DESIGN AND SIMULATION OF SUSTAINABLE TRIBOELECTRIC NANOGENERATORS FOR BIOMEDICAL APPLICATION

Project Reference No.: *48S_BE_3129*

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Keywords:

Triboelectric Nanogenerators, Energy Harvesting, Biomedical Applications, Biocompatible Materials, Power Management, Wearable Devices, Implantable Devices, Prosthetics, Sustainable Energy.

Introduction:

Triboelectric nanogenerators:

Triboelectric nanogenerators (TENGs) are innovative devices that utilize the principles of contact electrification and electrostatic induction to convert mechanical energy into electrical energy. This energy-harvesting mechanism is highly efficient, scalable, and capable of generating power from a variety of mechanical stimuli, such as motion, vibrations, or pressure. TENGs represent a significant advancement in sustainable energy solutions, particularly for applications where conventional power sources are impractical or unsustainable

Application Relevance

In the biomedical field, there is a growing demand for self-powered devices that can operate without frequent external power input. These devices include wearable health monitors, implantable sensors, and drug delivery systems. The integration of TENGs into such applications offers the potential for continuous energy supply through biomechanical movements, such as walking, heartbeat, or respiratory motions, thereby enhancing device autonomy and reliability. This capability is particularly critical in scenarios where battery replacement or external charging is inconvenient or risky.

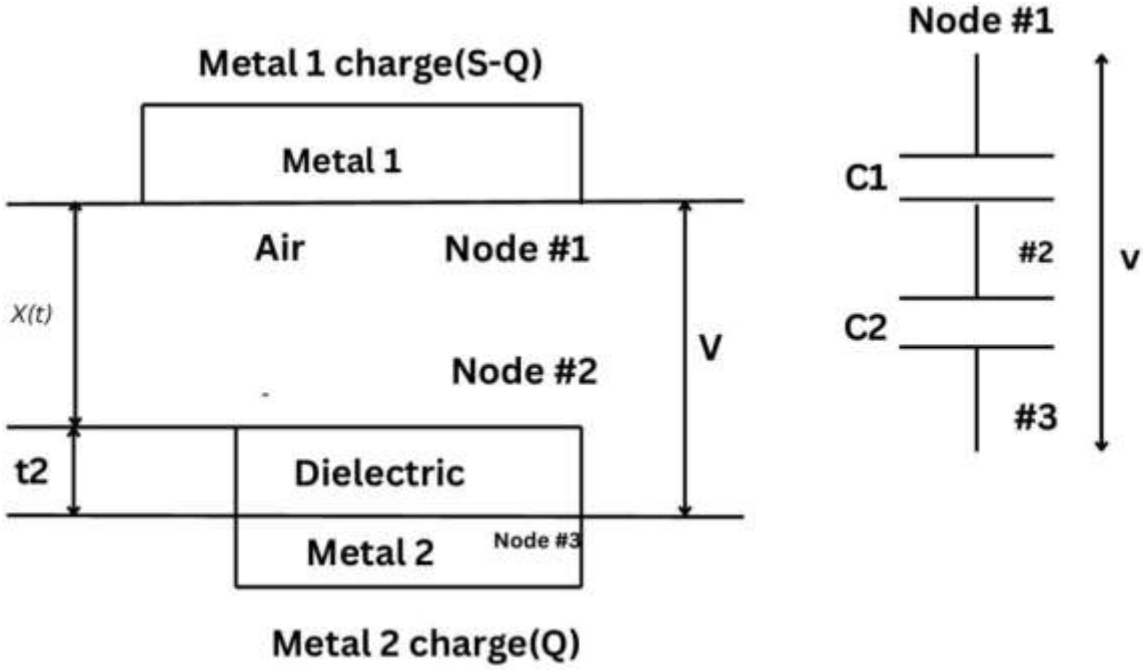

Figure 1: The Proposed System Design

Objectives:

1. To explore the potential of triboelectric nanogenerators (TENGs) for energy harvesting in biomedical applications.

2. To identify suitable biocompatible materials for safe integration into wearable and implantable devices.

3. To evaluate the performance and efficiency of TENGs in powering medical devices such as sensors, monitors, and drug delivery systems.

Methodology:

1. Material Selection and Design: Selection of suitable triboelectric and biocompatible materials based on mechanical flexibility, energy output, and compatibility with human tissue.

2. Biomechanical Energy Capture: Harvesting energy from body movements such as walking, respiration, joint motion, and heartbeat using TENGs placed

at strategic body locations.

3. To analyse the influence of different material properties and geometries on TENG performance through simulation.

4. To evaluate the output voltage, current, and power under simulated biomechanical conditions (e.g., breathing, joint movement).

