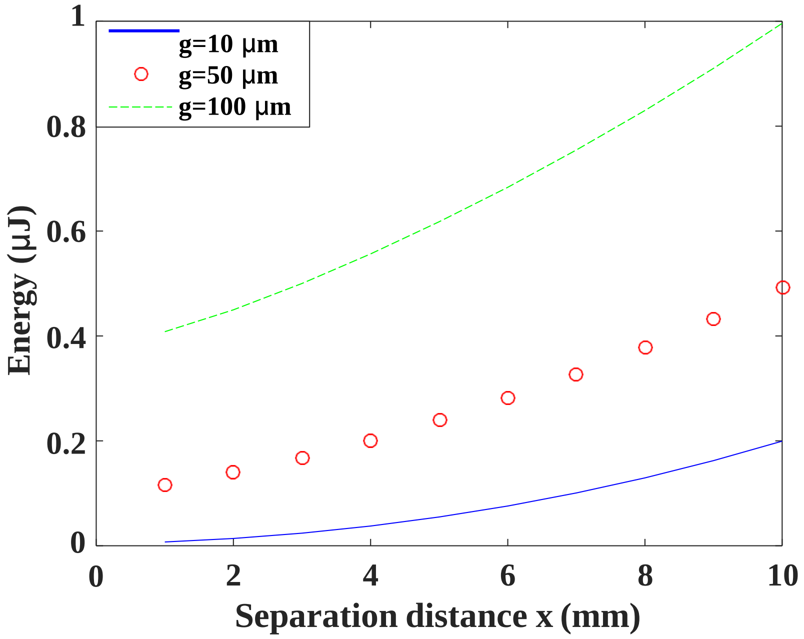


Figure 3.30 Impact of gap on the output energy in the attached electrode sliding mode dielectric to dielectric

From Figures 3.23-3.30, it is clear that the open circuit voltage and output energy when the gap is equal to 100µm at the attached electrode sliding mode dielectric-to-dielectric is greater than that in the sliding mode conductor-to-dielectric due to the effect of the dielectric thickness, while the capacitance and the short circuit charge in the dielectric-to-dielectric type are less than that in the conductor-to-dielectric.

3.8. Effect of the Metal Thickness on the attached Electrode Sliding mode

The sliding mode is assumed to have a very small metal thickness compared to the dielectric thickness. The electrode thickness has been studied physically by using COMSOL Multiphysics and analytically using the MATLAB. Also, the metal thickness has the same effect as the gap on the open circuit voltage and capacitance.

So, the open circuit voltage equation (3.1) can be modified by:

$$V_{oc} = \frac{\sigma x (d_0 + g + 2 * d_m)}{\varepsilon_0 (w - x)} + \frac{\sigma g}{\varepsilon_0} \tag{3.3}$$

The capacitance equation (3.2) can be modified by the following equation:

$$Cap = \frac{\varepsilon_0 l (w - x)}{d_0 + g + 2 * d_m} \tag{3.4}$$

From (3.3) and (3.4), the metal thickness (dm) has an effect on both of the open circuit voltage and on the capacitance.

3.8.1 Effect of the metal thickness on the attached electrode sliding mode conductor-to-dielectric

The metal thickness has the same effect as the gap. The increase in the metal thickness leads to an increase in the open circuit voltage and the output energy but a decrease in the short circuit charge, capacitance, and output energy at large gaps. Figures 3.31-3.34 show the relation between the metal thickness and the TENG output parameters when the gap is equal 100 μm.

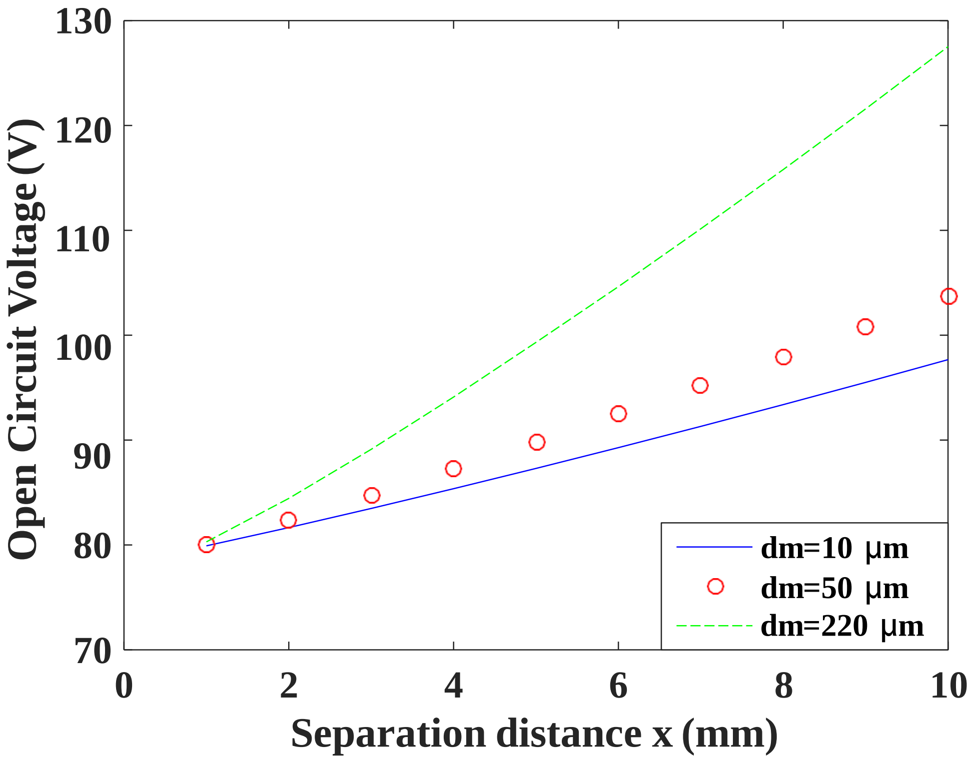


Figure 3.31 Impact of the conductor thickness on the open circuit voltage in the attached electrode sliding mode conductor to dielectric

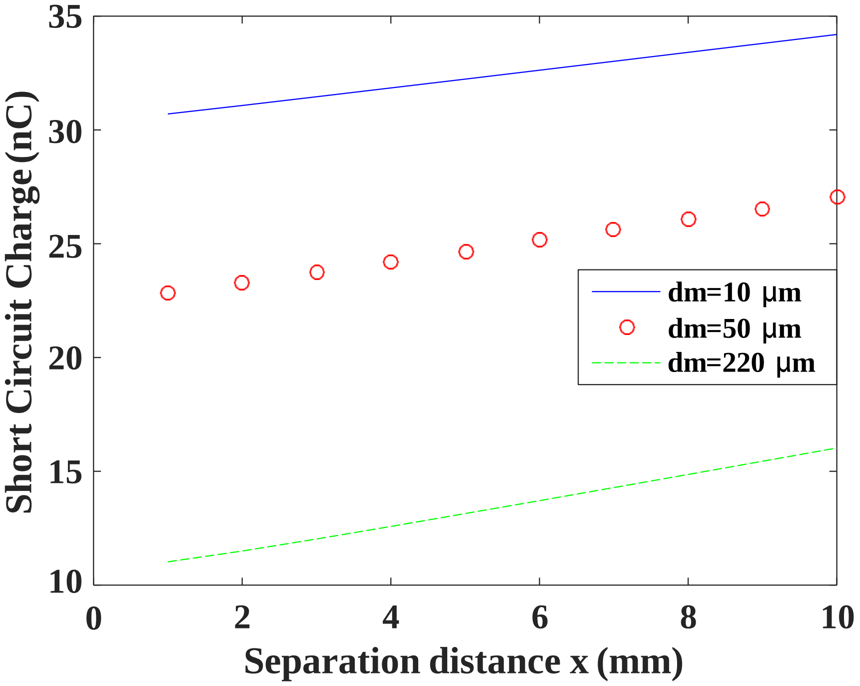


Figure 3.32 Impact of the conductor thickness on the short circuit charge in the attached electrode sliding mode conductor to dielectric

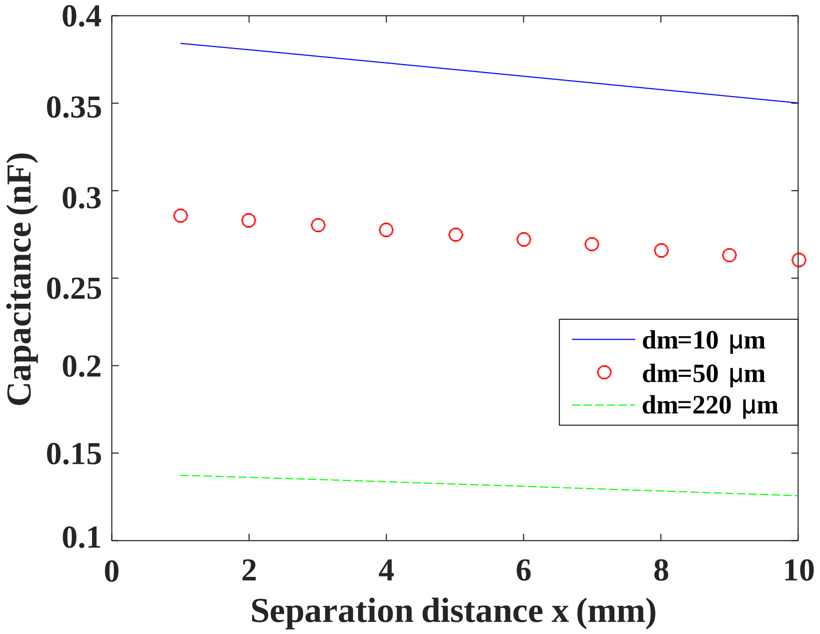


Figure 3.33 Impact of the conductor thickness on the capacitance in the attached electrode sliding mode conductor to dielectric

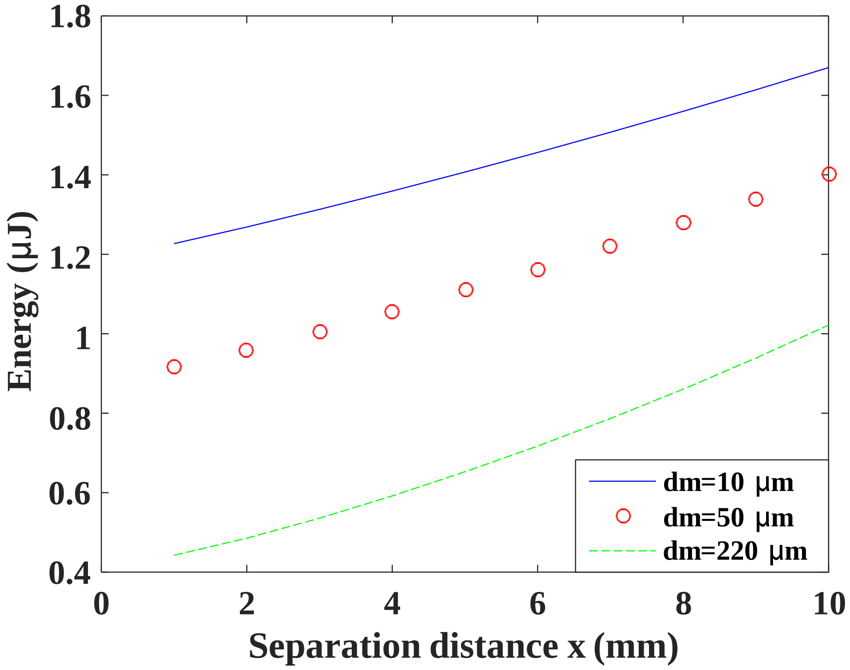


Figure 3.34 Impact of the conductor thickness on the output energy in the attached electrode sliding mode conductor-to-dielectric

When the gap is small, the increase in the conductor thickness leads to an increase in output energy as shown in Figure 3.35 because the dielectric comes out of the electric field.

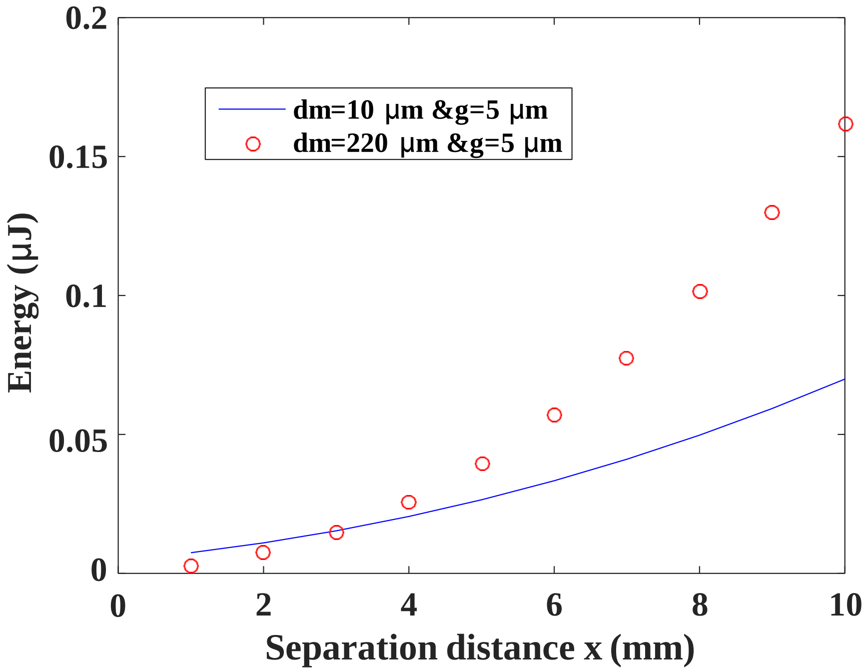


Figure 3.35 Impact of the conductor thickness on the output energy in the attached electrode sliding mode conductor-to-dielectric at small gap

3.8.2 Effect of the metal thickness on the attached electrode sliding mode dielectric-to-dielectric

The metal thickness in the attached electrode sliding mode dielectric-to-dielectric has the same effect as that in the attached electrode sliding mode conductor-to-dielectric. Figures 3.36- 3.39 show the effect of the conductor thickness on the open circuit voltage, the short circuit charge, the capacitance, and the output energy.

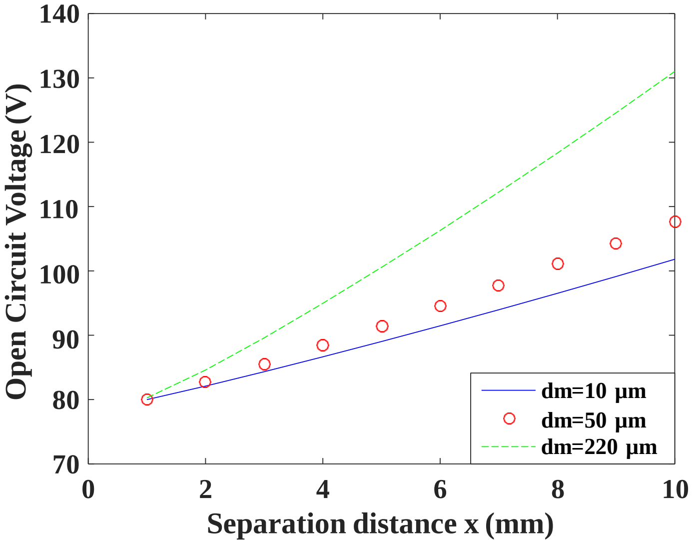


Figure 3.36 Impact of the conductor thickness on the open circuit voltage in the attached electrode sliding mode dielectric to dielectric

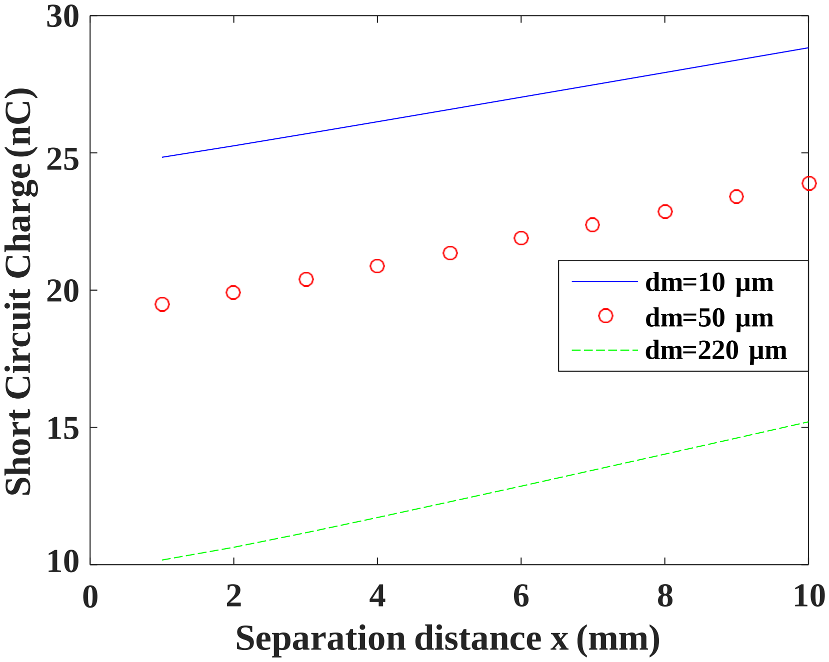


Figure 3.37 Impact of the conductor thickness on the short circuit charge in the attached electrode sliding mode dielectric-to-dielectric

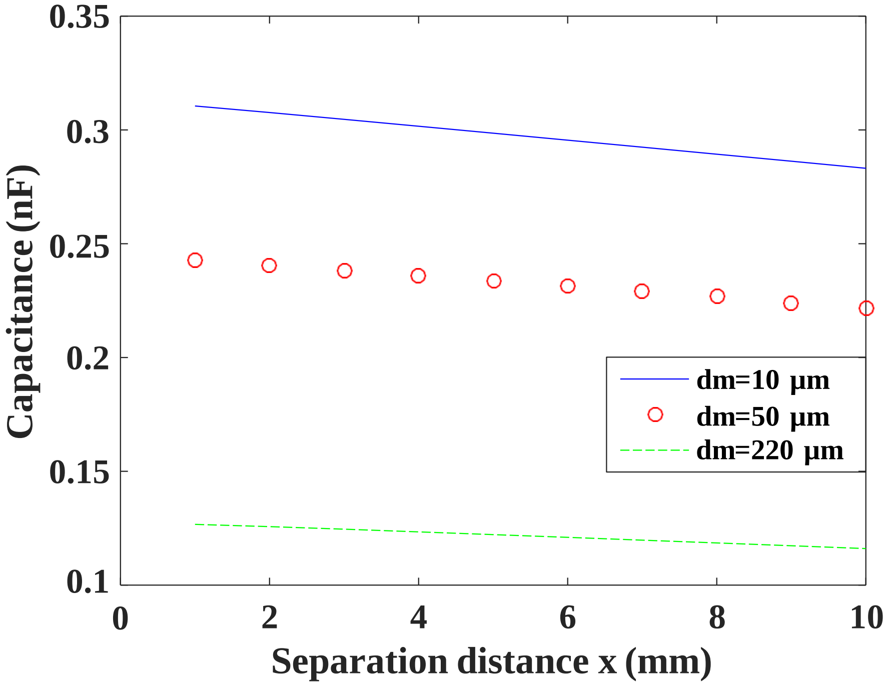


Figure 3.38 Impact of the conductor thickness on the capacitance in the attached electrode sliding mode dielectric-to-dielectric

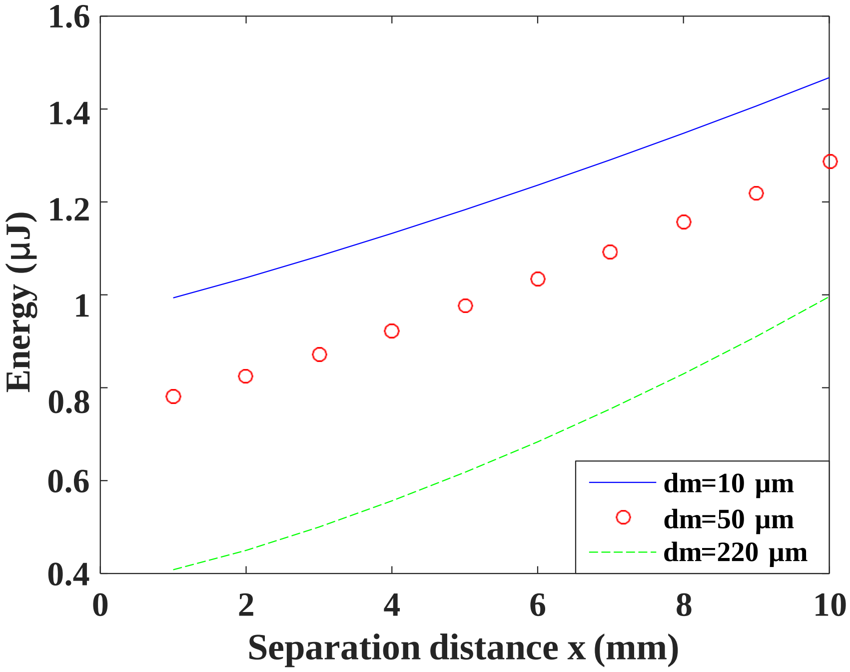


Figure 3.39 Impact of the conductor thickness on the output energy in the attached electrode sliding mode dielectric-to-dielectric

Figure 3.40 shows the impact of conductor thickness on the output energy when the gap is small and is equal to 5μm.

