International Journal of Technology 13(6) 1308-1316 (2022)
Received April 2022 / Revised August 2022 / Accepted September 2022

International Journal of Technology

http://ijtech.eng.ui.ac.id

Design of DC-Triboelectric Nanogenerator for Energy Harvesting

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Abstract. Triboelectric nanogenerators (TENGs) is a term used to describe harvested electricity made by the use of electrostatic charge between two triboelectric materials. It works in 4 different methods; vertical contact-separation mode, linear sliding mode, single-electrode mode, and free-standing mode. This project focuses on vertical contact-separation mode whereby two materials of different electron affinities are vertically placed in contact with each other, and as they are separated from each other, an electric potential is induced in the interfacial region and the electrodes, causing a flow of electrons within the circuit to maintain equilibrium in the electrostatic field. The two materials are then brought in contact again, and the triboelectric charges disappear, causing the induced electrons to return. The project examines the triboelectric effect of the vertical contact-separation mode as it is tested against four different combinations of different materials: Aluminum and Copper as fixed electrodes, and Polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), Kapton, and skin as the triboelectric layers. The results of this experiment showed that PTFE as a triboelectric layer generated the highest peak voltage of 0.888 V among the 4 different materials, with an estimated surface charge density of 8.58525 x 10^{-12} C.m^{-2}. This shows that the developed DC-TENG can generate satisfactory results and can be further improved to be used in various applications.

Keywords: DC triboelectric nanogenerators (TENGs); Triboelectrification; Triboelectric effect

1. Introduction

Home Upcoming generations of IoT devices are expected to extract their operational power from their working environments due to the massive amounts of research being conducted in obtaining electrical energy from mechanical energy. An example of such energy source is triboelectric nanogenerators (TENG). TENG working principle is based on the triboelectric effect, a term referring to the electrification that occurs as a result of two compatible materials coming in contact with each other and separating.

TENGs traditionally generate alternate current (AC), and this limits their usage. However, in recent years and through wave rectification techniques such as half-wave rectification and full-wave rectification (Fang et al., 2019), an exciting type of nanogenerators was developed known as direct current triboelectric nanogenerators (DC-TENGs).

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doi: 10.14716/ijtech.v13i6.5929

DC-TENGs use different materials that are widely available and are not costly. In addition, DC-TENGs have 4 different working modes, namely, vertical contact separationmode, linear sliding mode, freestanding triboelectric layer mode, and single electrode mode. This increases its flexibility and compatibility, making it an exciting area of research for renewable and sustainable energy source to power various IoT devices.

More recent research includes quantifying surface charge density via charge injection in the DC-TENG (Wu et al., 2022). The technique utilizes an excitation circuit to realize the directional accumulation of charge and provides a more effective method for modifying dielectric materials. Environment factor is also considered in achieving effective surface charge density of DC-TENG as mentioned by (Liu et al., 2022). It is found that high humidity not only enhances the sliding triboelectrification effect of triboelectric materials but also improves the DC-TENG output.

Research in the area of DC-TENGs usually focuses on utilizing a particular working mode of DC-TENG (e.g., single electrode mode) and analyzing its output power against different sets of materials to determine which materials are more compatible with each other. This has led to the development of a concept known as the triboelectric series, which will be discussed in this paper.

The main objectives of this research are to analyze different types of materials that are compatible as tribo-pairs by constructing a DC-TENG that works in vertical contact separation mode and comparing the charges obtained.

2. Methods

2.1. Working Principles of TENGs

TENG comprises two triboelectric layers with varying electronegativities for triboelectrification, as well as the electrodes that output electrical power. Contact electrification (CE) can occur in a wide range of materials (e.g., ceramics, polymers, metals, semiconductors) and any condition, according to research (e.g., solid, liquid, gas). TENGs outperform other technologies in terms of area, power density, volume density, and conversion efficiency in contrast to other systems that work by harvesting mechanical systems. Additionally, TENGs have the advantages of a wide range of materials, flexibility, lightweight, and low cost (Yang et al., 2021).