Flowchart: Material Selection

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Geometry Design (COMSOL)

↓

Meshing & Physics Setup

↓

Simulation Setup (Modes & Parameters)

↓

Solve Electrostatic Equations

↓

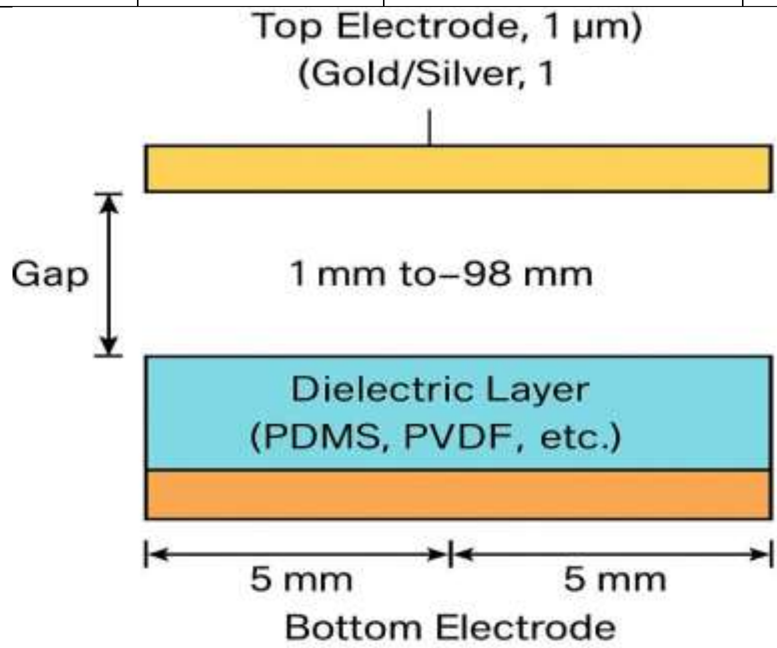
Post-Processing (Electric Field, Voltage, Surface Charge)

↓

Result Analysis (Comparative Material/Mode Study)

Component	Material	Property	Value
Dielectric Layer	**PDMS**	**Relative Permittivity (εr)**	**2**
	PVDF	**Relative Permittivity (εr)**	**~10**
	Mica	**Relative Permittivity (εr)**	**5–7**

	PTFE	**Relative Permittivity (εr)**	**2.1**
Electrodes	**Gold (Au)**	**Thickness**	**1 μm**
	Silver (Ag)	**Thickness**	**1 μm**
Substrate Coating	**Biocompatible polymer**		**Used for bio- safety**



The above Schematic depicts the proposed system Methodology with the materials and dimensions included.