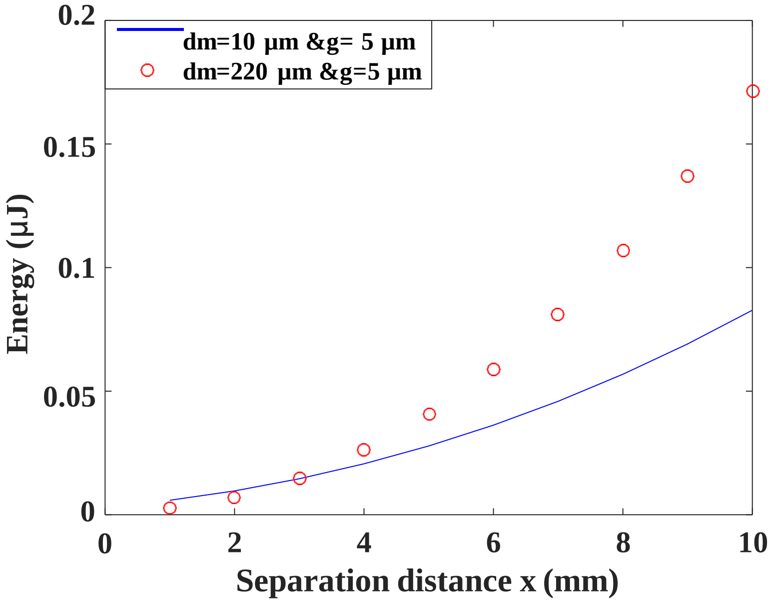


Figure 3.40 Impact of the conductor thickness on the output energy in the attached electrode sliding mode dielectric-to-dielectric at small gap

3.9 Comparison between the attached electrode sliding mode conductor-to-dielectric and dielectric-to-dielectric

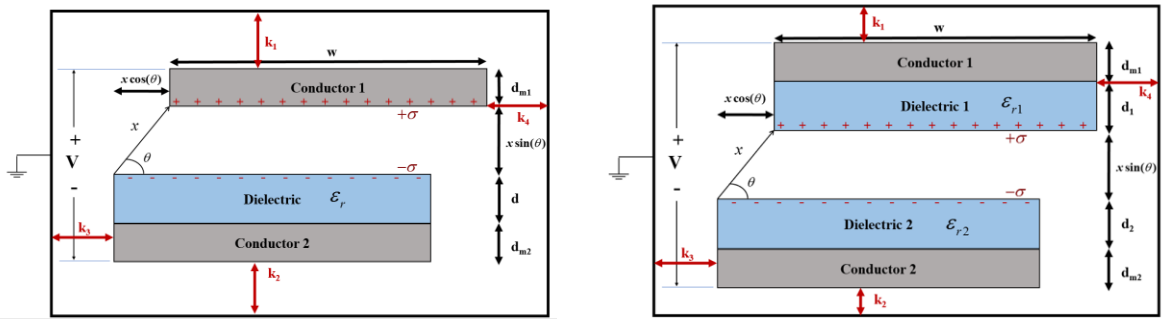
In this study, a comparison between the attached electrode sliding mode conductor-to-dielectric and dielectric-to-dielectric has been conducted. A complete comparison between the attached electrode conductor-to-dielectric and dielectric-to-dielectric is shown in Table 3.7 regarding to the open circuit voltage, short circuit charge, capacitance, and energy.

Table 3.7 Comparison between the maximum output parameters of the attached electrode sliding mode conductor-to-dielectric and dielectric-to-dielectric to dielectric

Point of comparison	Attached electrode sliding mode Conductor-to-dielectric	Attached electrode sliding mode Dielectric-to-dielectric
Open Circuit voltage	127.5 V	131.5 V
Short Circuit Charge	16 nC	15 nC
Capacitance	137 pF	13 pF
Energy	1.02 μJ	0.99 μJ

3.10 Attached electrode Diagonal mode

A new motion mode of the attached electrode TENG has been proposed [59]. This mode is a diagonal motion regime in which motion angle, namely theta, offers a new degree of freedom. By consequence, theta can be optimized to reach the maximum energy for each TENG configuration. Figure 3.41 shows the setup of the diagonal mode for both conductor-to-dielectric and dielectric-to-dielectric.



(a) (b)

Figure 3.41 The attached electrode diagonal mode for (a) conductor-to-dielectric (b) dielectric to dielectric

The V-Q-x relation can be derived by 2 ways which are the curve fitting or solving Gauss's theorem.

3.10.1 Approximate method

Since the equation of the open circuit voltage is linear, the open circuit voltage of the diagonal mode can be derived using this equation from (2.1) and (2.6).

$$V_{OC} = A * \frac{\sigma x \sin(\theta)}{\varepsilon_0} + B * \frac{\sigma (x \cos\theta) * d_0}{\varepsilon_0 * (w - x \cos\theta)} + C \tag{3.5}$$

where A, B, and C are fitting parameters,

θ is the diagonal mode angle in degrees, and

V_{oc} is the open circuit voltage.

The capacitance of the diagonal mode is given by the following equation:

$$Cap = D * \left(\frac{\varepsilon_0 l (w - x \cos\theta)}{d_0 + x \sin\theta}\right) + F \tag{3.6}$$

where D and F are fitting parameters,

and Cap is the Capacitance.

The short circuit charge (Q_{sc}) can be derived by (38) and (39):

$$Q_{sc} = (A * \frac{\sigma x \sin(\theta)}{\varepsilon_0} + B * \frac{\sigma(x \cos\theta) * d_0}{\varepsilon_0 * (w - x \cos\theta)} + C) * (D * (\frac{\varepsilon_0 l (w - x \cos\theta)}{d_0 + x \sin\theta}) + F) \tag{3.7}$$

The energy (E) can be calculated by:

$$E = 0.5 * V_{oc} * Q_{sc} \tag{3.8}$$

3.10.2 Exact method

The diagonal mode in the attached electrode TENG with air insulation is equivalent to 4 parallel capacitors as shown in Fig.3.39. The first capacitor is between the bottom and upper electrodes, the second capacitor is between the right wall and the upper electrode, the third capacitor is between the left wall and the upper electrode, and the fourth capacitor is between the upper wall and the upper electrode. So, the total charge on the four capacitors is the addition of all of the charges on every capacitor. [60]

$$Q_{SC} = Q_{SC_1} + Q_{SC_2} + Q_{SC_3} + Q_{SC_4} \tag{3.9}$$

And according to the TENG main equation, QSC = VOC × C, so:

$$Q_{SC} = V_{OC_1} C_1 + V_{OC_2} C_2 + V_{OC_3} C_3 + V_{OC_4} C_4 \tag{3.10}$$

V_{OC} of every capacitor can be calculated by understanding of the distribution of the charges. At the non-overlapped zone of the setup, the dielectric induces an equal in magnitude but different charge on the conductor. The overlapped zone charge is calculated by open circuit conditions. The assumed non-overlapped zone charges of the bottom and the top conductors are given by B and A respectively, then to substitute the open circuit condition:

$$\Sigma Q_{top} = -\sigma x \cos(\theta) l + A(w - x \cos(\theta)) l = 0 \tag{3.11}$$

$$\Sigma Q_{bottom} = \sigma x \cos(\theta) l + B(w - x \cos(\theta)) l = 0 \tag{3.12}$$

Therefore, A and B are given by:

$$A = \frac{\sigma x \cos(\theta)}{(w - x\cos(\theta))}, B = \frac{-\sigma x \cos(\theta)}{(w - x\cos(\theta))} \tag{3.13}$$

For the first capacitor between the first and second conductors, the electric field is found to be in the z-direction and is calculated by applying Gauss’s law in every five zones of the structure which are the two dielectrics, two copper electrodes, and the air gap:

$$\oint E \cdot dA = \frac{Q_{enclosed}}{\varepsilon} \tag{3.14}$$

First, E1 that is the electric field inside the upper copper electrode can be derived by the following equation:

$$-E_1(w - x\cos(\theta))l = \frac{A(w - x\cos(\theta))l}{\varepsilon_0} \tag{3.15}$$

$$E_1 = \frac{-A}{\varepsilon_0} = \frac{-\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))} \tag{3.16}$$

Similarly, E2, E3, E4, E5 can be found as follows:

$$E_2 = \frac{-A}{\varepsilon_0\varepsilon_{r1}} = \frac{\sigma x\cos(\theta)}{\varepsilon_0\varepsilon_{r1}(w - x\cos(\theta))} \tag{3.17}$$

$$E_3 = -\frac{A}{\varepsilon_0} - \frac{\sigma}{\varepsilon_0} = -\frac{\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))} - \frac{\sigma}{\varepsilon_0} \tag{3.18}$$

$$E_4 = \frac{B}{\varepsilon_0\varepsilon_{r2}} = \frac{-\sigma x\cos(\theta)}{\varepsilon_0\varepsilon_{r2}(w - x\cos(\theta))} \tag{3.19}$$

$$E_5 = \frac{B}{\varepsilon_0} = \frac{-\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))} \tag{3.20}$$

Thus, Voc is determined using the line integral formula:

$$V_{OC1} = -\int_{0}^{d_{m1}+d_1+g+x\sin(\theta)+d_2+d_{m2}} E \cdot dz \tag{3.21}$$

$$V_{OC1} = \frac{\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))}(g + x\sin(\theta) + d_0 + d_{m1} + d_{m2}) + \frac{\sigma(g + x\sin(\theta))}{\varepsilon_0} \tag{3.22}$$

With d_0 known as the effective dielectric equivalent thickness is given by $d_0 = (d1/\varepsilon r1 + d2/\varepsilon r2)$. Since the overlapping zone of the whole structure is the most governing part for the capacitance, the 1st capacitance is calculated by:

$$C_1 = \frac{\varepsilon_0(w - x\cos(\theta))l}{(g + x\sin(\theta) + d_0 + d_{m1} + d_{m2})} \tag{3.23}$$

For the capacitor between the top electrode and the right wall, the electric field is in the horizontal positive direction (x-direction) and is calculated by using Gauss's law:

$$E_6 d_{m1} l = \frac{-\sigma d_{m1} l}{\varepsilon_0} \tag{3.24}$$

$$E_6 = \frac{-\sigma}{\varepsilon_0} \tag{3.25}$$

$$V_{OC2} = -\int_{k_3+x\cos(\theta)+w+k_4}^{k_3+x\cos(\theta)+w} E_6 dx' = \frac{-\sigma}{\varepsilon_0}k_4 \tag{3.26}$$

And the 2nd capacitance given by:

$$C_2 = \frac{\varepsilon_0 d_{m1} l}{k_4} \tag{3.27}$$

For the 3rd capacitor between the top electrode and the left wall, the horizontal electric field (in the x-direction) is found by applying Gauss's law:

$$-E_7 d_{m1} l = \frac{A d_{m1} l}{\varepsilon_0} \tag{3.28}$$

$$E_7 = \frac{-A}{\varepsilon_0} \tag{3.29}$$

$$V_{OC3} = -\int_0^{k_3 + x\cos(\theta)} E_7 dx' = \frac{A}{\varepsilon_0}(k_3 + x\cos(\theta)) = \frac{\sigma x \cos(\theta)}{\varepsilon_0 (w - x\cos(\theta))}(k_3 + x\cos(\theta)) \tag{3.30}$$

And the 3rd capacitance is calculated by the following equation:

$$C_3 = \frac{\varepsilon_0 d_{m1} l}{(k_3 + x\cos(\theta))} \tag{3.31}$$

For the 4th capacitor between the top electrode and upper wall, by applying Gauss law under the open circuit condition:

$$E_8 w l = \frac{Q_{enclosed}}{\varepsilon_0} = 0 \tag{3.32}$$

Therefore,

$$E_8 = 0 \tag{3.33}$$

$$V_{OC4} = 0 \tag{3.34}$$

And the capacitance is found to be:

$$C_4 = \frac{\varepsilon_0 w l}{k_1} \tag{3.35}$$

From equations (3.11-3.12, 3.22-3.23, 3.26-3.27, and 3.30-3.31), Q_{SC} is found to be:

$$Q_{SC} = \sigma l x \cos(\theta) + \frac{\sigma l (g + x\sin(\theta))(w - x\cos(\theta))}{(g + x\sin(\theta) + d_0 + d_{m1} + d_{m2})} - \sigma d_{m1} l + \frac{\sigma d_{m1} l x \cos(\theta)}{(w - x\cos(\theta))} \tag{3.36}$$

And the total capacitance of the structure is the equivalent of four parallel capacitors as mentioned earlier:

$$C_{total} = C_1 + C_2 + C_3 + C_4 \tag{3.37}$$

And finally V_{OC} can be found as: $V_{OC} = Q_{SC}/C_{total}$. By substituting with Q_{SC} shown in equation (3.36) and C_{total} shown in equation (3.37) in the V-Q-x relation, the closed form (V-Q-x) relation can be determined.

3.11 Simulation Results of the Attached Electrode Diagonal Mode Conductor-to-dielectric

The setup of the diagonal mode TENG conductor-to-dielectric setup is shown in Figure 3.42, with the terminal denoted as V.

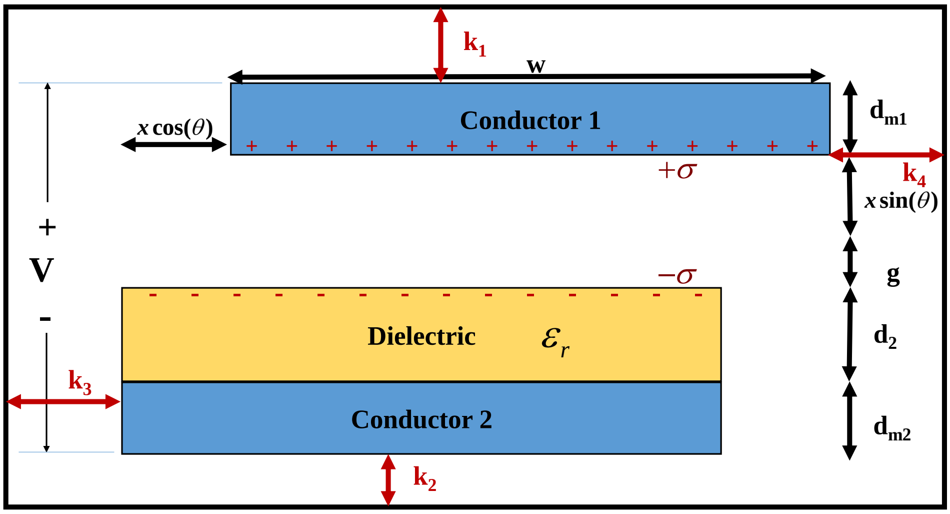


Figure 3.42 The attached electrode diagonal mode conductor-to-dielectric used in COMSOL

The parameters used in COMSOL to calculate the FEM results are shown in Table 3.8.

Table 3.8 Parameters used in COMSOL in the attached electrode diagonal mode conductor-to-dielectric

Parameter	Value
Width (w)	0.1 m
Length (l)	0.1 m
Conductor thickness (d_m)	220 µm
Dielectric thickness (d_1)	220 µm
Gap (g)	100 µm
Surface charge density (σ)	7 µC/m^2
Angle of inclination (θ)	0:1:90
Vertical separation (k1 and k2)	100 µm
Lateral separation (k3 and k4)	100 µm
Diagonal Distance (x)	10 mm

3.11.1 The relation between the open circuit voltage and the angle of inclination

Figure 3.43 shows the relation between the open circuit voltage and the angle of inclination.