The concept of triboelectrification is the main principle behind lighting, a common natural phenomenon. The accumulation of electrostatic charge induced by the triboelectric effect in a thundercloud and electrostatic breakdown in the air causes lightning, which releases enormous amounts of energy (many billions of joules) that are not easy to capture. TENG was created to extract mechanical energy from the environment via the triboelectrification effect and electrostatic induction (Liu et al., 2019).

2.2. Working Modes of DC-TENG

DC-TENGs operates in four different working modes, with each working method having its benefits as well as drawbacks

2.2.1. Vertical Contact Separation Mode

This is the simplest working mode of DC-TENG and is demonstrated in Figure 1. In contact-separation mode, two materials of different electron affinities are vertically placed in contact with each other. When they are separated, an electric potential is induced in the interfacial region and the back-deposited electrodes. This causes electrons to flow in the circuit in order to maintain balance in the electrostatic field. The two materials are then brought in contact again, and the triboelectric charges disappear, causing the induced electrons to return. Repeating this process, an alternating current can be noticed in the connected load. While this method is the easiest to fabricate, it is also the most prone to wear and tear (Pu et al., 2021).

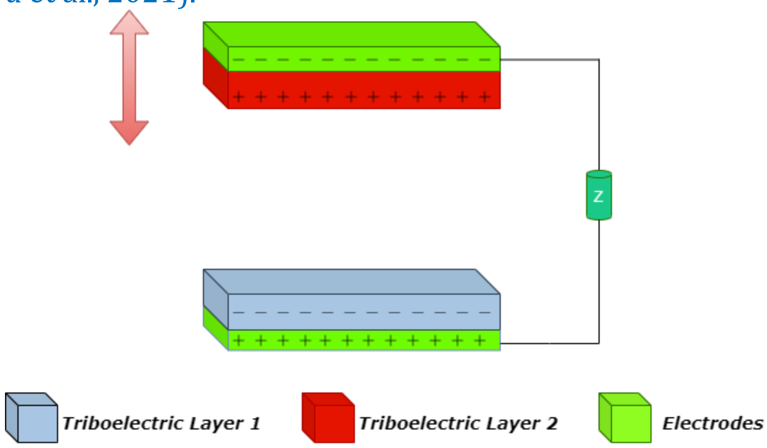


Figure 1 A schematic illustration of the vertical contact-separation mode

2.2.2. Linear Sliding Mode

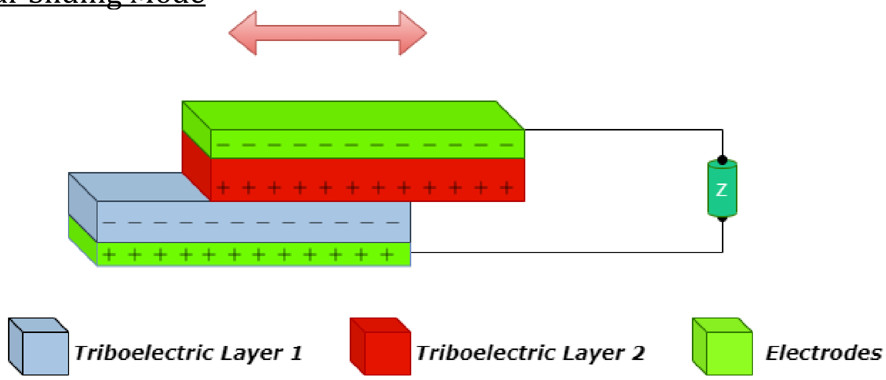


Figure 2 Schematic illustration of the linear-sliding mode

In this mode, the triboelectric charge is generated due to the back-and-forth sliding between the layers of TENG as shown in Figure 2. In terms of how the circuit is constructed, the linear-sliding mode shares similarities to contact-separation method whereby electrodes adhere to the back of the triboelectric layers. The main difference is that in linear-sliding mode, the layers remain in contact with each other, and the displacement is performed sidewards. The circuit construction of the linear-sliding method gives it an advantage over the contact-separation way since it can generate more charge density at a much more effective rate because of its high contact area (Vivekananthan et al., 2020).