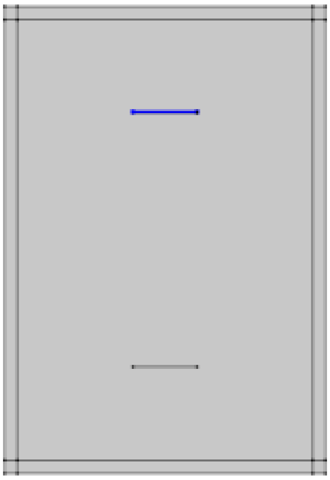


Figure 1: Top electrode of TENG

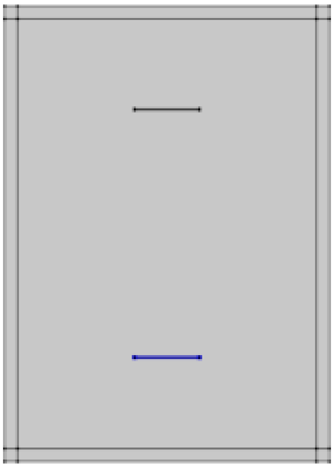


Figure 2: Bottom electrode of TENG

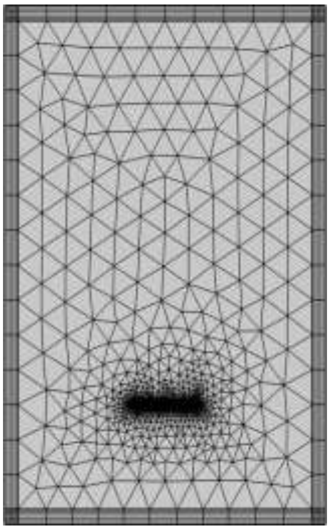


Figure 3: Controlled mesh

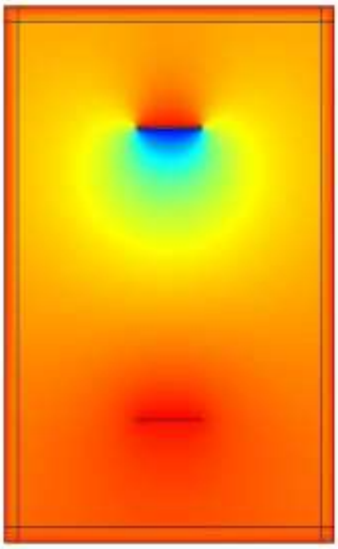


Figure 4: Electric potential

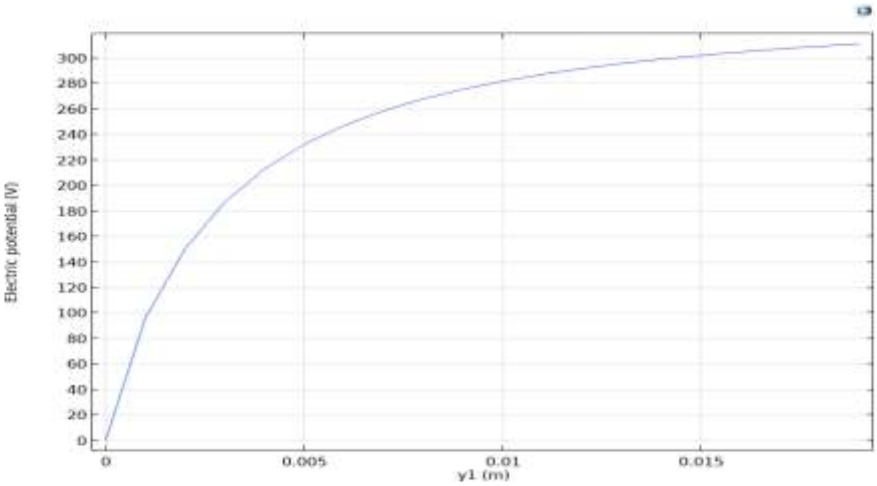