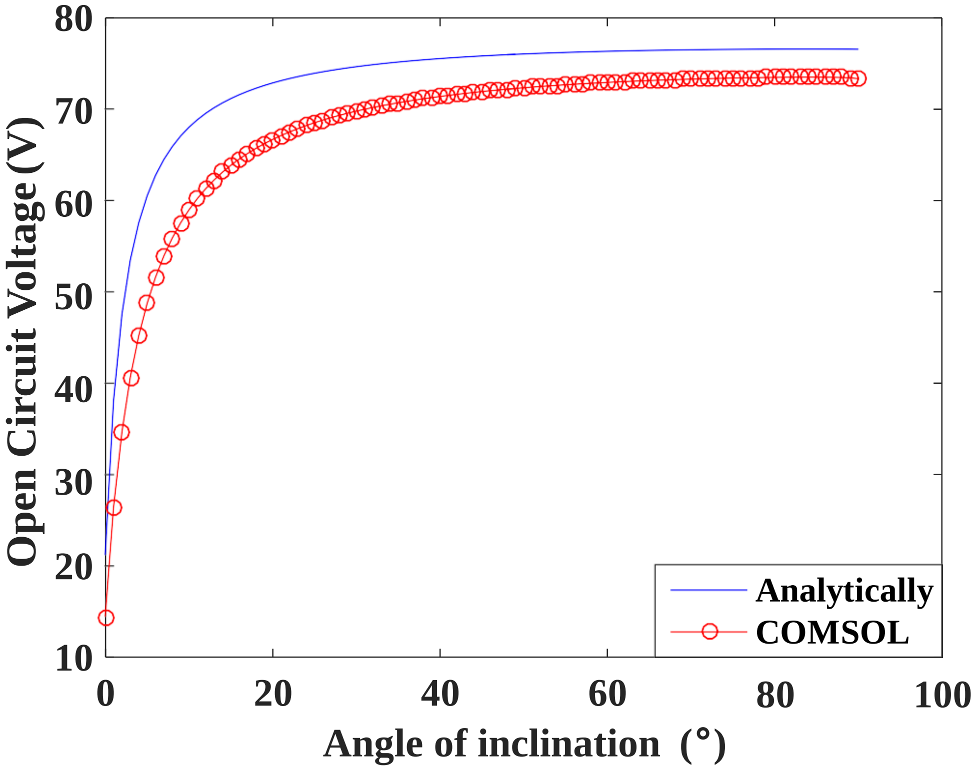


Figure 3.43 The calculated open circuit voltages at different angles of inclination at the attached electrode diagonal mode conductor-to-dielectric

3.11.2 The relation between the short circuit charge and the angle of inclination

Figure 3.44 shows the relation between the short circuit charge and the angle of inclination.

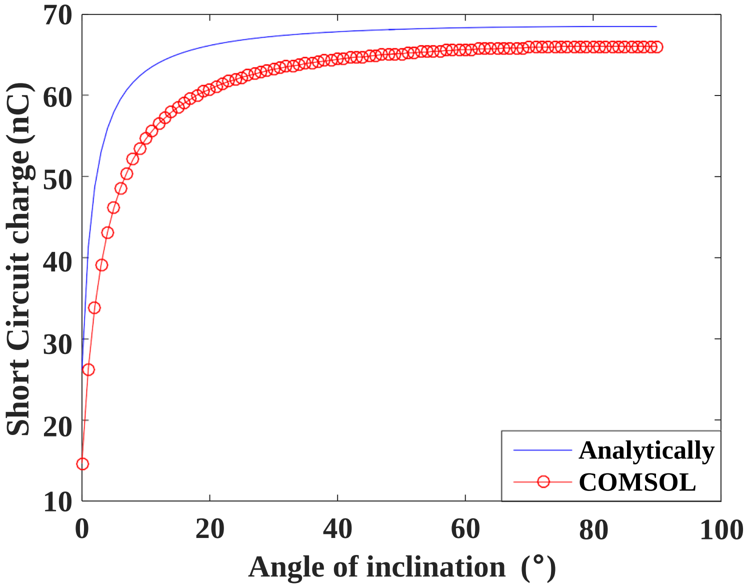


Figure 3.44 The calculated short circuit charges at different angles of inclination at the attached electrode diagonal mode conductor-to-dielectric

3.11.3 The relation between the capacitance and the Angle of Inclination in the Attached Electrode Conductor-to-dielectric

Figure 3.45 shows the relation between the open circuit voltage and the angle of inclination.

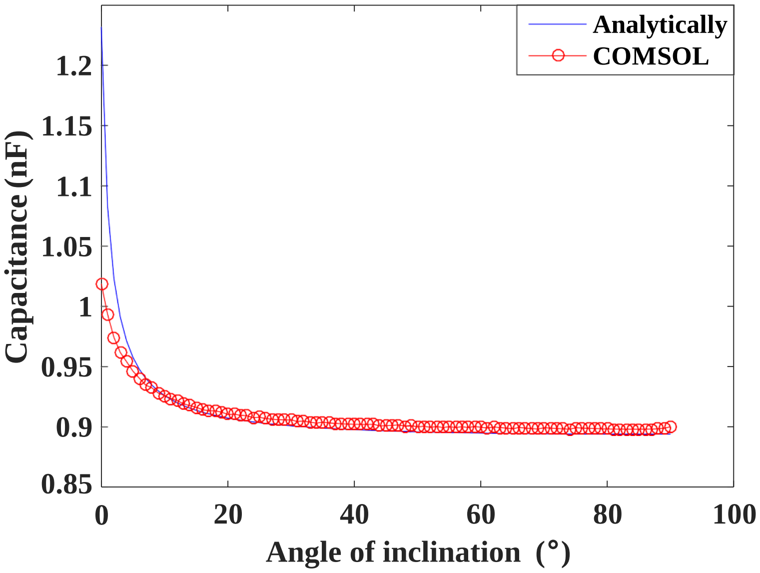


Figure 3.45 The calculated capacitances at different angles of inclination at the attached electrode diagonal mode conductor-to-dielectric

3.11.4 The relation between the energy and the angle of inclination

Figure 3.46 shows the relation between the output energy and the angle of inclination.

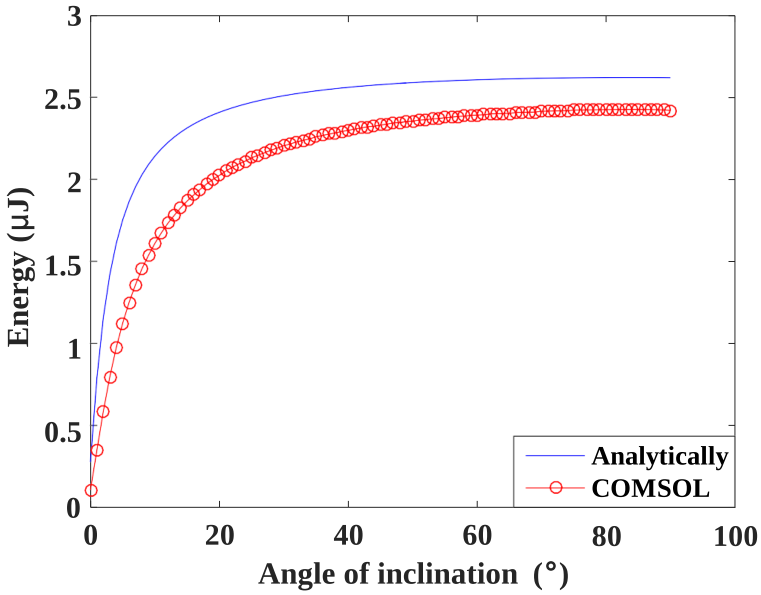


Figure 3.46 The calculated output energies at different angles of inclination at the attached electrode diagonal mode conductor-to-dielectric

3.11.5 Effect of different widths on the output energy of the TENG

The width of the TENG has an effect for knowing which angle can be used to obtain the maximum energy. When the width increases, it is better to move in the vertical direction (i.e. the angle of inclination is equal to 90˚). Figure 3.47 shows the relation between the angle of inclination and the output energy when the diagonal distance is equal to 100 µm.

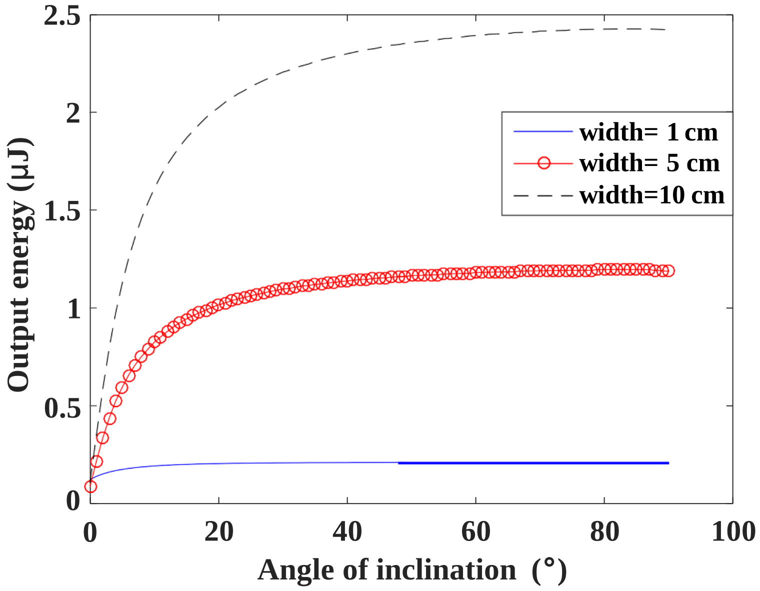


Figure 3.47 Impact of different widths on the output energy at the attached electrode diagonal mode conductor to dielectric

From Figure 3.47, it is clear that the output energy is the largest at width is equal to 10 cm, and the optimum angle is 90˚.

From Figures 3.41-3.44, the maximum open circuit voltage obtained from COMSOL is found to be equal to 73.49 V, the maximum short circuit charge is found to be equal to 66 nC, the maximum capacitance is found to be equal to 1.019 nF, and the maximum output energy is found to be equal to 2.43 µJ.

3.12 Simulation Results of the Attached Electrode Diagonal Mode Dielectric-to-dielectric

The setup of the diagonal mode TENG conductor-to-dielectric setup is shown in Figure 3.48, with the terminal denoted as V.

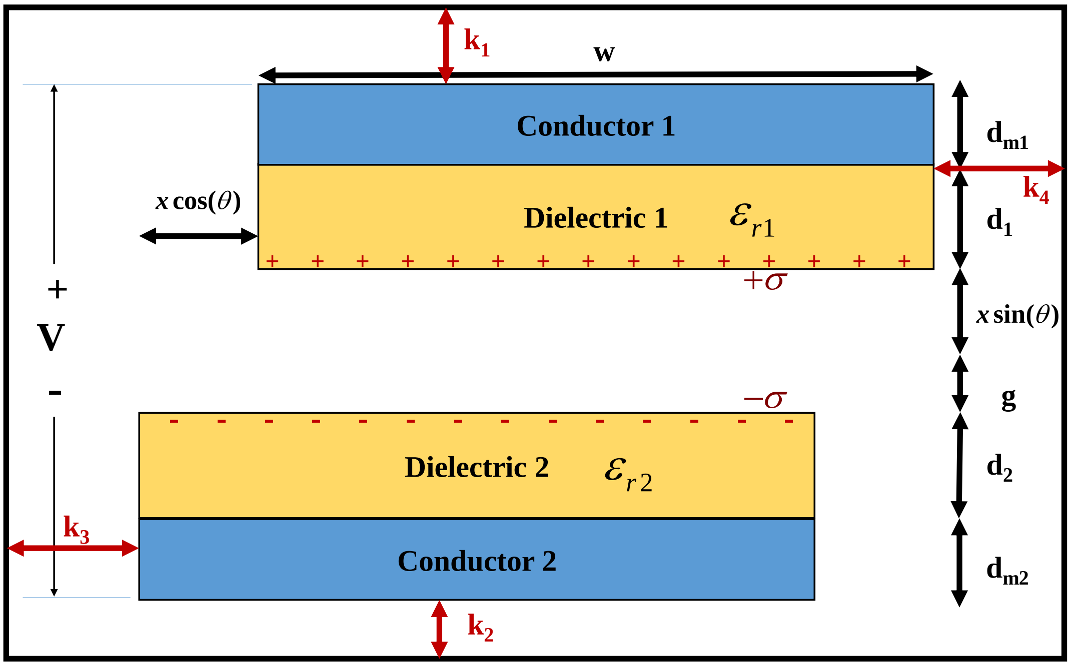


Figure 3.48 The attached electrode diagonal mode dielectric-to-dielectric used in COMSOL

The parameters used in COMSOL to calculate the FEM results are shown in Table 3.9 as follows.

Table 3.9 Parameters used in COMSOL in the attached electrode diagonal mode conductor-to-dielectric

Parameter	Value
Width (w)	0.1 m
Length (l)	0.1 m
Conductor thickness (d_m)	220 µm
Dielectric thickness (d_1)	220 µm, ε_{r1}=4
Dielectric thickness (d_2)	220 µm, ε_{r2}=2
Gap (g)	10 µm
Surface charge density (σ)	7 µC/m^2
Angle of inclination (Θ)	0:1:90
Vertical separation (k1 and k2)	100µm
Lateral separation (k3 and k4)	100µm
Diagonal Distance (x)	10 mm

3.12.1 The relation between the open circuit voltage and the angle of inclination

Figure 3.49 shows the relation between the open circuit voltage and the angle of inclination.

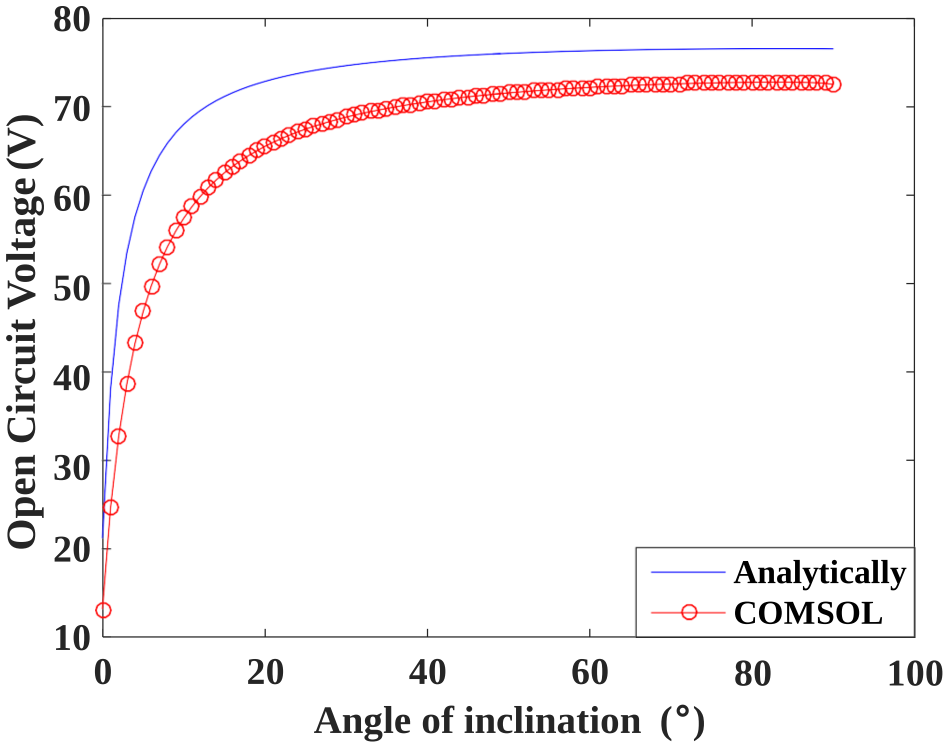


Figure 3.49 The calculated open circuit voltages at different angles of inclination at the attached electrode diagonal mode dielectric-to-dielectric

3.12.2 The relation between the short circuit charge and the angle of inclination

Figure 3.50 shows the relation between the short circuit charge and the angle of inclination.

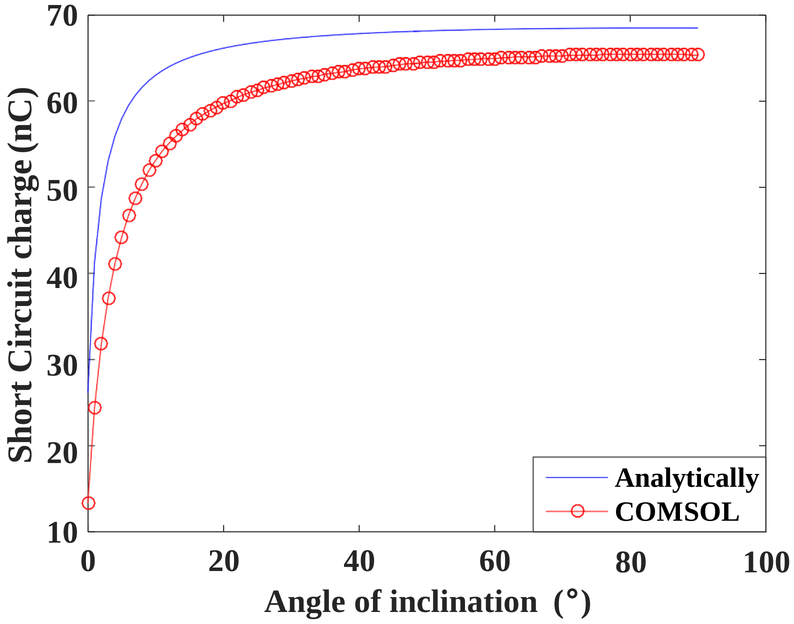


Figure 3.50 The calculated short circuit charges at different angles of inclination at the attached electrode diagonal mode dielectric-to-dielectric

3.12.3 The relation between the capacitance and the angle of inclination

Figure 3.51 shows the relation between the capacitance and the angle of inclination.

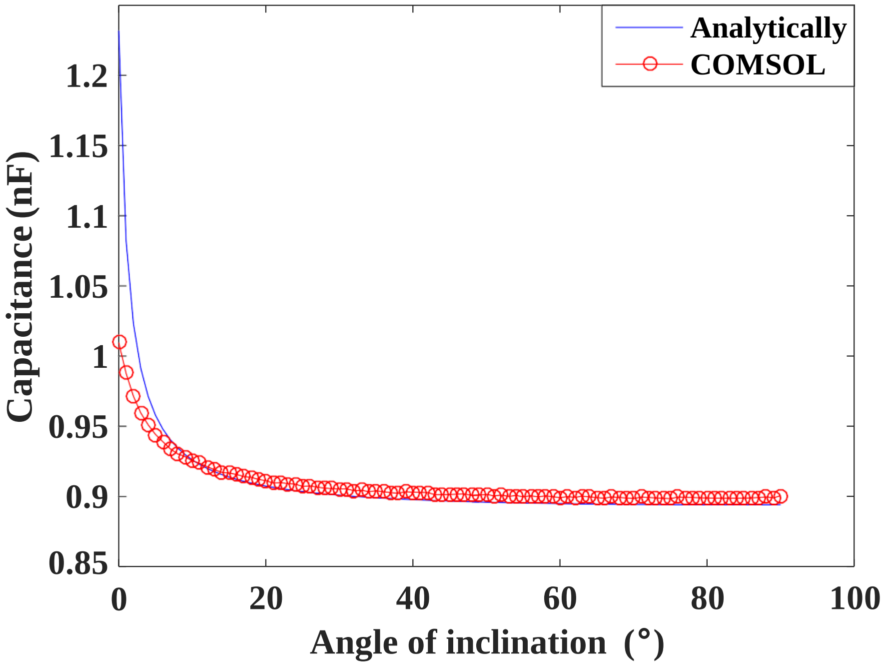


Figure 3.51 The calculated capacitances at different angles of inclination at the attached electrode diagonal mode dielectric-to-dielectric

3.12.4 The relation between the energy and the angle of inclination

Figure 3.52 shows the relation between the energy and the angle of inclination.