2.2.3. Single Electrode Mode

The construction of the single-electrode mode is the simplest among other TENG working modes. Figure 3 shows the schematic illustration of the single-electrode mode. However, it has a deficient output performance due to its construction, and as a result, the voltage and current generated are also very low. On the bright side, this makes it highly efficient for self-powered applications (Vivekananthan et al., 2020).

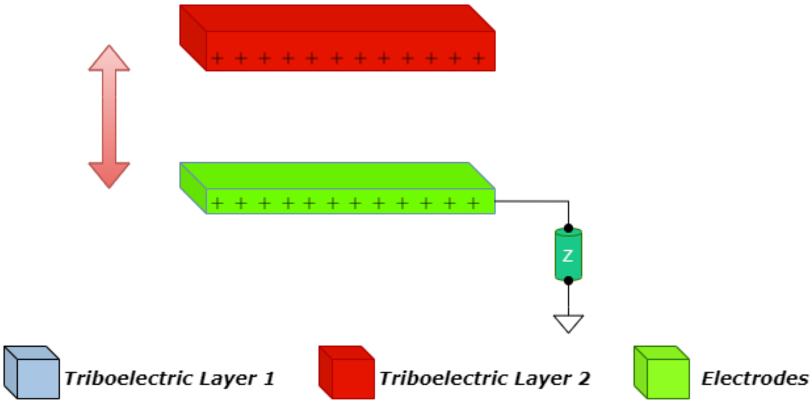


Figure 3 Schematic illustration of single-electrode mode

2.2.4. Freestanding Triboelectric-layer Mode

This mode consists of one electrode that is free to move from one triboelectric layer to another, as depicted in Figure 4. Unlike the other modes, in freestanding triboelectric-layer mode the electrodes are fixed in their respective positions, and the triboelectric layers can travel over it. The freestanding mode is the most efficient and produces the highest electrical output. In addition, this mode makes it easy to implement TENG in several real-time applications (Vivekananthan et al., 2020).

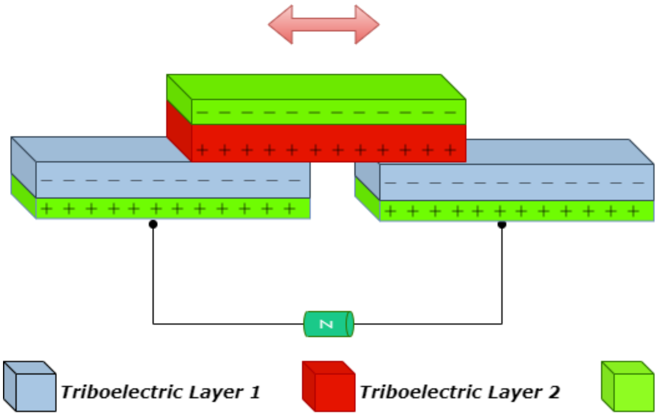


Figure 4 Schematic illustration of the freestanding triboelectric-layer mode

For this experiment, we used the vertical contact-separation mode of work and tested it against 4 different sets of materials. The main reason why this mode was chosen for this analysis is that the vertical contact-separation mode is the easiest to set up and can be implemented in several different designs for it to be used with various applications. For example, in a smart shoe, electrodes of a vertical contact-separation mode DC-TENG can be fitted on the shoe's sole to harvest energy.

2.3. Material Choices for DC-TENG

The materials chosen for this experiment were obtained after reviewing research on the concept of the triboelectric series and other research summarizing the typical choices of materials for a DC-TENG.