Figure 5: Plot Graph of Electric Potential

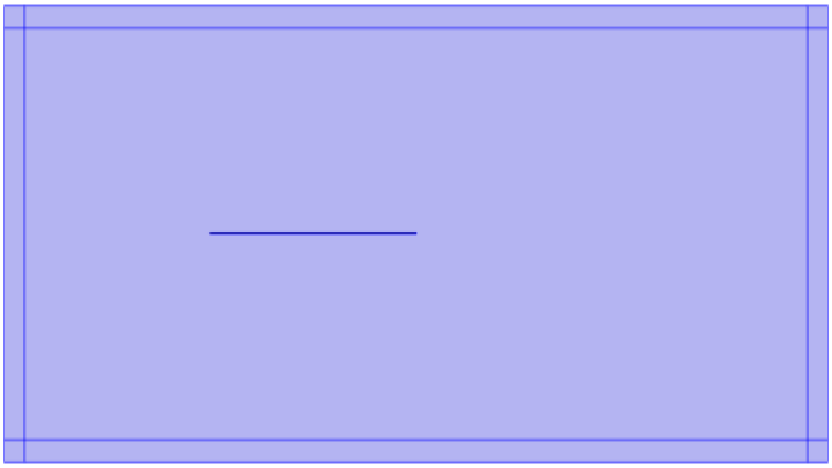


Figure 6 : Basic model of sliding mode

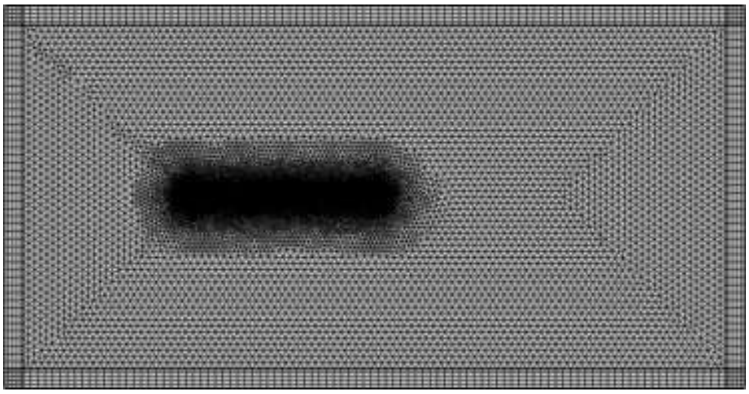


Figure 7 : Mesh structure

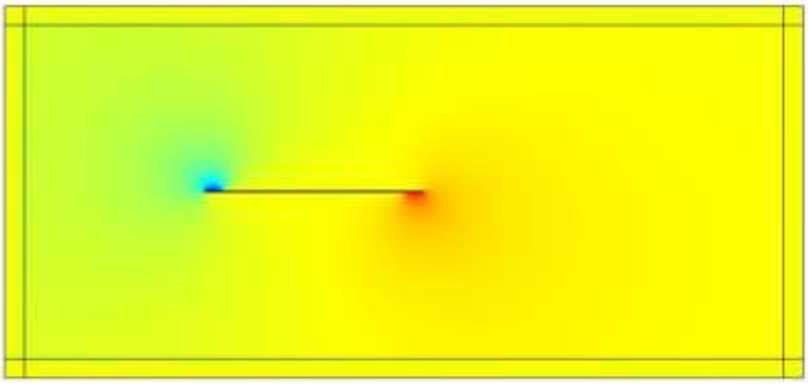


Figure 8 : 10mm separation

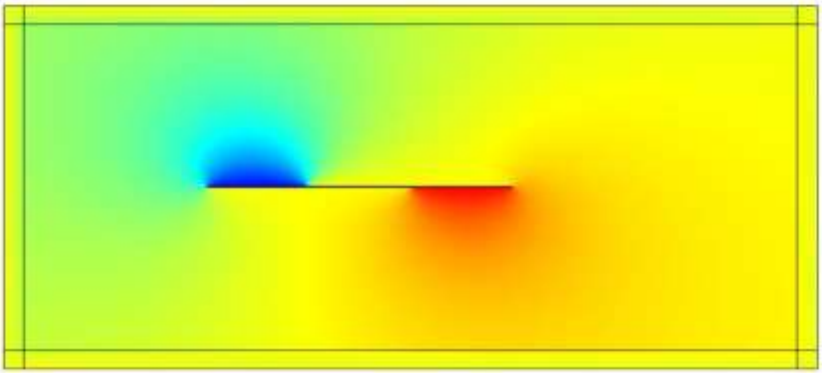


Figure 9 : 50mm separation