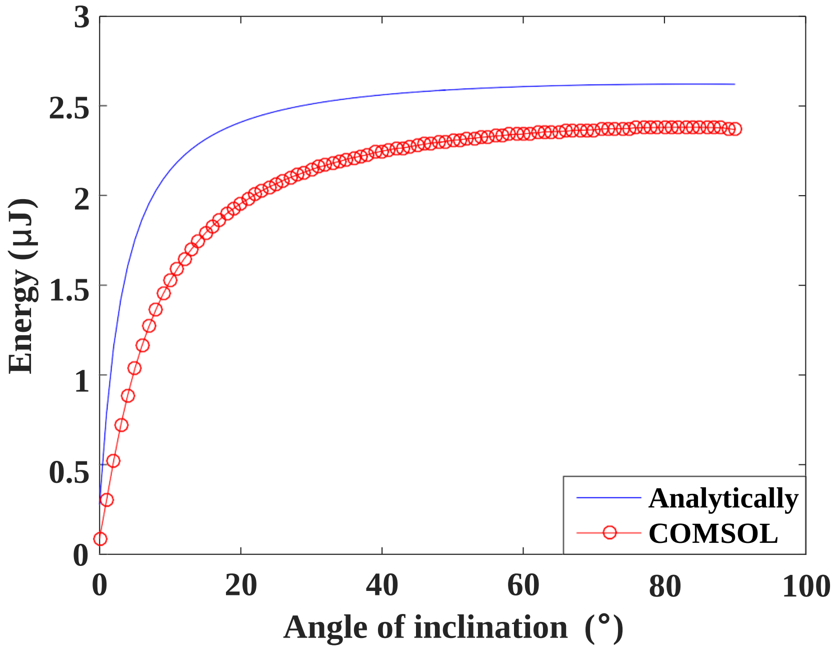


Figure 3.52 The calculated output energies at different angles of inclination at the attached electrode diagonal mode dielectric-to-dielectric

3.12.5 Effect of different widths on the output energy of the TENG

Figure 3.53 shows the relation between the output energies and the angle of inclination at different widths

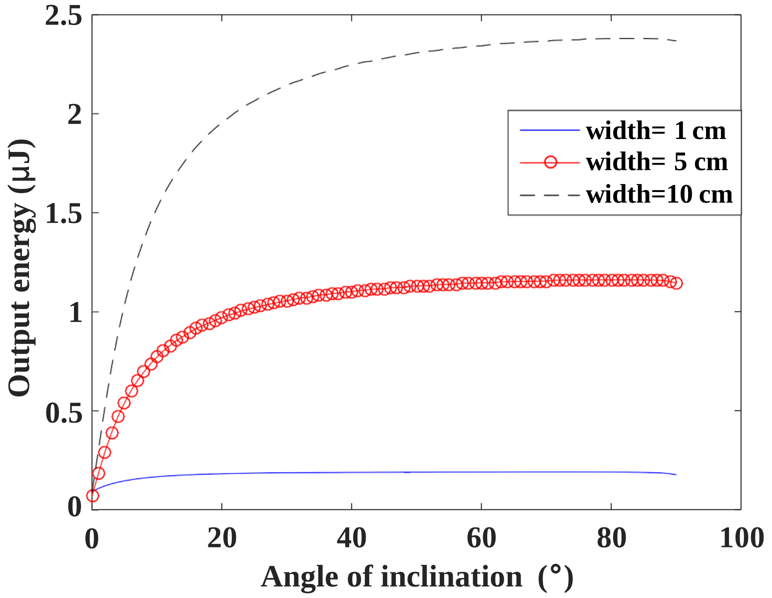


Figure 3.53 Impact of different widths on the output energy at the attached electrode diagonal mode dielectric-to-dielectric

From Figures 3.49-3.53, the maximum open circuit voltage obtained from COMSOL is found to be equal to 72.76 V, the maximum short circuit charge is found to be equal to 65 nC, the maximum capacitance is found to be equal to 1 nF, and the maximum output energy is found to be equal to 2.38 µJ.

3.13 Comparison between the attached electrode diagonal mode conductor-to-dielectric and dielectric-to-dielectric

A study between diagonal mode conductor-to-dielectric and dielectric-to-dielectric has been conducted in Table 3.10

Table 3.10 Comparison between the maximum output parameters of the attached electrode diagonal mode conductor-to-dielectric and dielectric-to-dielectric

Point of comparison	Attached electrode diagonal mode Conductor-to-dielectric	Attached electrode diagonal mode Dielectric-to-dielectric
Open Circuit voltage	73.49 V	72.76 V
Short Circuit Charge	66 nC	65 nC
Capacitance	1 nF	1 nF
Energy	2.43 µJ	2.38 µJ

Unlike the attached electrode contact and sliding modes, the open circuit voltage in the attached electrode diagonal mode in the conductor-to-dielectric is greater than that in the dielectric-to-dielectric due to the effect of the air insulation (sides of the box connecting to the ground). As there is air insulation, there is an increase in the number of capacitors (i.e. the increase in the capacitance). This leads to a decrease in the voltage in case of the attached electrode diagonal mode dielectric-to-dielectric.

3.14 Comparison between the Simulation Results of All Different Attached Electrode TENG Modes

A comparison between different modes of the attached electrode TENG in the attached electrode has been studied in Table 3.11 showing all results for the previous structures of the TENG modes. The attached electrode TENG modes are the attached electrode contact mode conductor-to-dielectric (AE CM CD), the attached electrode contact mode dielectric-to-dielectric (AE CM DD), attached electrode sliding mode conductor-to-dielectric (AE SM CD), the attached electrode sliding mode dielectric-to-dielectric (AE SM DD), the attached electrode diagonal mode conductor-to-dielectric (AE DM CD), and the attached electrode diagonal mode dielectric-to-dielectric (AE DM DD). The points of comparison are the open circuit voltage (Voc), the short circuit charge (Qsc), the capacitance (Cap), and the output energy (Energy)

Table 3.11 Comparison between the results of all attached electrode modes

P.O.C	AE CM CD	AE CM DD	AE SM CD	AE SM DD	AE DM CD	AE DM DD
V_{oc}	7.2 KV	7.2 KV	127.5 V	131.5 V	73.49 V	72.76 V
Q_{sc}	67 nC	66 nC	16 nC	15 nC	66 nC	65 nC
C	63 pF	53 pF	137 pF	13 pF	1.019 nF	1 nF
Energy	243 µJ	238 µJ	1.02 µJ	0.99 µJ	2.43 µJ	2.38 µJ

From Table 3.11, the maximum open circuit voltage is found in the attached electrode contact mode conductor-to-dielectric and dielectric-to-dielectric, the maximum short circuit charge is found in the attached electrode contact mode contact mode conductor-to-dielectric, the maximum capacitance is found in the attached electrode diagonal mode conductor-to-dielectric and the maximum output energy is found in the attached electrode sliding mode conductor-to-dielectric.

The diagonal mode gives a free motion in all directions of the TENG. Also, it has better capacitance than the attached electrode contact mode and sliding mode. So, it can be used in the energy storage to be used as a backup for solar panels at night since the photovoltaic works only in the morning.

Chapter 4

Conclusion and Future Development

4. Recommendations for Future Developments

4.1 Summary

Triboelectrification is considered as a promising technology to produce electrical energy from mechanical energy. The work summary is as follows:

- A study between different attached electrode modes has been conducted.
- A new diagonal mode is proposed and gives high capacitance to store charges.
- The effect of the gap in the attached electrode sliding mode is studied. The increase in the gap leads to increase in the open circuit voltage and the output energy as well.
- The effect of the conductor thickness in the attached electrode sliding mode is conducted. The increase in the conductor thickness at small gap leads to increase in the output energy while at large gap the increase in the conductor thickness leads to decrease in the output energy since the TENG comes out of the electric field.
- A new CAD tool is built to be used instead of COMSOL using the analytical equations.
- The results show that the highest open circuit voltage, short circuit charge, and output energy are yielded from the attached electrode Contact mode, while the highest capacitance is yielded from the attached electrode Diagonal mode.

4.2 Future Work (Further Development)

This study initiated the conversion of mechanical energy to electrical energy. The comparison between the attached electrode TENG modes has been conducted. However, there are many works that can be done on the TENG.

Following future work is recommended:

- The output currents of all modes of the TENG have to be characterized using Verilog-A
- The effect of the multi-layer TENG must be investigated
- The study of the 2 modes which are single electrode and freestanding modes has to be conducted.
- The effect of the piezoelectric must be studied well specially, the inverse piezo which is when the voltage is applied at the terminals of the piezoelectric, the piezoelectric moves i.e. the electric energy is converted to the mechanical energy. This mechanical energy can be used to move the TENG
- The study of different materials used in the fabrication of the TENG must be done. This can be accomplished by the programs COMSOL Multiphysics and Matlab.to know which type of materials is the best in the fabrication.

Publications

[1] E. Onsy, R. A. El-Sttar, G. S. Maximous, A. Zaky, and H. Mostafa, “Complete Study for Diagonal Triboelectric Nanogenerators Based Energy Harvester with CAD Tool”, Journal of Low Power Electronics (JOLPE), vol. 15, no. 1, pp. 51-63, 2019.

[2] G. S. Maximous, A. M. Fatahalla, A. Seleym, T. A. Ashour, and Hassan Mostafa, ”A New CAD Tool for Energy Optimization of Diagonal Motion Mode of Attached Electrode Triboelectric Nanogenerators”, IEEE International NEW Circuits and Systems Conference (NEWCAS 2018), Montreal, Canada, pp.331-334, 2018.

[3] R. AbdEl-Sttar, E. Onsy, G. S. Maximous, A. Zaky, Tamer A. Ashour, Ashraf Seleym, and H. Mostafa, “Diagonal Mode: A New Mode for Triboelectric Nanogenerators Energy Harvesters”, IEEE International Conference on Next Generation Circuits and Systems (NGCAS 2018), Malta, December 2018.

References

[1] Beeby, S.P., Torah, R.N., Tudor, M.J., Glynne-Jones, P., O'donnell, T., Saha, C.R. and Roy, S., “A micro electromagnetic generator for vibration energy harvesting”, Journal of Micromechanics and microengineering, vol. 17, no. 7, p. 1257, June 2007 .

[2] Saha, C.R., O’donnell, T., Wang, N. and McCloskey, P., “Electromagnetic generator for harvesting energy from human motion”, Sensors and Actuators A: Physical, vol. 147, no. 1, pp.248-253, September 2008

[3] Y. Suzuki, “Recent progress in MEMS electret generator for energy harvesting”, IEEE Transactions on Electrical and Electronic Engineering, vol. 6, no. 2, pp.101-111, January 2011.

[4] Wang, Z.L. and Song, J., “Piezoelectric nanogenerators based on zinc oxide nanowire arrays”, Science, vol. 312, no. 5771, pp.242-246, April 2006.

[5] B. Tian, X. Zheng, T.J. Kempa, Y. Fang, N. Yu, G. Yu, J. Huang, and C.M. Lieber, “Coaxial silicon nanowires as solar cells and nanoelectronic power sources”, Nature, vol. 449, no. 716, p.885, October 2007.

[6] Dresselhaus, M.S., Chen, G., Tang, M.Y., Yang, R.G., Lee, H., Wang, D.Z., Ren, Z.F., Fleurial, J.P. and Gogna, P., “New directions for low-dimensional thermoelectric materials”, Advanced materials, vol. 19, no. 8, pp.1043-1053, March 2007.

[7] O'regan, B. and Grätzel, M.,”A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films”, Nature, vol. 353, no. 6346, p.737, October 1991.

[8] Murray, E.P., Tsai, T. and Barnett, S.A., “A direct-methane fuel cell with a ceria-based anode”, Nature, vol. 400, no. 6745, p.649, August 1999.

[9] P. Chaudhary and P. Azad, “Demonstration of double electrode vertical-sliding triboelectric generator”, 2017 International Conference on Computing, Communication and Automation (ICCCA), pp. 1483-1487, May 2017.

[10] H.W. Lo and Y.C. Tai, “Parylene-based electret power generators”, Journal of Micromechanics and Microengineering, vol. 18, no. 10, p.104006, September 2008.

[11] Roundy, Shad, Eli S. Leland, Jessy Baker, Eric Carleton, Elizabeth Reilly, Elaine Lai, Brian Otis, Jan M. Rabaey, Paul K. Wright, and V. Sundararajan, "Improving power output for vibration-based energy scavengers." IEEE Pervasive computing, vol. 4, no. 1, pp. 28-36, March 2005.

[12] A. Khaligh, P. Zeng, and C. Zheng, “Kinetic energy harvesting using piezoelectric and electromagnetic technologies —state of the art.” IEEE Transactions on Industrial Electronics, vol. 57, no. 3, pp. 850-860, June 2009.

[13] Y. Gao, and Z.L. Wang , “ Electrostatic potential in a bent piezoelectric nanowire”, The fundamental theory of nanogenerator and nanopiezotronics, Nano letters, vol. 7, no. 8, pp. 2499-2505, July 2007.

[14] Qin, Yong, Xudong Wang, and Zhong Lin Wang. "Microfibre–nanowire hybrid structure for energy scavenging", Nature, vol. 451, no. 7180, p. 809, February 2008.

[15] Wang, X., Song, J., Liu, J. and Wang, Z.L., “Direct-current nanogenerator driven by ultrasonic waves”, Science, vol. 316, no. 5821, pp.102-105, April 2007.

[16] Xu, Sheng, Benjamin J. Hansen, and Zhong Lin Wang, "Piezoelectric-nanowire-enabled power source for driving wireless microelectronics", Nature communications, vol. 1, no. 93, October 2010.

[17] Sheng Xu, Yong Qin, Chen Xu, Yaguang Wei, Rusen Yang, and Zhong Lin Wang. "Self-powered nanowire devices." Nature nanotechnology, vol. 5, no. 5, pp. 366-373, March 2010.

[18] Rusen Yang, Yong Qin, Liming Dai, and Zhong Lin Wang, "Power generation with laterally packaged piezoelectric fine wires." Nature nanotechnology, vol. 4, no. 1, pp. 34-39, November 2009.

[19] Geon-Tae Hwang, Youngsoo Kim, Jeong-Ho Lee, Sekwon Oh, Chang Kyu Jeong, Dae Yong Park, Jungho Ryu, HyukSang Kwon, Sang-Goo Lee, Boyoung Joung, Daesoo Kim and Keon Jae Lee, "Self-powered deep brain stimulation via a flexible PIMNT energy harvester" Energy & Environmental Science, vol. 8, no. 9, pp. 2677-2684, September 2015.

[20] Wang, Zhong Lin, and Jinhui Song. "Piezoelectric nanogenerators based on zinc oxide nanowire arrays" Science, vol. 312, no. 5771, pp. 242-246, April 2006.

[21] Wang, Zhong Lin, "Progress in nanogenerators for portable electronics", Materials today, vol. 15, no. 12, pp. 532-543, December 2012.

[22] Wang, Zhong Lin. "Triboelectric nanogenerators as new energy technology and self-powered sensors–principles, problems and perspectives", Faraday discussions, vol. 176, pp. 447-458, February 2015.

[23] S.M. Niu and Z.L. Wang, “Theoretical systems of triboelectric nanogenerators”, Nano Energy, vol. 14, no. 14, pp. 161–192, May 2015.

[24] Zhong Lin Wang,, "Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors", ACS nano, vol. 7, no. 11, pp. 9533-9557, September 2013.

[25] Fan, Feng-Ru, et al. "Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films" Nano letters, vol. 12, no. 6, pp. 3109-3114, 2012.

[26] Zhu, G., Pan, C., Guo, W., Chen, C. Y., Zhou, Y., Yu, R., & Wang, Z. L., "Triboelectric-generator-driven pulse electrodeposition for micropatterning", Nano letters, vol. 12, no. 9, pp. 4960-4965, August 2012.

[27] Guang Zhu, Zong-Hong Lin, Qingshen Jing, Peng Bai, Caofeng Pan, Ya Yang, Yusheng Zhou, and Zhong Lin Wang, "Toward large-scale energy harvesting by a nanoparticle-enhanced triboelectric nanogenerator", Nano letters, vol. 13, no. 2, pp. 847-853, January 2013.

[28] Guang Zhu, J. Chen, Y. Liu, P. Bai, Y. S. Zhou, Q. Jing, and Z. L. Wang, "Linear-grating triboelectric generator based on sliding electrification", Nano letters, vol. 13, no. 5, pp. 2282-2289, April 2013.

[29] Guang Zhu, et al. "Triboelectric nanogenerators as a new energy technology: From fundamentals, devices, to applications", Nano Energy, vol. 14, pp. 126-138, May 2015.

[30] Sihong Wang, Yannan Xie, Simiao Niu, Long Lin, Chang Liu, Yu Sheng Zhou, and Zhong Lin Wang, "Maximum Surface Charge Density for Triboelectric Nanogenerators Achieved by Ionized-Air Injection: Methodology and Theoretical Understanding", Advanced Materials, vol. 26, no. 39 pp. 6720-6728, August 2014.

[31] Yunlong Zi, Simiao Niu, Jie Wang, Zhen Wen, Wei Tang, and Zhong Lin Wang, "Standards and Figure-of-merits for quantifying the performance of triboelectric nanogenerators", Nature communications, vol. 6, no. 8376, September 2015.

[32] Zhiming Lin, Jun Chen, and Jin Yang, "Recent Progress in Triboelectric Nanogenerators as a Renewable and Sustainable Power Source", Journal of Nanomaterials, vol.14, pp.1-24, April 2016.

[33] Wang Z.L., Lin L., Chen J., Niu S., Zi Y., "Triboelectric Nanogenerator: Lateral Sliding Mode", Triboelectric Nanogenerators, Green Energy and Technology. Springer, Cham, August 2016.

[34] Sihong Wang, Long Lin, Yannan Xie, Qingshen Jing, Simiao Niu, and Zhong Lin Wang, "Sliding-triboelectric nanogenerators based on in-plane charge-separation mechanism", Nano letter, vol. 13, no. 5, pp. 2226-2233, April 2013.

[35] Sai Sunil Kumar Mallineni, Yongchang Dong, Herbert Behlow, Apparao M. Rao, and Ramakrishna Podila, "A wireless triboelectric nanogenerator" Advanced Energy Materials, vol. 8, no. 10, p. 1702736, December 2017.