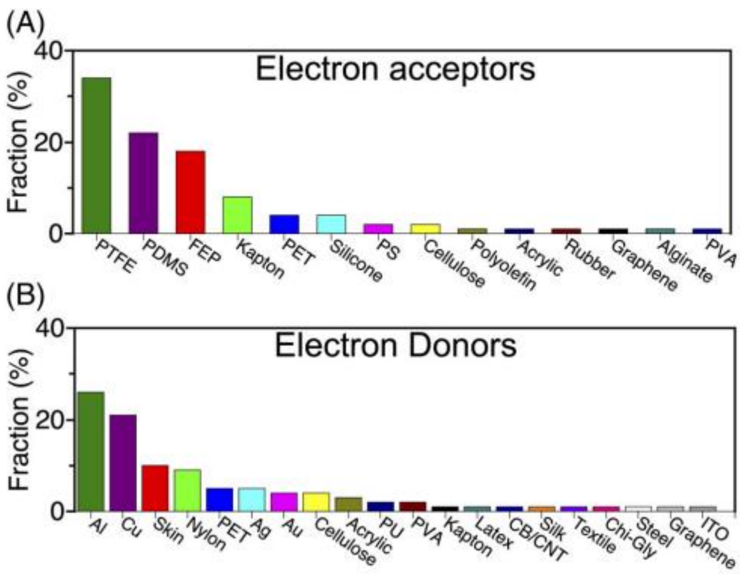
The triboelectric series gives a broad sense of how charging may occur when two materials come into contact via rubbing, pressing, or friction. This simplifies the triboelectrification analysis for other applications, like as TENGs (e.g., when Cu and PTFE are used as surface materials) (Pan et al., 2018). Table 1 demonstrates a detailed triboelectric series list that separates materials based on their charge.

Table 1 Summary of triboelectric series

More positively charged (+)	Δ
Rabbit Fur, Hair	Brass
Glass	Silver
Mica	Gold
Wool	Polyester
Nylon	Polystyrene
Lead	Acrylic
Silk	Polyvinyl chloride
Aluminium	Polyvinyl chloride w/plasticizer
Paper	Silicon
Wood	Polyethylene
Amber	Polypropylene
Sealing wax	Polytrifluorochloroethylene
Rubber balloon	Teflon (PTFE)
Nickel	Silicone rubber
Copper	Ebonite
Δ	More negatively charged (-)

*Pure polymers are marked in red and pure metals are marked in blue

In addition to the triboelectric series, Zhang et al. has summarized the most common material choices for DC-TENGs as shown in Figure 5. Zhang describes the nature of triboelectrification as the transfer of electrons between two materials that are in contact. Electron affinities of the two materials determine the direction of travel for the electrons, whereby the material with the lower electron affinity is the donor, and the material with the higher electron affinity is the acceptor. Donors and acceptors can be determined through their order in the triboelectric series, as shown in Table 1.



*Cellulose refers to materials that are made of cellulose fibers, like paper and cellulose nanofibrils

Figure 5 Graphical statistic of the most commonly used materials in 100 articles selected randomly from 2012 to 2020 (Zhang et al., 2020)

As electrodes for this experiment, the materials copper and aluminium were chosen. This is because they are the most widely available pure metals. The material PTFE/Teflon was selected for the first triboelectric layer since it is the most commonly available pure polymer. Ideally, pure metals paired against pure polymers should yield the highest charge due to the difference in electron affinities.

The materials FEP, Kapton, and Skin were also selected to be used as triboelectric layers following the research conducted by Zhang et al.