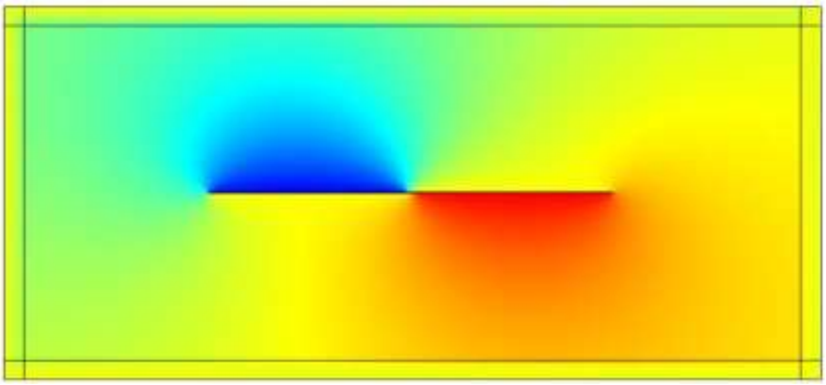


Figure 10 : 98mm separation

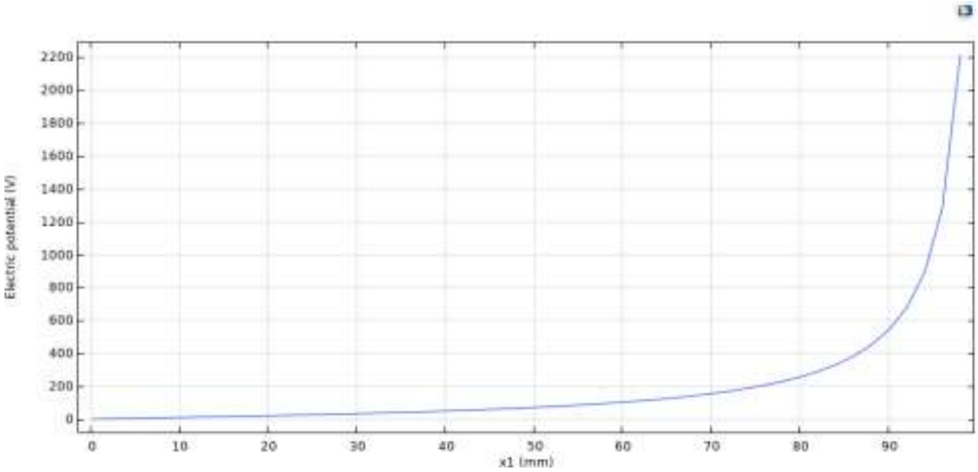


Figure 11 : Graph for electric potential

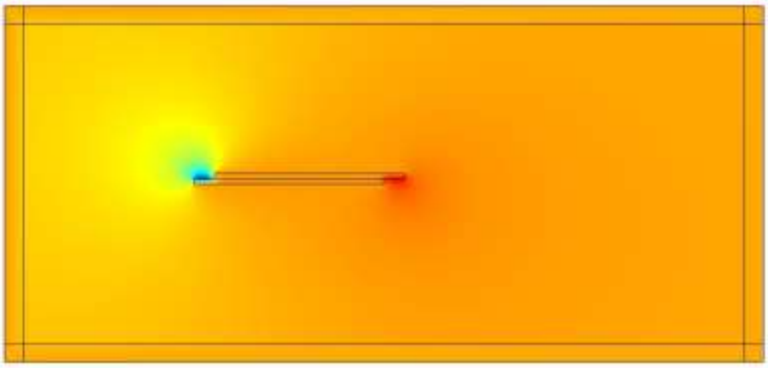


Figure 12: By using 10_mm PVDF

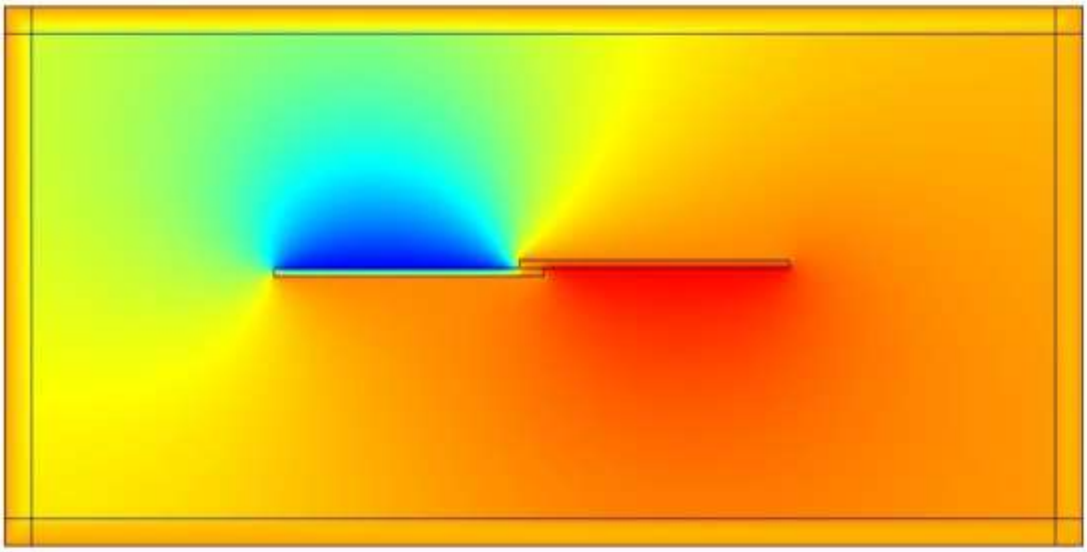


Figure 13: By using 90_mm PVDF

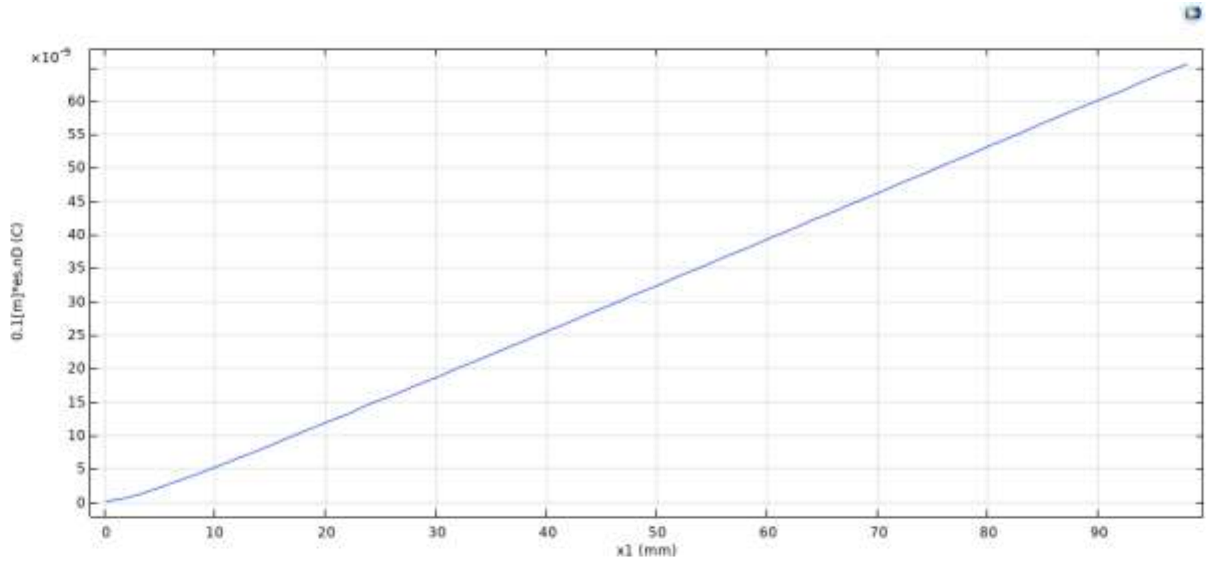