[36] Bera, Binoy, "Literature review on triboelectric nanogenerator.", Imperial Journal of Interdisciplinary Research, vol. 2, no. 10, pp. 1263-1271, December 2016.

[37] Sihong Wang, Yannan Xie, Simiao Niu, Long Lin, and Zhong Lin Wang, "Freestanding triboelectric-layer-based nanogenerators for harvesting energy from a moving object or human motion in contact and non-contact modes", Advanced Materials, vol. 26, no. 18, pp. 2818-2824, January 2014.

[38] Z. L. Wang, L. Lin, J. Chen, S. Niu, & Y. Zi., “Triboelectric Nanogenerators”. Berlin, Heidelberg, Germany: Springer International Publishing, 2016

[39] Disputatio physica experimentalis, de electricitatibus contrariis, Typis Ioannis Iacobi Adleri, 1757.

[40] D. K. Davies, "Charge generation on dielectric surfaces", Journal of Physics D: Applied Physics, vol. 2, no. 11, p. 1533, December 1969.

[41] Simiao Niu, Sihong Wang, Long Lin, Ying Liu, Yu Sheng Zhou, Youfan Hu, and Zhong Lin Wang, "Theoretical study of contact-mode triboelectric nanogenerators as an effective power source", Energy & Environmental Science, vol. 6, no. 12, pp. 3576-3583, September 2013.

[42] Halliday, Resnick. "Walker. 2006. Fundamental of Physics.", vol. 6, June 2006

[43] G. S. Maximous, A. M. Fatahalla, A. Seleym, T. A. Ashour, and Hassan Mostafa, ”A New CAD Tool for Energy Optimization of Diagonal Motion Mode of Attached Electrode Triboelectric Nanogenerators”, IEEE International NEW Circuits and Systems Conference (NEWCAS 2018), Montreal, Canada, pp.331-334, 2018.

[44] Wang, Yang, Ya Yang, and Zhong Lin Wang. "Triboelectric nanogenerators as flexible power sources", npj Flexible Electronics, vol. 1, no. 1, p. 10, November 2017.

[45] Simiao Niu, Ying Liu, Sihong Wang, Long Lin, Yu Sheng Zhou, Youfan Hu, and Zhong Lin Wang, “Theory of Sliding-Mode Triboelectric Nanogenerators”, Advanced Materials, vol. 25, no. 43, pp. 6184-6193, November 2013.

[46] Simiao Niu, Ying Liu, Sihong Wang, Long Lin, Yu Sheng Zhou, Youfan Hu, and Zhong Lin Wang, "Theoretical investigation and structural optimization of single-electrode triboelectric nanogenerators", Advanced Functional Materials, vol. 24, no. 22, pp. 3332-3340, February 2014.

[47] Yanchao Mao, Dalong Cheng, Erjun Liang, and Xudong Wang, "Single-electrode triboelectric nanogenerator for scavenging friction energy from rolling tires" Nano Energy, vol. 15, pp. 227-234, July 2015.

[48] Meng Wang, Nan Zhang, Yingjje Tang, Heng Zhang, Chuan Ning, Lan Tian, Weihan Li, Jiahao Zhang, Yanchao Mao, and Erjun Liang, "Single-electrode triboelectric nanogenerators based on sponge-like porous PTFE thin films for mechanical energy harvesting and self-powered electronics", Journal of Materials Chemistry A, vol. 5, no. 24, pp. 12252-12257, May 2017.

[49] Li Yong, Li Yuhe, Li Qingxiang, Zi Yanyang, “Computation of electrostatic forces with edge effects for non-parallel comb-actuators", Qinghua Daxue Xuebao/Journal of Tsinghua University(China), vol. 43, no. 8, pp. 1024-1026, August 2003.

[50] B. Palmer, “Capacitance of a parallel-plate capacitor by the Schwartz-Christoffel transformation,” Trans. AIEE, vol. 56, pp. 363, March 1927.

[51] Leus, Vitaly, and David Elata. "Fringing field effect in electrostatic actuators", Technion-Israel Institute of Technology Technical Report No. ETR-2004-2, January 2004.

[52] Hosseini, Mehran, Guchuan Zhu, and Y-A. Peter. "A new model of fringing capacitance and its application to the control of parallel-plate electrostatic micro actuators", arXiv preprint arXiv, November 2007.

[53] Niu, Simiao, Ying Liu, Xiangyu Chen, Sihong Wang, Yu Sheng Zhou, Long Lin, Yannan Xie, and Zhong Lin Wang,"Theory of freestanding triboelectric-layer-based nanogenerators", Nano Energy, vol. 12, pp. 760-774, January 2015.

[54] Sihong Wang, Yannan Xie, Simiao Niu, Long Lin, and Zhong Lin Wang, "Freestanding triboelectric-layer-based nanogenerators for harvesting energy from a moving object or human motion in contact and non-contact modes", Advanced Materials, vol. 26, no. 18, pp. 2818-2824, January 2014.

[55] Yannan Xie, Sihong Wang, Simiao Niu, Long Lin, Qingshen Jing, Jin Wang, Zhengyun Wu, and Zhong Lin Wang,"Grating-structured freestanding triboelectric-layer nanogenerator for harvesting mechanical energy at 85% total conversion efficiency", advanced materials, vol. 26, no. 38, pp. 6599-6607, August 2014.

[56] Tao Jiang, Xiangyu Chen, Chang Bao Han, Wei Tang, and Zhong Lin Wang,"Theoretical study of rotary freestanding triboelectric nanogenerators", Advanced Functional Materials, vol. 25, no. 19, pp. 2928-2938, April 2015.

[57] Sihong,Wang, Simiao Niu, Jin Yang, Long Lin, and Zhong Lin Wang, "Quantitative measurements of vibration amplitude using a contact-mode freestanding triboelectric nanogenerator" ACS nano, vol. 8, no. 12, pp. 12004-12013, November 2014.

[58] Zhiming Lin, Jun Chen, and Jin Yang. "Recent progress in triboelectric nanogenerators as a renewable and sustainable power source" Journal of Nanomaterials 2016, January 2016.

[59] A. Zaky, M. Shehata, Y. Ismail and H. Mostafa, "Characterization and model validation of triboelectric nanogenerators using Verilog-A," 2017 IEEE 60th International Midwest Symposium on Circuits and Systems (MWSCAS), Boston, MA, 2017, pp. 1536-1539, August 2017.

[60] R. AbdEl-Sttar, E. Onsy, G. Maximous, A. Zaky, Tamer A. Ashour, Ashraf Seleym, and H. Mostafa, “Diagonal Mode: A New Mode for Triboelectric Nanogenerators Energy Harvesters”, IEEE International Conference on Next Generation Circuits and Systems (NGCAS 2018), Malta, December 2018.

Appendix 1 – The derivation of the open circuit voltage in the single electrode TENG Contact mode

At the open circuit condition, the overall charges on Node 3, 2, and 1 are 0, -σwl, and σwl respectively. Thus:

$$V_2 = V_1 + V_3$$

$$C_2V_2 + C_1V_1 = -\sigma wl$$

$$-C_1V_1 + C_3V_3 = \sigma wl \tag{1}$$

From (1):

$$\therefore V_1 = \frac{\sigma wl - C_3V_3}{-C_1} \tag{2}$$

From (1) and (2) by substitution,

$$C_2(V_1 + V_3) + C_1V_1 = -\sigma wl \tag{3}$$

$$C_2V_1 + C_2V_3 + C_1V_1 = -\sigma wl \tag{4}$$

From (3) and (4) by addition:

$$C_2V_1 + C_2V_3 + C_3V_3 = 0$$

$$C_2\left(\frac{\sigma wl - C_3V_3}{-C_1}\right) + C_2V_3 + C_3V_3 = 0$$

$$-\frac{C_2}{C_1}\sigma wl + \frac{C_3C_2V_3}{C_1} + C_2V_3 + C_3V_3 = 0$$

$$\frac{C_3C_2V_3}{C_1} + C_2V_3 + C_3V_3 = \frac{C_2}{C_1}\sigma wl \tag{5}$$

(5) is multiplied by C_1

$$C_3C_2V_3 + C_2C_1V_3 + C_3C_1V_3 = C_2\sigma wl$$

$$\therefore V_{oc} = V_3 = \frac{C_2\sigma wl}{C_3C_1 + C_2C_1 + C_3C_2}$$

Appendix 2 – Steps in COMSOL Multiphysics version 5.3a for attached electrode Dielectric-to-dielectric Contact mode

1. 2D has been selected after selecting a new Model wizard
2. AC/DC has to be expanded and Electrostatics (es) has been added
3. Study is selected
4. From Preset studies, stationary is selected
5. “Done” is selected
6. Right click on global window and Enter the parameters in Table 1
7. Draw 5 rectangles where:
    - A. rectangle 1 is the lower copper electrode
    - B. rectangle 2 is the first dielectric attached
    - C. rectangle 3 is the second dielectric
    - D. rectangle 4 is the upper copper electrode
    - E. rectangle 5 is the box
8. Choose the materials such that Dielectric1and Dielectric 2 take the PTFE with relative permittivity (εr1)=2 and Nylon (εr2)=4 respectively, and the conductor takes the Copper in case of Conductor-to-dielectric and in case of dielectric-to-dielectric,
9. From the electrostatics settings, Replace the out-of-plane thickness to be the length (l) instead of 1
10. Set the boundaries as shown in Figure 15
11. Right click on “study 1” and add parametric sweep
12. Add the distance (x) to be in range (10µm:150µm:1360µm)
13. Press Compute

Appendix 3– Steps in COMSOL Multiphysics version 5.3a for attached electrode Conductor-to-dielectric Contact mode

1. 2D has been selected after selecting a new Model wizard
2. AC/DC has to be expanded and Electrostatics (es) has been added
3. Study is selected
4. From Preset studies, stationary is selected
5. “Done” is selected
6. Right click on global window and fill in the following Table
   A. Draw 4 rectangles rectangle 1 is the lower copper electrode
   B. rectangle 2 is the first dielectric attached
   C. rectangle 3 is the second dielectric
   D. rectangle 4 is the upper copper electrode
7. Choose the materials such that Dielectric takes the PTFE and the conductor takes the Copper in case of Conductor-to-dielectric
8. From the electrostatics settings, Replace the out-of-plane thickness to be the length (l) instead of 1
9. Set the boundaries as shown in Figure 9
10. Right click on “study 1” and add parametric sweep
11. Add the gap (g) to be in range(10µm:20µm:90µm)
12. Press Compute

Appendix 4– Steps in COMSOL Multiphysics version 5.3a for attached electrode Conductor-to-dielectric Sliding mode

1. 2D has been selected after selecting a new Model wizard
2. AC/DC has to be expanded and Electrostatics (es) has been added
3. Study is selected
4. From Preset studies, stationary is selected
5. “Done” is selected
6. Right click on global window and fill in the following Table
7. Draw 4 rectangles rectangle 1 is the lower copper electrode
8. rectangle 2 is the first dielectric attached
9. rectangle 3 is the second dielectric
10. rectangle 4 is the upper copper electrode
11. Add the gap (g) to be equal to 5µm
12. Choose the materials such that Dielectric takes the PTFE and the conductor takes the Copper in case of Conductor-to-dielectric
13. From the electrostatics settings, Replace the out-of-plane thickness to be the length (l) instead of 1
14. Set the boundaries as shown in Figure
15. Right click on “study 1” and add parametric sweep
16. Add the lateral distance to be in the range (10µm, 150µm, 1360µm)
17. Press Compute

Appendix 5 – MATLAB Code for the attached electrode TENG Contact mode Conductor-to-dielectric

```
%% Author George Sherif
%% Attached electrode contact mode Conductor-to-dielectric

clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=10e-6:150e-6:1360e-6;
Er=2;
dm=220e-6;
d=220e-6;
sigma=7e-6;
d0=d/Er;
%% Open Circuit Voltage
Voc_analytically=sigma.*x./E0;
Voc_Comsol=[7.8192 124.75 241.11 356.94 472.28 587.17 701.61 815.64 929.27 1042.5];

fig=Figure
plot(x.*10^3,Voc_analytically,'b');
hold on
plot(x.*10^3,Voc_Comsol,'r');
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
%% Short Circuit charge
Qsc_Comsol=[1.0898E-9 1.5639E-8 2.5110E-8 3.1766E-8 3.6700E-8 4.0504E-8 4.3526E-8 4.5985E-8 4.8024E-8 4.9743E-8];
Qsc_analytically=w.*l.*x.*sigma./(d0+x+2*dm)

fig=Figure
plot(x.*10^3,Qsc_analytically.*10^9,'b');
hold on
plot(x.*10^3,Qsc_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Capacitance
```

```
Cap_Comsol=Qsc_Comsol./Voc_Comsol;
Cap_analytically=Qsc_analytically./Voc_analytically;

fig=Figure
plot(x.*10^3,Cap_analytically.*10^9,'b');
hold on
plot(x.*10^3,Cap_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
%% Energy

Energy_Comsol=0.5.*Qsc_Comsol.*Voc_Comsol;
Energy_analytically=0.5.*Qsc_analytically.*Voc_analytically;

fig=Figure
plot(x.*10^3,Energy_analytically.*10^9,'b');
hold on
plot(x.*10^3,Energy_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Enegry (nJ)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 6 – MATLAB Code for the attached electrode TENG Contact mode Dielectric-to-dielectric

```
%% Author George Sherif
%% Attached electrode contact mode Dielectric-to-dielectric
clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=10e-6:150e-6:1360e-6;
Er1=2;
Er2=4;
dm=220e-6;
d1=220e-6;
d2=220e-6;
sigma=7e-6;
d0=d1/Er1+d2/Er2;

%% Open Circuit Voltage
Voc_analytically=sigma.*x./E0;
Voc_Comsol=[7.8174 124.69 240.97 356.72 471.98 586.77 701.11 815.04 928.57 1041.7];

fig=Figure
plot(x.*10^3,Voc_analytically,'b');
hold on
plot(x.*10^3,Voc_Comsol,'r');
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
%% Short Circuit charge
Qsc_Comsol=[1.1381E-9 1.4630E-8 2.3693E-8 3.0202E-8 3.5103E-8 3.8926E-8 4.1992E-8 4.4506E-8 4.6604E-8 4.8381E-8];
Qsc_analytically=w.*l.*x.*sigma./(d0+x+2*dm)

fig=Figure
plot(x.*10^3,Qsc_analytically.*10^9,'b');
hold on
plot(x.*10^3,Qsc_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
```

```
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Capacitance
Cap_Comsol=Qsc_Comsol./Voc_Comsol;
Cap_analytically=Qsc_analytically./Voc_analytically;

fig=Figure
plot(x.*10^3,Cap_analytically.*10^9,'b');
hold on
plot(x.*10^3,Cap_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
%% Energy

Energy_Comsol=0.5.*Qsc_Comsol.*Voc_Comsol;
Energy_analytically=0.5.*Qsc_analytically.*Voc_analytically;

fig=Figure
plot(x.*10^3,Energy_analytically.*10^9,'b');
hold on
plot(x.*10^3,Energy_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Enegry (nJ)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 7 – MATLAB Code for the attached electrode TENG Sliding mode Conductor-to-dielectric

```
%% Author George Sherif
%% Attached electrode Sliding mode Conductor-to-dielectric

clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=10e-6:150e-6:1360e-6;
Er1=2;
Er2=4;
dm=10e-6;
d1=220e-6;
d2=0;
sigma=7e-6;
g=5e-6;
d0=d1/Er1+d2/Er2;

%% Open Circuit Voltage
Voc_analytically=(sigma.*x.*(d0+g+2*dm)./(E0.*(w-x)))+sigma.*g./E0;
Voc_Comsol=[3.9420 4.0024 4.1128 4.2441 4.3857 4.5327 4.6835 4.8367 4.9916 5.1482];

fig=Figure
plot(x.*10^3,Voc_analytically,'b');
hold on
plot(x.*10^3,Voc_Comsol,'r');
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here
%% Short Circuit charge
Qsc_Comsol=[    2.5932E-9 2.6315E-9 2.7013E-9 2.7841E-9 2.8731E-9 2.9654E-9 3.0597E-9 3.1552E-9
3.2516E-9 3.3487E-9];
Qsc_analytically=sigma.*l.*x+(sigma.*l.*(w-x).*g/(d0+g+2*dm))

fig=Figure
plot(x.*10^3,Qsc_analytically.*10^9,'b');
hold on
plot(x.*10^3,Qsc_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
```

```
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here

%% Capacitance
Cap_Comsol=Qsc_Comsol./Voc_Comsol;
Cap_analytically=Qsc_analytically./Voc_analytically;

fig=Figure
plot(x.*10^3,Cap_analytically.*10^9,'b');
hold on
plot(x.*10^3,Cap_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here
%% Energy

Energy_Comsol=0.5.*Qsc_Comsol.*Voc_Comsol;
Energy_analytically=0.5.*Qsc_analytically.*Voc_analytically;

fig=Figure
plot(x.*10^3,Energy_analytically.*10^3,'b');
hold on
plot(x.*10^3,Energy_Comsol.*10^3,'r');
xlabel('Separation distance x (mm)');
ylabel('Enegry (\mu J)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here
```