2.4. Experimental Setup

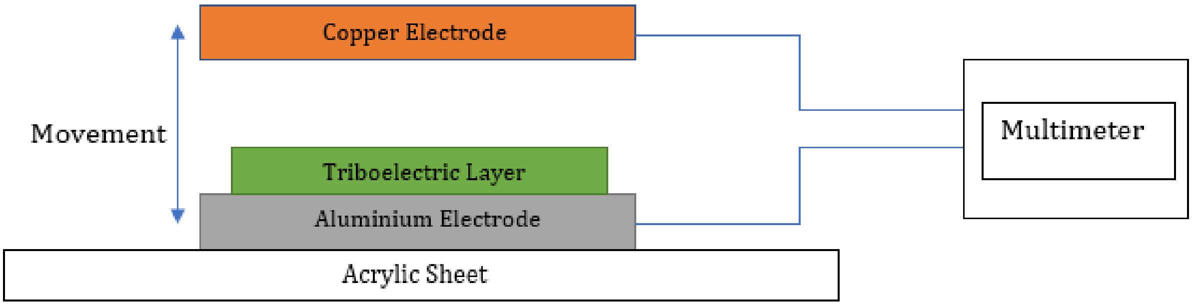


Figure 6 Schematic diagram demonstrating the experimental setup used for this research

The basic design used for this experiment is shown in Figure 6. It is a DC-TENG designed in vertical contact-separation mode. The vertical contact-separation mode was chosen for this experiment is that it is the simplest mode to set up, making easier to test against many different materials. In this experiment, the two electrodes shown are copper and aluminium. An acrylic sheet will reside at the base of the stationary electrode (in this case, the aluminium electrode). The DC-TENG is tested using 4 different materials to compare their compatibility. These materials are PTFE, FEP, Kapton and skin (fingers). Since the Kapton layer is a skinny film, it was wrapped around a layer of PTFE of 0.7mm thickness in this experiment. Then, two jumper wires connected to a separate electrode by Kapton tapes, were used to connect the set-up to a multimeter. Figure 7 shows how the experiment was set up.

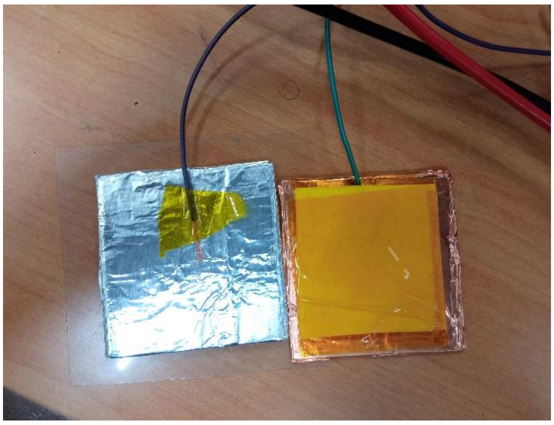


Figure 7 An example of the experimental set-up. Here it shows the two electrodes made of aluminium, copper, and Kapton being the triboelectric layer

The experiment for each set-up was done for a period of 30 seconds, and the two plates were tapped against each other by lifting and pressing one electrode against the other at a rate of 1 tap per second, the readings were observed on the multimeter. The voltage readings of each instance of a tap were recorded, and the average voltage obtained was manually calculated. The ultimate goal would be to calculate the charge. Ideally, an electrometer is the best instrument for this experiment since it gives charge readings.

However, due to budget and lack of resources, a multimeter or an oscilloscope could be used. In this experiment, a multimeter was used to record voltages as shown in Figure 8.

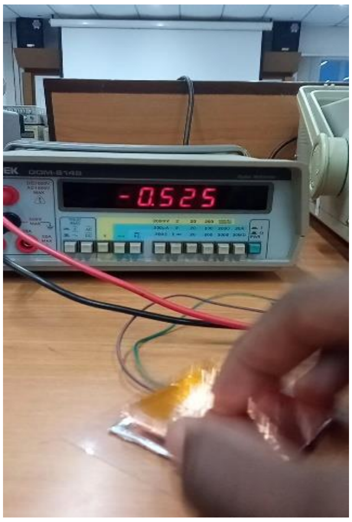


Figure 8 Demonstration of how the experiment was conducted and how the multimeter readings were recorded

In order to calculate the charge, the capacitance would need to be calculated first using equation [1]:

$$C = \varepsilon \frac{A}{D} \quad (1)$$

Where C is the capacitance, ε is the permittivity of air which is 8.854 x 10^{-12} F/m, A is the area of the plate, and D is the distance between the plates. Next, the charge Q was calculated using equation [2]:

$$Q = C \times V \quad (2)$$

where V is the voltage. Finally, the surface charge density σ is calculated using equation [3]:

$$\sigma = \frac{Q}{A} \quad (3)$$

where σ is the surface charge density in Coulombs per square meter (Cm^{-2}), and A is the area of the surface.