Figure 14: Surface Charge Density Of PVDF

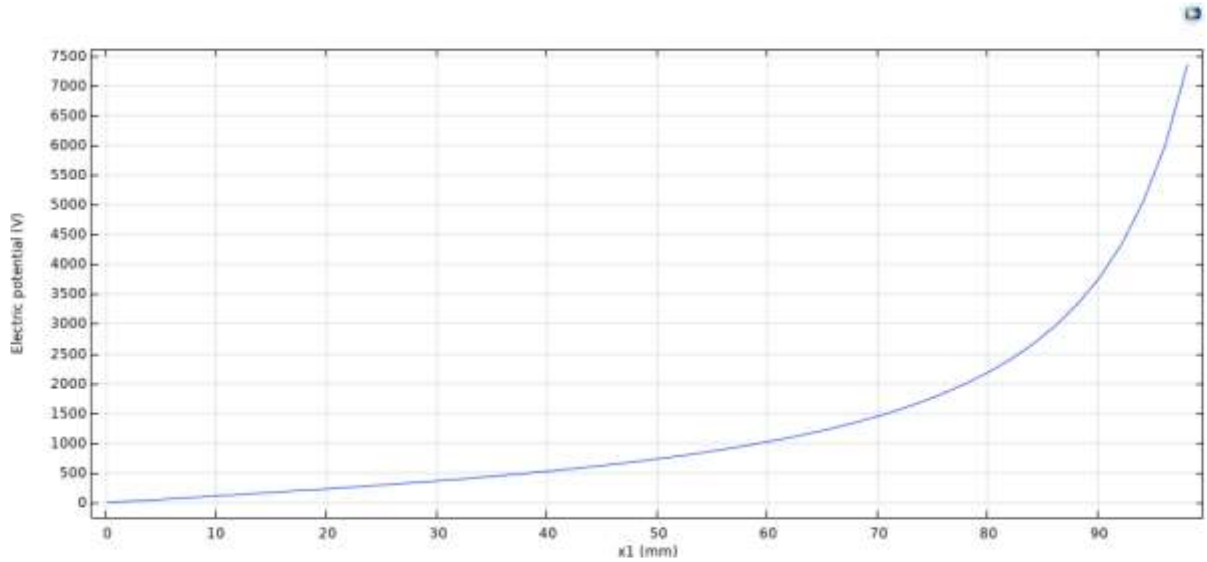


Figure 15: Electric Potential using PVDF

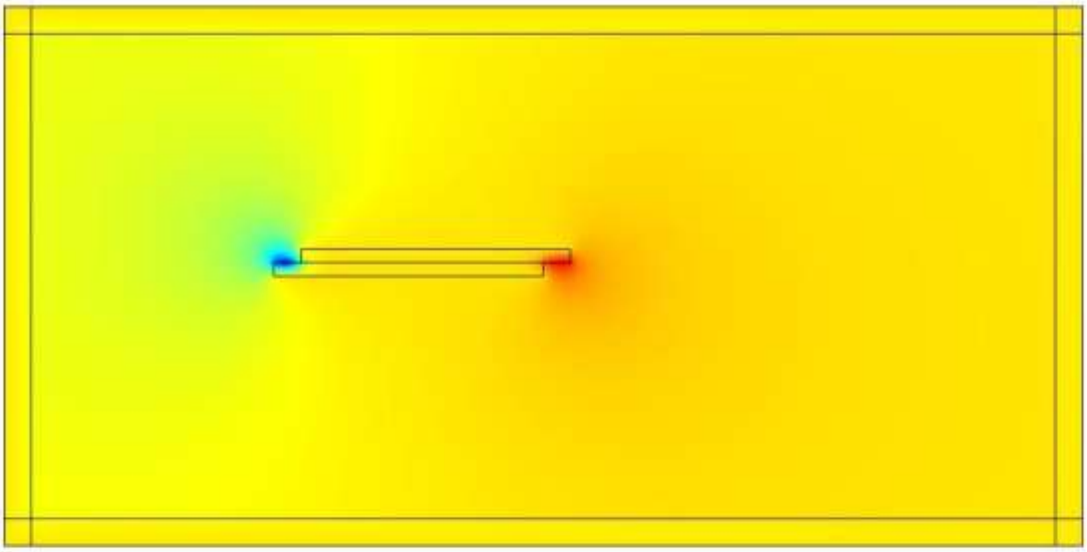


Figure 16: 10_mm Mica

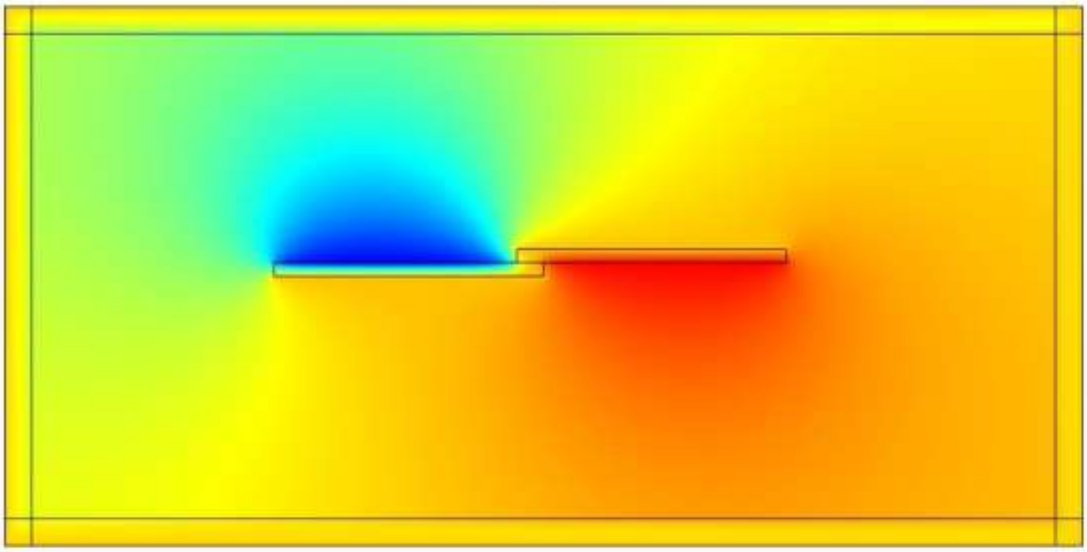


Figure 17: 90_mm Mica

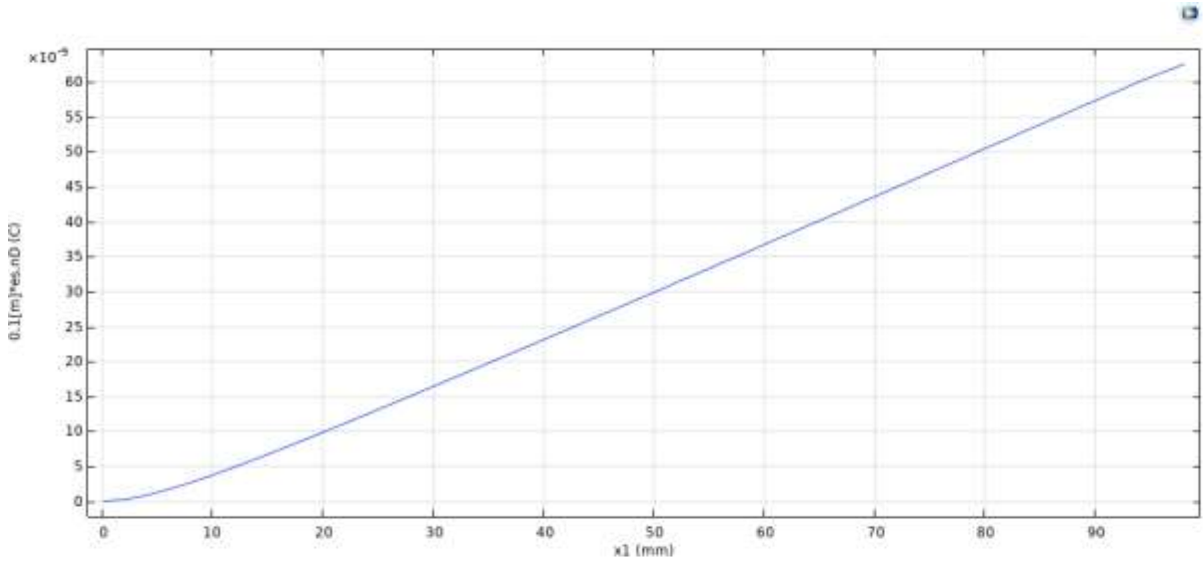


Figure 18: Surface Charge Density for PTFE and Mica