Appendix 8 – MATLAB Code for the impact of the gap on the output TENG characteristics at the attached electrode sliding mode conductor-to-dielectric

```matlab
%% Author George Sherif
%% Attached electrode sliding mode Dielectric-to-dielectric
clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=0:0.01:0.09;
Er1=2;
Er2=4;
dm=10e-6;
d1=220e-6;
d2=0;
sigma=7e-6;
g=5e-6;
d0=d1/Er1+d2/Er2;
%% Open Circuit Voltage
Voc_Comsol_5um=[3.9101 46.931 105.26 180.09 279.15 416.36 618.78 947.87 1575.0 3244.9];
Voc_Comsol_7um=[5.4738 48.628 107.16 182.25 281.67 419.29 622.41 952.35 1581.7 3256.1];
Voc_Comsol_10um=[7.8192 51.181 110.01 185.49 285.42 423.71 627.98 959.39 1591.7 3273.3];
Voc_Comsol_50um=[39.065 85.179 148.00 228.59 335.22 482.77 700.32 1053.1 1724.5 3497.7];
Voc_Comsol_100um=[78.053 127.51 195.31 282.25 397.19 556.15 790.21 1169.4 1887.4 3770.6];
%% Short Circuit Charge
Qsc_Comsol_5um=[6.3044E-10 6.8864E-9 1.3774E-8 2.0696E-8 2.7627E-8 3.4561E-8 4.1496E-8 4.8434E-8 5.5369E-8 6.2306E-8];
Qsc_Comsol_7um=[8.7945E-10 7.1105E-9 1.3973E-8 2.0870E-8 2.7777E-8 3.4686E-8 4.1596E-8 4.8508E-8 5.5419E-8 6.2331E-8];
Qsc_Comsol_10um=[1.2496E-9 7.4444E-9 1.4270E-8 2.1130E-8 2.8000E-8 3.4871E-8 4.1746E-8 4.8619E-8 5.5494E-8 6.2369E-8];
Qsc_Comsol_50um=[5.8309E-9 1.1578E-8 1.7944E-8 2.4345E-8 3.0756E-8 3.7169E-8 4.3585E-8 5.0001E-8 5.6418E-8 6.2834E-8];
Qsc_Comsol_100um=[1.0764E-8 1.6026E-8 2.1899E-8 2.7807E-8 3.3723E-8 3.9644E-8 4.5566E-8 5.1489E-8 5.7411E-8 6.3334E-8];

%% Capacitance
Cap_Comsol_5um=Qsc_Comsol_5um./Voc_Comsol_5um;
Cap_Comsol_7um=Qsc_Comsol_7um./Voc_Comsol_7um;
Cap_Comsol_10um=Qsc_Comsol_10um./Voc_Comsol_10um;
Cap_Comsol_50um=Qsc_Comsol_50um./Voc_Comsol_50um;
Cap_Comsol_100um=Qsc_Comsol_100um./Voc_Comsol_100um;

%% Energy
Energy_Comsol_5um=0.5.*Qsc_Comsol_5um.*Voc_Comsol_5um;
Energy_Comsol_7um=0.5.*Qsc_Comsol_7um.*Voc_Comsol_7um;
Energy_Comsol_10um=0.5.*Qsc_Comsol_10um.*Voc_Comsol_10um;
Energy_Comsol_50um=0.5.*Qsc_Comsol_50um.*Voc_Comsol_50um;
Energy_Comsol_100um=0.5.*Qsc_Comsol_100um.*Voc_Comsol_100um;

%% Plotting Voltage
```

```
fig=Figure
plot(x.*10^3,Voc_Comsol_5um);
hold on
plot(x.*10^3,Voc_Comsol_7um);
hold on
plot(x.*10^3,Voc_Comsol_10um);
hold on
plot(x.*10^3,Voc_Comsol_50um);
hold on
plot(x.*10^3,Voc_Comsol_100um);
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here


%% Plotting Short Circuit Charge
fig=Figure
plot(x.*10^3,Qsc_Comsol_5um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_7um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_10um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_50um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_100um.*10^9);
xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% plotting Capacitance
fig=Figure
plot(x.*10^3,Cap_Comsol_5um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_7um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_10um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_50um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_100um.*10^9);
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
```

```
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here

%% Plotting Energy
fig=Figure
plot(x.*10^3,Energy_Comsol_5um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_7um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_10um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_50um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_100um.*10^3);
xlabel('Separation distance x (mm)');
ylabel('Energy (mJ)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here
```

Appendix 9 – MATLAB Code for the impact of the gap on the output TENG characteristics at the attached electrode sliding mode Dielectric-to-dielectric

```
%% Author George Sherif
%% Attached electrode sliding mode Dielectric-to-dielectric
clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=0:0.01:0.09;
Er1=2;
Er2=4;
dm=10e-6;
d1=220e-6;
d2=0;
sigma=7e-6;
g=5e-6;
d0=d1/Er1+d2/Er2;
%% Open Circuit Voltage
Voc_Comsol_5um=[3.9092 50.588 114.47 196.40 304.80 454.80 675.98 1034.6 1715.8 3515.2];
Voc_Comsol_7um=[5.4726 52.285 116.37 198.58 307.35 457.74 679.61 1039.0 1723.1 3526.6];
Voc_Comsol_10um=[7.8174 54.830 119.21 201.78 311.02 462.16 684.93 1046.0 1732.3 3542.3];
Voc_Comsol_50um=[39.053 88.749 157.10 244.76 360.68 521.03 757.02 1139.1 1863.4 3764.7];
Voc_Comsol_100um=[78.018 130.99 204.26 298.22 422.39 593.95 846.31 1254.0 2024.4 4028.8];
%% Short Circuit Charge
Qsc_Comsol_5um=[5.7373E-10 6.7651E-9 1.3655E-8 2.0580E-8 2.7517E-8 3.4457E-8 4.1399E-8 4.8342E-8 5.5282E-8 6.2225E-8];
Qsc_Comsol_7um=[8.0058E-10 6.9697E-9 1.3836E-8 2.0741E-8 2.7655E-8 3.4571E-8 4.1491E-8 4.8409E-8 5.5330E-8 6.2249E-8];
Qsc_Comsol_10um=[1.1381E-9 7.2740E-9 1.4107E-8 2.0977E-8 2.7857E-8 3.4740E-8 4.1625E-8 4.8510E-8 5.5396E-8 6.2282E-8];
Qsc_Comsol_50um=[5.3414E-9 1.1068E-8 1.7480E-8 2.3930E-8 3.0389E-8 3.6853E-8 4.3316E-8  4.9781E-8 5.6246E-8 6.2713E-8];
Qsc_Comsol_100um=[9.9236E-9 1.5203E-8 2.1156E-8 2.7147E-8 3.3147E-8 3.9151E-8 4.5157E-8 5.1163E-8 5.7170E-8 6.3177E-8];
%% Capacitance
Cap_Comsol_5um=Qsc_Comsol_5um./Voc_Comsol_5um;
Cap_Comsol_7um=Qsc_Comsol_7um./Voc_Comsol_7um;
Cap_Comsol_10um=Qsc_Comsol_10um./Voc_Comsol_10um;
Cap_Comsol_50um=Qsc_Comsol_50um./Voc_Comsol_50um;
Cap_Comsol_100um=Qsc_Comsol_100um./Voc_Comsol_100um;
%% Energy
Energy_Comsol_5um=0.5.*Qsc_Comsol_5um.*Voc_Comsol_5um;
Energy_Comsol_7um=0.5.*Qsc_Comsol_7um.*Voc_Comsol_7um;
Energy_Comsol_10um=0.5.*Qsc_Comsol_10um.*Voc_Comsol_10um;
Energy_Comsol_50um=0.5.*Qsc_Comsol_50um.*Voc_Comsol_50um;
Energy_Comsol_100um=0.5.*Qsc_Comsol_100um.*Voc_Comsol_100um;

%% Plotting Voltage
fig=Figure
plot(x.*10^3,Voc_Comsol_5um);
```

```
hold on
plot(x.*10^3,Voc_Comsol_7um);
hold on
plot(x.*10^3,Voc_Comsol_10um);
hold on
plot(x.*10^3,Voc_Comsol_50um);
hold on
plot(x.*10^3,Voc_Comsol_100um);
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here


%% Plotting Short Circuit Charge
fig=Figure
plot(x.*10^3,Qsc_Comsol_5um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_7um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_10um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_50um.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_100um.*10^9);
xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here



%% plotting Capacitance
fig=Figure
plot(x.*10^3,Cap_Comsol_5um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_7um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_10um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_50um.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_100um.*10^9);
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
```

```
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Plotting Energy
fig=Figure
plot(x.*10^3,Energy_Comsol_5um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_7um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_10um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_50um.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_100um.*10^3);
xlabel('Separation distance x (mm)');
ylabel('Energy (mJ)');
legend('g=5 \mu m','g=7 \mu m','g=10 \mu m','g=50 \mu m','g=100 \mu m')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 10 – MATLAB Code for the impact of the conductor thickness on the output TENG characteristics at the attached electrode sliding mode Conductor-to-dielectric

```
%% Author George Sherif
%% Attached electrode sliding mode Dielectric-to-dielectric
clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=0:0.01:0.09;
Er1=2;
Er2=4;
dm=10e-6;
d1=220e-6;
d2=0;
sigma=7e-6;
g=5e-6;
d0=d1/Er1+d2/Er2;

%% Open Circuit Voltage
Voc_Comsol_5um_10umdm=[3.9416 15.340 29.968 48.756 73.749 108.62 160.67 246.71 416.23 905.08];
Voc_Comsol_5um_220umdm=[3.9101 46.931 105.26 180.09 279.15 416.36 618.78 947.87 1575.0 3244.9];

%% Short Circuit Charge
Qsc_Comsol_5um_10umdm=[2.5929E-9 9.1158E-9 1.5844E-8 2.2581E-8 2.9320E-8 3.6060E-8 4.2800E-8
4.9541E-8 5.6281E-8 6.3022E-8];
Qsc_Comsol_5um_220umdm=[6.3044E-10 6.8864E-9 1.3774E-8 2.0696E-8 2.7627E-8 3.4561E-8 4.1496E-
8 4.8434E-8 5.5369E-8 6.2306E-8];

%% Capacitance
Cap_Comsol_5um_10umdm=Qsc_Comsol_5um_10umdm./Voc_Comsol_5um_10umdm;
Cap_Comsol_5um_220umdm=Qsc_Comsol_5um_220umdm./Voc_Comsol_5um_220umdm;

%% Energy
Energy_Comsol_5um_10umdm=0.5.*Qsc_Comsol_5um_10umdm.*Voc_Comsol_5um_10umdm;
Energy_Comsol_5um_220umdm=0.5.*Qsc_Comsol_5um_220umdm.*Voc_Comsol_5um_220umdm;

%% Plotting Voltage
fig=Figure
plot(x.*10^3,Voc_Comsol_5um_10umdm);
hold on
plot(x.*10^3,Voc_Comsol_5um_220umdm);
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
```

```
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here


%% Plotting Short Circuit Charge
fig=Figure
plot(x.*10^3,Qsc_Comsol_5um_10umdm.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_5um_220umdm.*10^9);

xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% plotting Capacitance
fig=Figure
plot(x.*10^3,Cap_Comsol_5um_10umdm.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_5um_220umdm.*10^9);
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Plotting Energy
fig=Figure
plot(x.*10^3,Energy_Comsol_5um_10umdm.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_5um_220umdm.*10^3);

xlabel('Separation distance x (mm)');
ylabel('Energy (mJ)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 11 – MATLAB Code for the impact of the conductor thickness on the output TENG characteristics at the attached electrode sliding mode Dielectric-to-dielectric

```
%% Author George Sherif
%% Attached electrode sliding mode Dielectric-to-dielectric
clc;
clear;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=0:0.01:0.09;
Er1=2;
Er2=4;
dm=10e-6;
d1=220e-6;
d2=0;
sigma=7e-6;
g=5e-6;
d0=d1/Er1+d2/Er2;

%% Open Circuit Voltage
Voc_Comsol_5um_10umdm=[3.9367 19.777 40.277 66.600 101.59 150.36 223.02 342.83 577.75 1246.9];
Voc_Comsol_5um_220umdm=[3.9092 50.588 114.47 196.40 304.80 454.80 675.98 1034.6 1715.8 3515.2];

%% Short Circuit Charge
Qsc_Comsol_5um_10umdm=[1.8417E-9 8.3684E-9 1.5169E-8 2.1980E-8 2.8793E-8 3.5608E-8 4.2424E-8
4.9239E-8 5.6055E-8 6.2871E-8];
Qsc_Comsol_5um_220umdm=[5.7373E-10 6.7651E-9 1.3655E-8  2.0580E-8 2.7517E-8 3.4457E-8
4.1399E-8 4.8342E-8 5.5282E-8 6.2225E-8];

%% Capacitance
Cap_Comsol_5um_10umdm=Qsc_Comsol_5um_10umdm./Voc_Comsol_5um_10umdm;
Cap_Comsol_5um_220umdm=Qsc_Comsol_5um_220umdm./Voc_Comsol_5um_220umdm;

%% Energy
Energy_Comsol_5um_10umdm=0.5.*Qsc_Comsol_5um_10umdm.*Voc_Comsol_5um_10umdm;
Energy_Comsol_5um_220umdm=0.5.*Qsc_Comsol_5um_220umdm.*Voc_Comsol_5um_220umdm;

%% Plotting Voltage
fig=Figure
plot(x.*10^3,Voc_Comsol_5um_10umdm);
hold on
plot(x.*10^3,Voc_Comsol_5um_220umdm);
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
```

```
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here


%% Plotting Short Circuit Charge
fig=Figure
plot(x.*10^3,Qsc_Comsol_5um_10umdm.*10^9);
hold on
plot(x.*10^3,Qsc_Comsol_5um_220umdm.*10^9);

xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% plotting Capacitance
fig=Figure
plot(x.*10^3,Cap_Comsol_5um_10umdm.*10^9);
hold on
plot(x.*10^3,Cap_Comsol_5um_220umdm.*10^9);
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Plotting Energy
fig=Figure
plot(x.*10^3,Energy_Comsol_5um_10umdm.*10^3);
hold on
plot(x.*10^3,Energy_Comsol_5um_220umdm.*10^3);

xlabel('Separation distance x (mm)');
ylabel('Energy (mJ)');
legend('dm = 10 \mu m','dm = 220 \mu m');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 12 – MATLAB Code for the attached electrode TENG Sliding mode Dielectric-to-dielectric

```
%% Author George Sherif
%% Attached electrode sliding mode Dielectric-to-dielectric
clc;
clear all;
close all;
%%
E0=8.854e-12;
w=0.1;
l=0.1;
x=10e-6:150e-6:1360e-6;
Er1=2;
Er2=4;
dm=10e-6;
d1=220e-6;
d2=220e-6;
sigma=7e-6;
g=5e-6;
d0=d1/Er1+d2/Er2;

%% Open Circuit Voltage
Voc_analytically=(sigma.*x.*(d0+g+2*dm)./(E0.*(w-x)))+sigma.*g./E0;
Voc_Comsol=[3.9371 4.0049 4.1397 4.3080 4.4944 4.6914 4.8953 5.1041 5.3165 5.5318];

fig=Figure
plot(x.*10^3,Voc_analytically,'b');
hold on
plot(x.*10^3,Voc_Comsol,'r');
xlabel('Separation distance x (mm)');
ylabel('Open Circuit Voltage (V)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
%% Short Circuit charge
Qsc_Comsol=[1.8419E-9 1.8728E-9   1.9342E-9 2.0106E-9 2.0950E-9 2.1840E-9 2.2758E-9 2.3696E-9 2.4647E-9 2.5609E-9];
Qsc_analytically=sigma.*l.*x+(sigma.*l.*(w-x).*g/(d0+g+2*dm))

fig=Figure
plot(x.*10^3,Qsc_analytically.*10^9,'b');
hold on
plot(x.*10^3,Qsc_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Short Circuit Charge (nC)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
```

```
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here

%% Capacitance
Cap_Comsol=Qsc_Comsol./Voc_Comsol;
Cap_analytically=Qsc_analytically./Voc_analytically;

fig=Figure
plot(x.*10^3,Cap_analytically.*10^9,'b');
hold on
plot(x.*10^3,Cap_Comsol.*10^9,'r');
xlabel('Separation distance x (mm)');
ylabel('Capacitance (nF)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here
%% Energy

Energy_Comsol=0.5.*Qsc_Comsol.*Voc_Comsol;
Energy_analytically=0.5.*Qsc_analytically.*Voc_analytically;

fig=Figure
plot(x.*10^3,Energy_analytically.*10^3,'b');
hold on
plot(x.*10^3,Energy_Comsol.*10^3,'r');
xlabel('Separation distance x (mm)');
ylabel('Enegry (\mu J)');
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
legend('Analytically','Comsol')
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont
need to change anything here
```

Appendix 13 – MATLAB Code for the impact of the different widths on the output TENG characteristics at the attached electrode Diagonal mode Conductor-to-dielectric

```
%% Author George Sherif
%% Attached electrode diagonal mode conductor-to-dielectric
clc;
clear;
close all;
theta=0:90;
%% Open circuit voltage
Voc_Comsol_w_1_cm=[42.818   46.781  49.685  51.927  53.647  55.052
56.194  57.145  57.938  58.614  59.187  59.681  60.109  60.463  60.795
61.08   61.342  61.551  61.758  61.933  62.101  62.229  62.36   62.479
62.587  62.671  62.767  62.844  62.933  62.979  63.036  63.09   63.135
63.177  63.218  63.26   63.284  63.321  63.344  63.375  63.402  63.425
63.451  63.466  63.485  63.506  63.52   63.546  63.588  63.58   63.596
63.605  63.622  63.637  63.649  63.663  63.663  63.684  63.689  63.7
63.742  63.724  63.737  63.749  63.744  63.755  63.763  63.77   63.769
63.784  63.79   63.784  63.786  63.806  63.798  63.79   63.79   63.771
63.752  63.726  63.688  63.659  63.607  63.54   63.444  63.325  63.195
62.963  62.642  62.077  60.91];
Voc_Comsol_w_5_cm=[16.525   27.239  34.712  40.222  44.457  47.806  50.53
52.766  54.647  56.255  57.63   58.837  59.886  60.818  61.632  62.384
63.051  63.65   64.197  64.696  65.149  65.566  65.951  66.307  66.632
66.936  67.218  67.482  67.724  67.956  68.168  68.368  68.558  68.734
68.901  69.06   69.208  69.35   69.482  69.61   69.734  69.842  69.948
70.048  70.147  70.234  70.324  70.403  70.483  70.559  70.633  70.703
70.767  70.82   70.88   70.938  70.993  71.045  71.102  71.149  71.194
71.236  71.277  71.316  71.352  71.388  71.421  71.452  71.479  71.511
71.541  71.559  71.578  71.599  71.62   71.631  71.645  71.663  71.671
71.67   71.677  71.687  71.683  71.677  71.665  71.647  71.614  71.571
71.502  71.382  71.116];
Voc_Comsol_w_10_cm=[13.172  24.7    32.735  38.665  43.214  46.812
49.732  52.141  54.169  55.895  57.382  58.676  59.81   60.814  61.709
62.507  63.228  63.875  64.469  65.008  65.507  65.96   66.379  66.765
67.123  67.455  67.764  68.052  68.321  68.574  68.808  69.029  69.238
69.434  69.619  69.794  69.959  70.115  70.263  70.402  70.534  70.66
70.78   70.893  71.002  71.109  71.202  71.295  71.384  71.47   71.549
71.627  71.698  71.77   71.834  71.9    71.956  72.017  72.072  72.119
72.175  72.224  72.27   72.313  72.355  72.394  72.43   72.465  72.498
72.529  72.559  72.587  72.611  72.635  72.658  72.678  72.697  72.712
72.727  72.739  72.749  72.758  72.762  72.764  72.763  72.758  72.744
72.724  72.692  72.633  72.499];
%% Short Circuit charge
Qsc_Comsol_w_1_cm=[4.32E-09 4.66E-09    4.90E-09    5.09E-09    5.23E-09
5.34E-09    5.43E-09    5.51E-09    5.57E-09    5.62E-09    5.67E-09
5.70E-09    5.74E-09    5.77E-09    5.79E-09    5.81E-09    5.83E-09
5.85E-09    5.87E-09    5.88E-09    5.89E-09    5.90E-09    5.91E-09
5.92E-09    5.93E-09    5.94E-09    5.94E-09    5.95E-09    5.95E-09
5.96E-09    5.96E-09    5.96E-09    5.97E-09    5.97E-09    5.97E-09
5.98E-09    5.98E-09    5.98E-09    5.98E-09    5.99E-09    5.99E-09
5.99E-09    5.99E-09    5.99E-09    6.00E-09    6.00E-09    6.00E-09
6.00E-09    6.00E-09    6.00E-09    6.00E-09    6.00E-09    6.00E-09
6.01E-09    6.01E-09    6.01E-09    6.01E-09    6.01E-09    6.01E-09
6.01E-09    6.01E-09    6.01E-09    6.01E-09    6.01E-09    6.02E-09
6.02E-09    6.02E-09    6.02E-09    6.02E-09    6.02E-09    6.02E-09
```