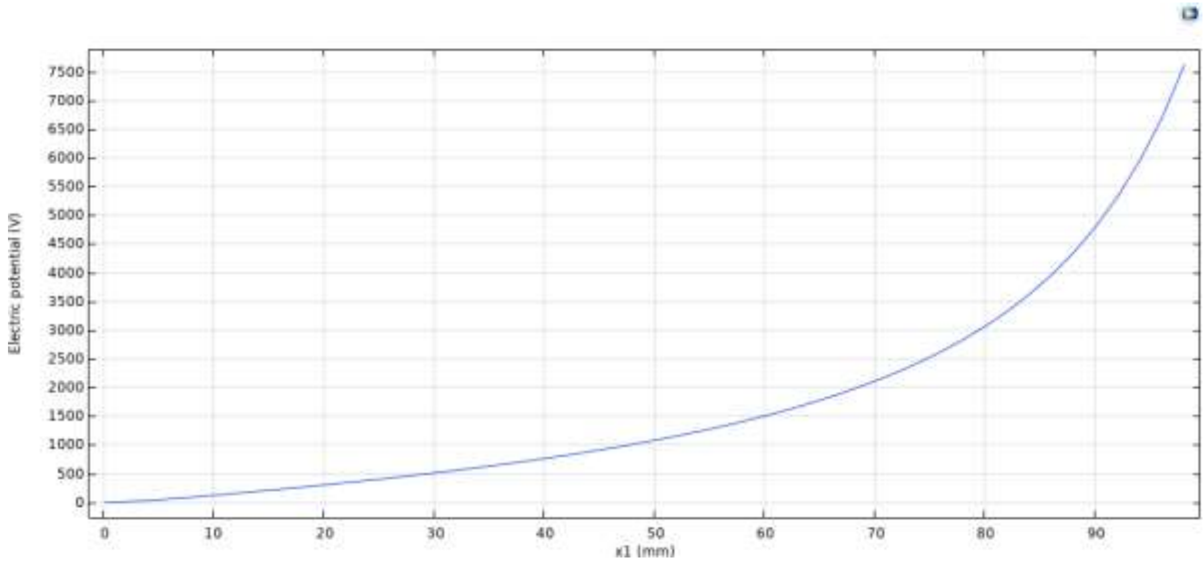


Figure 19: Electric Potential for PTFE and Mica

Electric Potential Distribution:

- Figures 4, 5, 11, 15, 19 visualize the electric field and voltage across TENG under various separations.
- Gradient of field intensifies with material having higher εr and separation distance.

Modelling Process (COMSOL Multiphysics):

Step-by-Step Procedure:

1. Geometry Creation
    - Define 3D blocks for top and bottom electrodes, dielectric layer, and separation air gap.
    - Dimensions as per input specs (e.g., 5 mm x 5 mm, gap = 1 mm – 98 mm).
2. Material Assignment
    - Assign different dielectric materials (PDMS, PVDF, PTFE, Mica).
    - Assign electrode materials (Au/Ag) and define layer thickness.
3. Mesh Generation
    - Fine mesh near the electrode-dielectric interfaces.
    - Use controlled meshing for precision in field intensity variation.
4. Physics Setup
    - Use Electrostatics module.
    - Define electric potential on one electrode and ground the other.
    - Assign material permittivities and tribocharge density.
5. Solver Settings
    - Stationary solver for static electric field.
    - Time-dependent studies for dynamic analysis with variable gap.

6. Post-Processing

    - Plot electric potential, surface charge density.
    - Extract voltage, short-circuit current, time-dependent response.

Result and Analysis:

Sliding Mode vs Vertical Mode:

- Sliding Mode (10 mm to 90 mm separation):
    - More gradual potential increase.
    - Higher surface contact = better charge generation.
- Vertical Mode:
    - Sharp increase in potential with increased separation.
    - Simpler geometry but slightly lower performance at low separation.

* Mesh Generation: The first few images demonstrate the meshing process in COMSOL. A fine mesh is crucial for accurate simulation results. The mesh appears to be well-refined around the electrodes and the dielectric layer, which are regions of high interest.

* Simulation Setup: The images show the settings for the simulation. The model likely involves solving the electrostatic equations to determine the electric potential distribution and the generated voltage. The boundary conditions would include specifying the potential at the electrodes and the dielectric properties of the materials.

* Electric Potential Distribution: The color plots visualize the electric potential distribution across the TENG device. The potential gradient between the electrodes indicates the presence of an electric field, which is essential for energy harvesting.

* Device Geometry: The geometry of the TENG device appears to be optimized for

wearable applications. The electrodes are likely designed to be flexible and conformable to the human body.

* Material Selection: The choice of materials for the electrodes and the dielectric layer is crucial for efficient energy harvesting. The dielectric material should have a high dielectric constant to maximize the generated voltage.

* Energy Generation: The simulation results show that the TENG device can generate a significant electric potential difference between the electrodes. This voltage can be used to power various biomedical devices.

* Wearable Integration: The TENG device is designed to be integrated into wearable devices. The flexible nature of the device and the low power requirements of biomedical sensors make it suitable for this application.

MATERIAL COMPARISON:

Material	**Surface Charge Density ($\mu C/m^2$)**	**Max Electric Potential (V)**	**Notes**
PVDF	8	Up to 4 kV	Best performance; strong piezoelectric properties
PTFE	7	~3.5 kV	Stable but slightly lower output
Mica	6	~2.8 kV	Biocompatible, good output
PDMS	5	~2.5 kV	Flexible, bio-safe, moderate output

Time-Dependent Voltage Response:

Resistance (Ω)	Voltage Output Range (V)
100 MΩ	50 – 100 V
1 GΩ	150 – 200 V
10 GΩ	250 – 300 V
Open Circuit	Up to 350 V

In conclusion :

The initial modelling and simulation efforts for the TENG project have shown promising results. The TENG device, as modelled in COMSOL, exhibits the potential to generate electrical energy from human motion. However, further analysis and optimization are necessary to assess the device's performance under realistic conditions and to improve its energy harvesting efficiency. Future work should focus on:

* Dynamic Simulations: Incorporating dynamic effects, such as human movement, to better understand the device's performance in real-world scenarios.

* Material Optimization: Exploring different materials for the electrodes and dielectric layer to enhance energy harvesting efficiency.

* Device Fabrication and Testing: Fabricating the TENG device and conducting experimental measurements to validate the simulation results.

* Integration with Biomedical Devices: Developing strategies to integrate the TENG device with various biomedical sensors and devices.

By addressing these aspects, the TENG project can move closer to realizing its potential as a practical energy harvesting solution for wearable biomedical applications.

Future Scope:

The future scope of this project includes:

1. Focuses on the design and development of a triboelectric nanogenerator optimized for biomedical applications.
2. The study aims to explore biocompatible materials, efficient energy conversion mechanisms, and miniaturized designs suitable for integration with low-power medical devices.
3. The ultimate goal is to create a TENG system that can serve as a reliable, sustainable energy source, paving the way for next-generation self-powered biomedical technologies.