```
6.02E-09    6.02E-09    6.02E-09    6.02E-09    6.02E-09    6.02E-09
6.02E-09    6.02E-09    6.02E-09    6.02E-09    6.01E-09    6.01E-09
6.00E-09    6.00E-09    5.99E-09    5.98E-09    5.96E-09    5.94E-09
5.90E-09    5.83E-09];
Qsc_Comsol_w_5_cm=[8.35E-09 1.35E-08    1.69E-08    1.93E-08    2.12E-08
2.26E-08    2.38E-08    2.47E-08    2.55E-08    2.62E-08    2.68E-08
2.73E-08    2.77E-08    2.81E-08    2.84E-08    2.87E-08    2.90E-08
2.92E-08    2.94E-08    2.96E-08    2.98E-08    3.00E-08    3.01E-08
3.03E-08    3.04E-08    3.05E-08    3.06E-08    3.07E-08    3.08E-08
3.09E-08    3.10E-08    3.11E-08    3.12E-08    3.12E-08    3.13E-08
3.14E-08    3.14E-08    3.15E-08    3.15E-08    3.16E-08    3.16E-08
3.17E-08    3.17E-08    3.18E-08    3.18E-08    3.18E-08    3.19E-08
3.19E-08    3.19E-08    3.20E-08    3.20E-08    3.20E-08    3.20E-08
3.21E-08    3.21E-08    3.21E-08    3.21E-08    3.22E-08    3.22E-08
3.22E-08    3.22E-08    3.22E-08    3.22E-08    3.23E-08    3.23E-08
3.23E-08    3.23E-08    3.23E-08    3.23E-08    3.23E-08    3.23E-08
3.24E-08    3.24E-08    3.24E-08    3.24E-08    3.24E-08    3.24E-08
3.24E-08    3.24E-08    3.24E-08    3.24E-08    3.24E-08    3.24E-08
3.24E-08    3.24E-08    3.24E-08    3.24E-08    3.24E-08    3.24E-08
3.23E-08    3.22E-08];
Qsc_Comsol_w_10_cm=[1.33E-08    2.44E-08    3.18E-08    3.71E-08
4.11E-08    4.42E-08    4.67E-08    4.87E-08    5.04E-08    5.19E-08
5.31E-08    5.42E-08    5.51E-08    5.59E-08    5.66E-08    5.73E-08
5.79E-08    5.84E-08    5.89E-08    5.93E-08    5.97E-08    6.00E-08
6.04E-08    6.07E-08    6.10E-08    6.12E-08    6.15E-08    6.17E-08
6.19E-08    6.21E-08    6.23E-08    6.25E-08    6.26E-08    6.28E-08
6.29E-08    6.31E-08    6.32E-08    6.33E-08    6.34E-08    6.36E-08
6.37E-08    6.38E-08    6.39E-08    6.39E-08    6.40E-08    6.41E-08
6.42E-08    6.43E-08    6.43E-08    6.44E-08    6.45E-08    6.45E-08
6.46E-08    6.46E-08    6.47E-08    6.47E-08    6.48E-08    6.48E-08
6.49E-08    6.49E-08    6.49E-08    6.50E-08    6.50E-08    6.51E-08
6.51E-08    6.51E-08    6.51E-08    6.52E-08    6.52E-08    6.52E-08
6.52E-08    6.53E-08    6.53E-08    6.53E-08    6.53E-08    6.53E-08
6.54E-08    6.54E-08    6.54E-08    6.54E-08    6.54E-08    6.54E-08
6.54E-08    6.54E-08    6.54E-08    6.54E-08    6.54E-08    6.54E-08
6.54E-08    6.53E-08    6.53E-08];

%% Capacitance
Cap_Comsol_w_1_cm=Qsc_Comsol_w_1_cm./Voc_Comsol_w_1_cm;
Cap_Comsol_w_5_cm=Qsc_Comsol_w_5_cm./Voc_Comsol_w_5_cm;
Cap_Comsol_w_10_cm=Qsc_Comsol_w_10_cm./Voc_Comsol_w_10_cm;

%% Energy
Energy_Comsol_w_1_cm=0.5.*Voc_Comsol_w_1_cm.*Qsc_Comsol_w_1_cm;
Energy_Comsol_w_5_cm=0.5.*Voc_Comsol_w_5_cm.*Qsc_Comsol_w_5_cm;
Energy_Comsol_w_10_cm=0.5.*Voc_Comsol_w_10_cm.*Qsc_Comsol_w_10_cm;

%% Plotting open circuit voltage
fig=Figure;
plot(theta,Voc_Comsol_w_1_cm,'-b');
hold on
plot(theta,Voc_Comsol_w_5_cm,'-or');
hold on
plot(theta,Voc_Comsol_w_10_cm,'--k');

xlabel('Angle of inclination  ({\circ})');
ylabel('Open Circuit Voltage (V)');
legend('width= 1 cm','width= 5 cm','width=10 cm')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
```

```
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
%% Plotting short circuit charge

fig=Figure;
plot(theta,Qsc_Comsol_w_1_cm.*10^9,'-b');
hold on
plot(theta,Qsc_Comsol_w_5_cm.*10^9,'-or');
hold on
plot(theta,Qsc_Comsol_w_10_cm.*10^9,'--k');

xlabel('Angle of inclination  ({\circ})');
ylabel('Short Circuit charge (nC)');
legend('width= 1 cm','width= 5 cm','width=10 cm')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% plotting Capacitance

fig=Figure;
plot(theta,Cap_Comsol_w_1_cm.*10^9,'-b');
hold on
plot(theta,Cap_Comsol_w_5_cm.*10^9,'-or');
hold on
plot(theta,Cap_Comsol_w_10_cm.*10^9,'--k');
xlabel('Angle of inclination  ({\circ})');
ylabel('Capacitance (nF)');
legend('width= 1 cm','width= 5 cm','width=10 cm')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Plotting energy

fig=Figure;
plot(theta,Energy_Comsol_w_1_cm.*10^6,'-b');
hold on
plot(theta,Energy_Comsol_w_5_cm.*10^6,'-or');
hold on
plot(theta,Energy_Comsol_w_10_cm.*10^6,'--k');
xlabel('Angle of inclination  ({\circ})');
ylabel('Output energy (\mu J)');
legend('width= 1 cm','width= 5 cm','width=10 cm')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
```

```
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 14 – MATLAB Code for the attached electrode TENG diagonal mode Conductor-to-dielectric

```
%% Author George Sherif
%% Attached electrode diagonal mode conductor-to-dielectric
clc;
clear all;
close all;
x=100e-6;
sigma=10e-6;
w=1000e-6;
l=0.1;
d1=220e-6;
d2=0;
Er1=2;
Er2=4;
d0=(d1/Er1)+(d2/Er2);
E0=8.854e-12;
g=90e-6;
dm=10e-6;
theta=0:90;

%% k1= 1um k2= 1 um

k1=1e-6; k2=1e-6;

Voc_Comsol=[0.5298  0.53493 0.53998 0.54495 0.54983 0.55463 0.55935 0.56399 0.56855 0.57303
0.57744 0.58176 0.58602 0.59021 0.59431 0.59835 0.60232 0.60621 0.61005 0.61381 0.6175  0.62114
0.62471 0.6282  0.63165 0.63502 0.63835 0.6416  0.64481 0.64795 0.65103 0.65407 0.65705 0.65997
0.66283 0.66567 0.66844 0.67115 0.67381 0.67643 0.67899 0.68151 0.68398 0.6864  0.68879 0.69116
0.6934  0.69563 0.69782 0.69998 0.70209 0.70414 0.70621 0.70816 0.71011 0.71196 0.71386 0.71567
0.71749 0.71925 0.72094 0.72252 0.72423 0.72582 0.72733 0.72888 0.73039 0.73184 0.73324 0.73461
0.7359  0.7372  0.73848 0.73969 0.74086 0.74198 0.74307 0.74411 0.7451  0.74604 0.74692 0.74775
0.74851 0.74919 0.74979 0.7503  0.75065 0.75084 0.75079 0.75041 0.74936];
Qsc_Comsol=[4.74E-10    4.79E-10    4.83E-10    4.88E-10    4.92E-10    4.96E-10    5.01E-10    5.05E-10
5.09E-10    5.13E-10    5.17E-10    5.21E-10    5.24E-10    5.28E-10    5.32E-10    5.35E-10    5.39E-10
5.42E-10    5.46E-10    5.49E-10    5.52E-10    5.56E-10    5.59E-10    5.62E-10    5.65E-10    5.68E-10
5.71E-10    5.74E-10    5.77E-10    5.80E-10    5.82E-10    5.85E-10    5.88E-10    5.90E-10    5.93E-10
5.95E-10    5.98E-10    6.00E-10    6.03E-10    6.05E-10    6.07E-10    6.09E-10    6.12E-10    6.14E-10
6.16E-10    6.18E-10    6.20E-10    6.22E-10    6.24E-10    6.26E-10    6.28E-10    6.30E-10    6.31E-10
6.33E-10    6.35E-10    6.37E-10    6.38E-10    6.40E-10    6.42E-10    6.43E-10    6.45E-10    6.46E-10
6.48E-10    6.49E-10    6.51E-10    6.52E-10    6.53E-10    6.54E-10    6.56E-10    6.57E-10    6.58E-10
6.59E-10    6.60E-10    6.62E-10    6.63E-10    6.64E-10    6.65E-10    6.65E-10    6.66E-10    6.67E-10
6.68E-10    6.69E-10    6.70E-10    6.70E-10    6.71E-10    6.71E-10    6.72E-10    6.72E-10    6.72E-10
6.72E-10    6.71E-10];

Qsc_analytically=sigma.*l.*x.*cosd(theta)+sigma.*l.*(w-
x.*cosd(theta)).*(x.*sind(theta)+g)./(d0+x.*sind(theta)+g+2.*dm+k1);

C1=(E0.*l.*(w-x.*cosd(theta))./(d0+2.*dm+x.*sind(theta)+g));
C2=E0.*(l.*w)./(k1);
C3=E0.*(dm).*l./k2;
C4=E0.*(dm).*l./((k2)+x.*cosd(theta));

Cap_Comsol=Qsc_Comsol./Voc_Comsol;
```

```
Cap_analytically=C1+C2+C3+C4;
Voc_analytically=Qsc_analytically./Cap_analytically;

Energy_Comsol=0.5*Qsc_Comsol.*Voc_Comsol;
Energy_analytically=0.5*Qsc_analytically.*Voc_analytically;

mean(abs(Voc_Comsol-Voc_analytically)./Voc_Comsol)*100
mean(abs(Cap_Comsol-Cap_analytically)./Cap_Comsol)*100
mean(abs(Qsc_Comsol-Qsc_analytically)./Qsc_Comsol)*100

%% Open circuit voltage
fig=Figure;
plot(theta,Voc_analytically,'b');
hold on
plot(theta,Voc_Comsol,'r');
xlabel('\Theta {\circ}');
ylabel('Open Circuit Voltage (V)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Short Circuit charge
fig=Figure;
plot(theta,Qsc_analytically.*10^9,'b');
hold on
plot(theta,Qsc_Comsol.*10^9,'r');
xlabel('\Theta {\circ}');
ylabel('Short Circuit charge (nC)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Capacitance

fig=Figure;
plot(theta,Cap_analytically.*10^9,'b');
hold on
plot(theta,Cap_Comsol.*10^9,'r');
xlabel('\Theta {\circ}');
ylabel('Capacitance (nF)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

```
%% Energy

fig=Figure;
plot(theta,Energy_analytically.*10^9,'b');
hold on
plot(theta,Energy_Comsol.*10^9,'r');
xlabel('\Theta {\circ}');
ylabel('Energy (nJ)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 15 – MATLAB Code for the attached electrode TENG diagonal mode Dielectric-to-dielectric

```
%% Author George Sherif
%% Attached electrode diagonal mode dielectric-to-dielectric
clc;
clear all;
close all;
x=100e-6;
sigma=10e-6;
w=1000e-6;
l=0.1;
d1=25e-6;
d2=25e-6;
Er1=2;
Er2=4;
d0=(d1/Er1)+(d2/Er2);
E0=8.854e-12;
g=90e-6;
dm=10e-6;
theta=0:90;

%% k1= 1um k2= 1 um

k1=1e-6; k2=1e-6;

Voc_Comsol=[0.7156  0.71992 0.72413 0.72823 0.73222 0.7361  0.73988 0.74355 0.74715 0.75064 0.75404
0.75736 0.76058 0.76372 0.76678 0.76975 0.77266 0.77549 0.77825 0.78092 0.78354 0.78606 0.78855
0.79095 0.79331 0.7956  0.79782 0.79998 0.8021  0.80414 0.80616 0.80809 0.81    0.81184 0.81363
0.81541 0.81709 0.81875 0.82035 0.8219  0.82344 0.82489 0.82633 0.8277  0.82906 0.83041 0.83162
0.83284 0.83401 0.83515 0.83627 0.83731 0.83835 0.83933 0.84031 0.84121 0.84206 0.84291 0.84375
0.84454 0.84525 0.84583 0.84658 0.84715 0.84776 0.84831 0.84884 0.84933 0.84973 0.85011 0.85045
0.85073 0.85096 0.85112 0.85126 0.85133 0.85134 0.85128 0.85111 0.85091 0.85061 0.8502  0.84966
0.84901 0.84823 0.84731 0.84613 0.84473 0.84306 0.84101 0.83828];
Qsc_Comsol=[6.42E-10    6.46E-10    6.50E-10    6.54E-10    6.57E-10    6.60E-10    6.64E-10    6.67E-10
6.70E-10    6.73E-10    6.76E-10    6.79E-10    6.82E-10    6.85E-10    6.88E-10    6.90E-10    6.93E-10
6.95E-10    6.98E-10    7.00E-10    7.02E-10    7.05E-10    7.07E-10    7.09E-10    7.11E-10    7.13E-10
7.15E-10    7.17E-10    7.19E-10    7.21E-10    7.22E-10    7.24E-10    7.26E-10    7.27E-10    7.29E-10
7.31E-10    7.32E-10    7.34E-10    7.35E-10    7.36E-10    7.38E-10    7.39E-10    7.40E-10    7.41E-10
7.43E-10    7.44E-10    7.45E-10    7.46E-10    7.47E-10    7.48E-10    7.49E-10    7.50E-10    7.51E-10
7.52E-10    7.53E-10    7.53E-10    7.54E-10    7.55E-10    7.56E-10    7.56E-10    7.57E-10    7.58E-10
7.58E-10    7.59E-10    7.59E-10    7.60E-10    7.60E-10    7.61E-10    7.61E-10    7.61E-10    7.62E-10
7.62E-10    7.62E-10    7.62E-10    7.62E-10    7.62E-10    7.62E-10    7.62E-10    7.62E-10    7.62E-10
7.62E-10    7.62E-10    7.61E-10    7.61E-10    7.60E-10    7.59E-10    7.58E-10    7.57E-10    7.56E-10
7.54E-10    7.52E-10];

Qsc_analytically=sigma.*l.*x.*cosd(theta)+sigma.*l.*(w-
x.*cosd(theta)).*(x.*sind(theta)+g)./(d0+x.*sind(theta)+g+2.*dm+k1);

C1=(E0.*l.*(w-x.*cosd(theta))./(d0+2.*dm+x.*sind(theta)+g));
C2=E0.*(l.*w)./(k1);
C3=E0.*(dm).*l./k2;
C4=E0.*(dm).*l./((k2)+x.*cosd(theta));

Cap_Comsol=Qsc_Comsol./Voc_Comsol;
```

```
Cap_analytically=C1+C2+C3+C4;
Voc_analytically=Qsc_analytically./Cap_analytically;

Energy_Comsol=0.5*Qsc_Comsol.*Voc_Comsol;
Energy_analytically=0.5*Qsc_analytically.*Voc_analytically;

mean(abs(Voc_Comsol-Voc_analytically)./Voc_Comsol)*100
mean(abs(Cap_Comsol-Cap_analytically)./Cap_Comsol)*100
mean(abs(Qsc_Comsol-Qsc_analytically)./Qsc_Comsol)*100

%% Open circuit voltage
fig=Figure;
plot(theta,Voc_analytically,'b');
hold on
plot(theta,Voc_Comsol,'r');
xlabel('Angle of inclination  ({\circ})');
ylabel('Open Circuit Voltage (V)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Short Circuit charge
fig=Figure;
plot(theta,Qsc_analytically.*10^9,'b');
hold on
plot(theta,Qsc_Comsol.*10^9,'r');
xlabel('Angle of inclination  ({\circ})');
ylabel('Short Circuit charge (nC)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here

%% Capacitance

fig=Figure;
plot(theta,Cap_analytically.*10^9,'b');
hold on
plot(theta,Cap_Comsol.*10^9,'r');
xlabel('Angle of inclination  ({\circ})');
ylabel('Capacitance (nF)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

```
%% Energy

fig=Figure;
plot(theta,Energy_analytically.*10^9,'b');
hold on
plot(theta,Energy_Comsol.*10^9,'r');
xlabel('Angle of inclination  ({\circ})');
ylabel('Energy (nJ)');
legend('Analytically','Comsol')
set(gca,'FontName','Times New Roman','FontSize',15,'FontWeight','bold');
rez=500; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the Figure you want to export
figpos=getpixelposition(f); %dont need to change anything here
resolution=get(0,'ScreenPixelsPerInch'); %dont need to change anything here
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,'paperposition',[0 0 figpos(3:4)/resolution]); %dont need to change anything here
```

Appendix 16 – User guide

1. Open the TENG CAD tool.exe and the following Figure appears

Figure A.16 1 Welcome Screen

2. Press Next

3. Choose between the modes (attached electrode and single electrode) as shown below

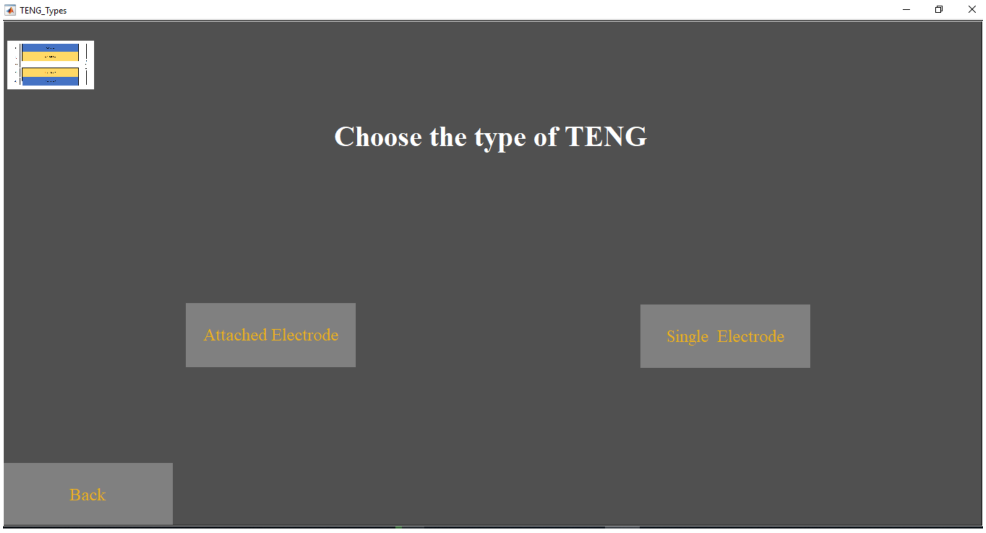


Figure A.16 2 Choice of different types of the TENG

4. <u>In case of the attached electrode:</u>

   Choose between the different modes of operation as shown below

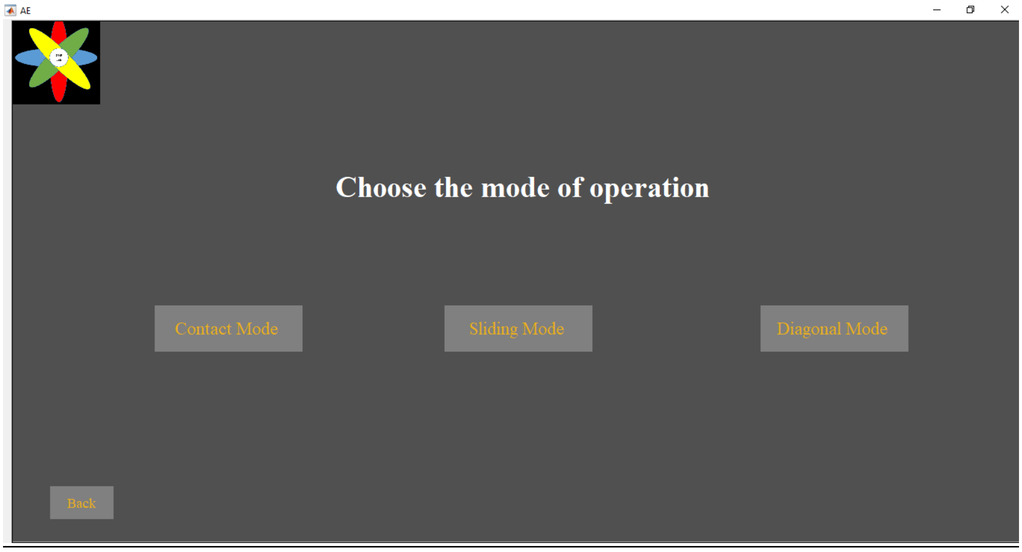


Figure A.16 3 Modes of operation in the attached electrode mode TENG

<u>**In case of Contact Mode:**</u>

Choose between the different types:

Figure A.16 4 Types of the Contact mode

i. <u>In case of the conductor-to-dielectric:</u>

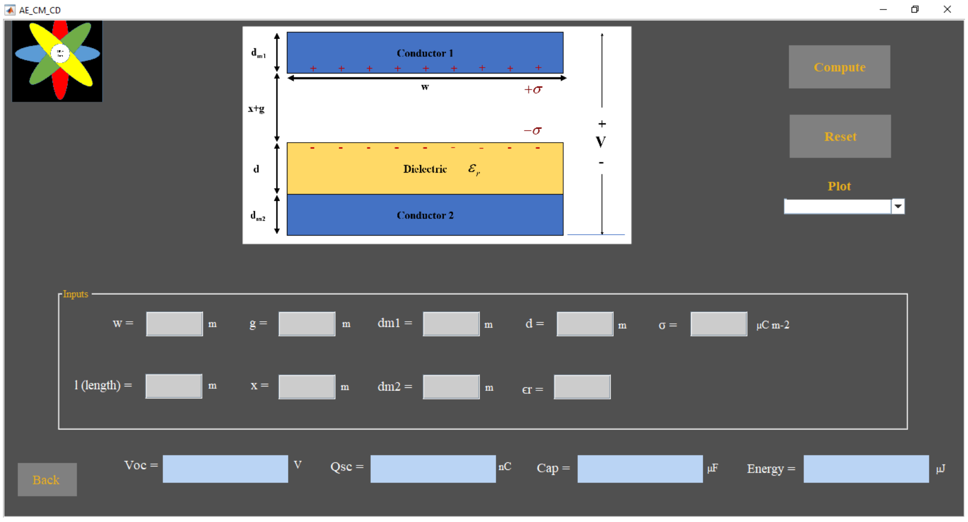


Figure A.16 5 GUI for the attached electrode contact mode TENG conductor-to-dielectric

- Press **Reset** button to get the default values of the parameters. These values can be edited by the user.
- Press **Compute** button to get V_{oc}, Q_{sc}, Cap, and Energy.
- Plot Button is to plot (V_{oc} vs. x), (Q_{sc} vs. x), (Cap vs. x), or (Energy vs. x)

Design restrictions:

(x+g) does not exceed 10*(d0+dm1+dm2)

.iiIn case of the dielectric-to-dielectric:

Follow the same steps as in the conductor-to-dielectric

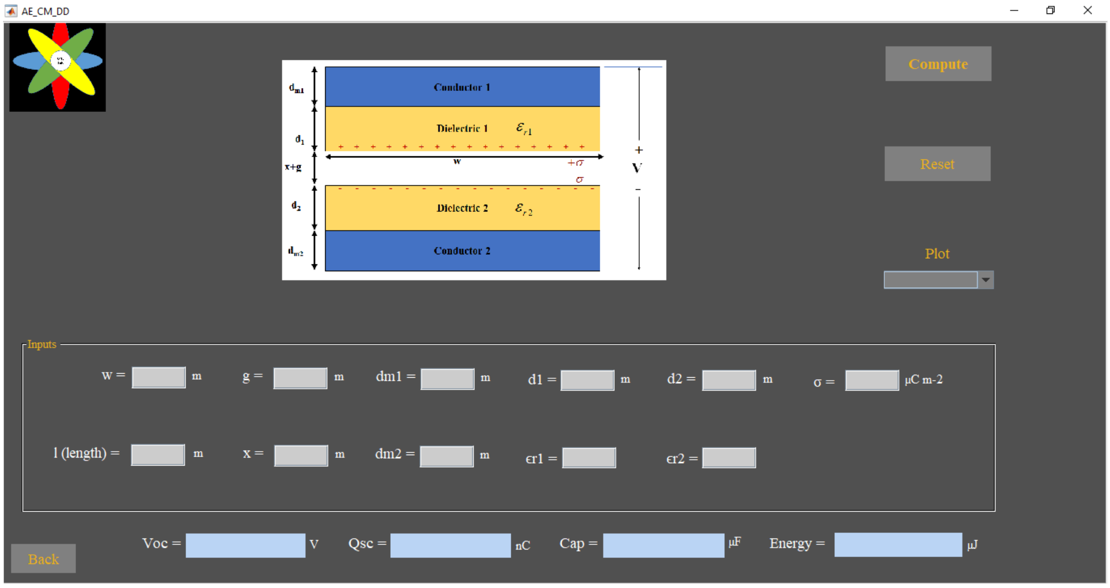


Figure A.16 6 GUI for the attached electrode contact mode TENG dielectric-to-dielectric

a. <u>In case of sliding mode:</u>

Follow up the same steps as in case of contact mode, but with the sliding mode conductor-to-dielectric and dielectric-to-dielectric Figures as shown below.

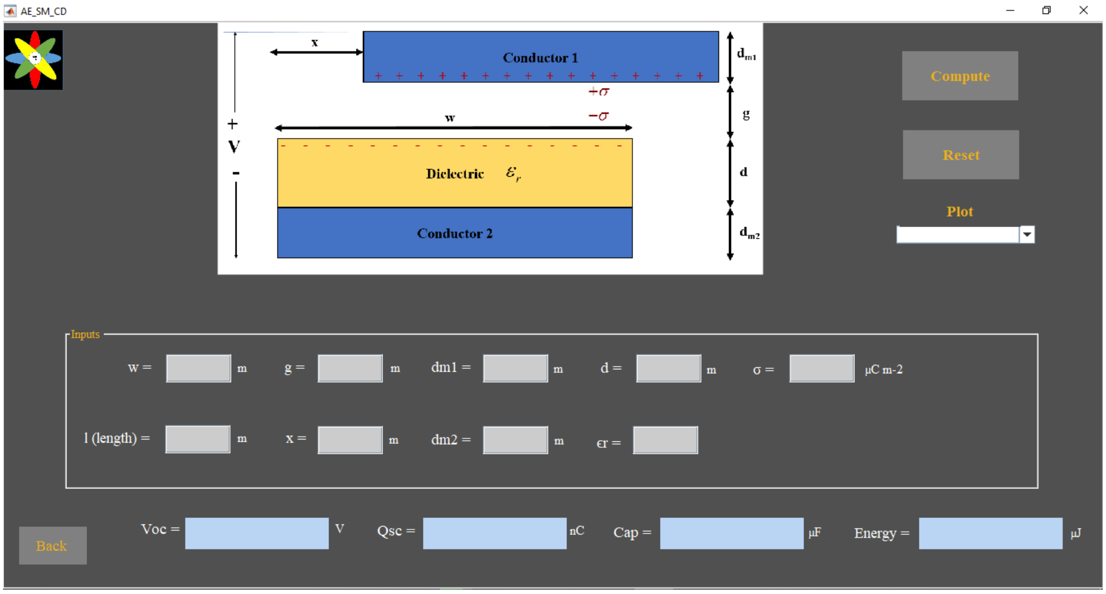


Figure A.16 7 GUI for the attached electrode sliding mode TENG conductor-to-dielectric

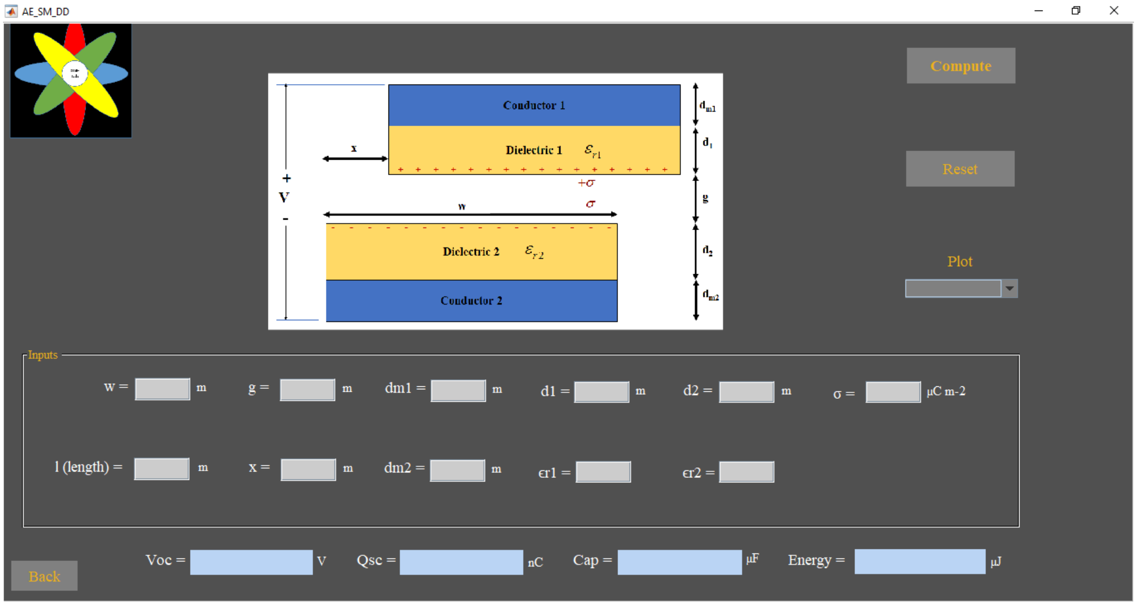


Figure A.16 8 GUI for the attached electrode sliding mode TENG dielectric-to-dielectric

<u>Design restrictions:</u>

- x cannot exceed 0.9w

b. <u>In case of Diagonal mode</u>

Follow the previous steps as in attached electrode contact mode conductor-to-dielectric, but with the diagonal mode conductor-to-dielectric and dielectric-to-dielectric Figures as shown below.

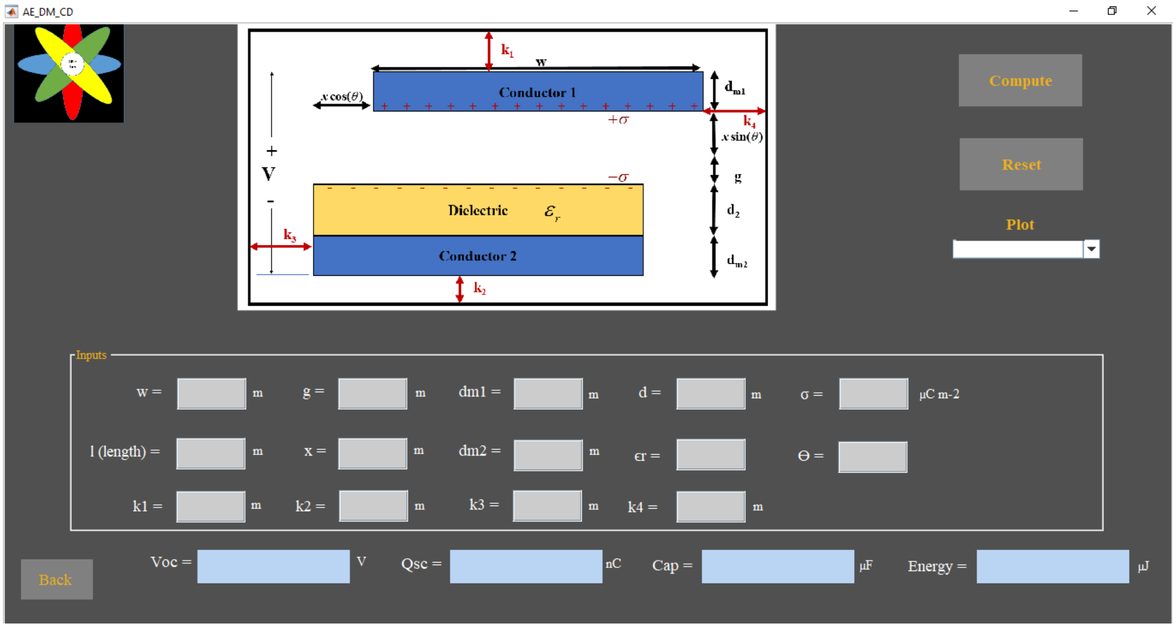


Figure A.16 9 GUI for the attached electrode diagonal mode TENG conductor-to-dielectric

Appendix 17 – Installation guide

1. In order to use the CAD tool, MATLAB must be installed on the computer.
2. Version of the windows must be 64 bit
3. Run TENG CAD Tool.exe

دراسة النماذج المختلفة للمولدات الكهربية الدقيقة المعتمدة على الإحتكاك

إعداد

جورج شريف نصيف جرجس

الرسالة مقدمة لكلية الهندسة
بالجامعة البريطانية في مصر

للحصول علي درجة الماجسيتير في
هندسة الطاقة الجديدة والمتجدة

2018 / 2019
القاهرة

دراسة النماذج المختلفة للمولدات الكهربية الدقيقة المعتمدة على الإحتكاك

رسالة ماجستير:

اسم الطالب: جورج شريف نصيف جرجس بشاي مكسيموس
عنوان الرسالة : دراسة النماذج المختلفة للمولدات الكهربية الدقيقة المعتمدة على الإحتكاك
اسم الدرجة : ماجستير في هندسة الطاقة الجديدة والمتجددة

لجنة الاشراف:

١. **د. أشرف سليم:**

مدرس بقسم الهندسة الكهربية – كلية الهندسة – الجامعة البريطانية في مصر

٢. **أ.د.م. حسن مصطفى:**

أستاذ دكتور مساعد بقسم هندسة الاتصالات و الاليكترونيات – كلية الهندسة – جامعة القاهرة

ملخص الرسالة باللغة العربية

عُرف تأثير الاحتكاك لتوليد الطاقة الكهربية " Triboelectrification" منذ العصر اليوناني القديم، وبناءً عليه قد أُخترع المولد الكهربي الاحتكاكي النانوي (TENG) والذي يستخدم لتحويل الطاقة الميكانيكية إلى طاقة كهربية، ويعد ال (TENG) مرشح واعد لتوليد وحصاد الطاقة الكهربية، حيث يستخدم لتحويل الطاقة الميكانيكة متسما بالعديد من المزايا. في هذا البحث؛ تم عمل دراسة استقصائية على الأنواع المختلفة المستخدمة لصناعة ال (TENG) المتصل الأقطاب. وتم عرض اقتراح تقنية جديدة لمولد ذا حركة قطرية ودراسته بشكل مكثف باستخدام برنامج كومسول (COMSOL) المحلل للعناصر المحدودة. فالحركة القطرية توفر درجة جديدة من الحرية مما يسمح بتحسين توليد الطاقة. تم بناء أداة CAD جديدة على أسس المعادلات التحليلية المستمدة من كلا من نتائج محاكاة COMSOL وأيضا الإطار النظري. وتم دراسة تأثير الفجوة على تقنية الانزلاق لتوليد الطاقة في ال (TENG) المتصل الأقطاب بشكل مكثف. فالفجوة لها تأثير عظيم على معلمات خرج ال (TENG) مثل جهد الدائرة المفتوحة، وشحنة الدائرة المقصورة، وسعة المكثف، وجهد الخرج. تم عمل مقارنة بين نتائج المحاكاة المثلى لكل تقنيات ال (TENG) المتصل الأقطاب المختلفة، وأظهرت النتائج أن المولد المتصل ذو الحركة القطرية ينتج عنه سعة كبيرة، بينما ينتج عن المولد المتصل جهد عالي للدائرة المفتوحة وطاقة خرج عالية و شحنة عالية للدائرة القصورية.