3. Results and Discussion

Table 2 shows the recorded values for the average voltage obtained for each material, along with the standard deviation. Figure 9 shows the graphical representation of the average voltage and the standard deviation for each material. Getting the average voltage is crucial for calculating the charge and surface charge density for each material to be used for comparison.

Table 2 Average voltage obtained for each set

Triboelectric Material	Average attained voltage (V)	Standard Deviation
PTFE	0.193875	5.4590E-05
FEP	0.229847	0.052829643
Kapton	0.159568	0.025461947
Skin	0.221764	0.049179272

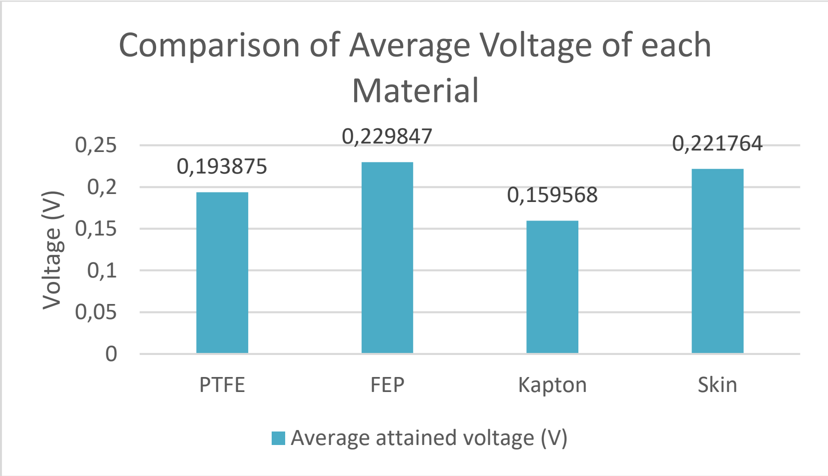


Figure 9 Graph comparing the output voltage obtained from each material

To calculate the charge and surface charge density, first, the capacitance for each set was calculated using Equation (1) to obtain the capacitance value, which is necessary for calculating the charge. Each set's charge value was manually calculated using Equation (2). Finally, the surface charge density for each triboelectric layer was manually computed using Equation (3), and the results are tabulated in Table 3.

Table 3 Calculated charge for each set of DC-TENG

Triboelectric Layer	Calculated Capacitance (F)	Calculated Charge (C)	Surface charge density (C.m^{-2})
PTFE	1.7708×10^{-12}	3.43314×10^{-13}	8.5828×10^{-12}
FEP	1.7708×10^{-12}	4.0713×10^{-13}	1.0178×10^{-11}
Kapton	5.423075×10^{-12}	8.65349×10^{-13}	7.0641×10^{-12}
Skin	3.32025×10^{-12}	7.36312×10^{-13}	9.8175×10^{-12}

The obtained results show that polymers such as PTFE are the most negatively charged materials, and when paired with metals such as Aluminium, the most positively charged metal in the triboelectric series yields the highest voltage.

The results also showed that FEP is the material with the highest surface charge density, making it a focal point of future research. In addition, using skin as an electron donor and a triboelectric layer seemed to yield significant results that are also interesting for IoT applications such as wearable devices.

4. Conclusions

In conclusion, the results demonstrated the triboelectric effect and the possibility of developing a renewable and sustainable energy source that harvests the environmental factors and converts them into electrical energy, which is highly in demand for the upcoming generations of IoT devices. In this manuscript, the triboelectric series, which ranks triboelectric materials based on how charging will occur when two different materials come into contact via rubbing, pressing, or friction, was examined and the obtained results matched the reviewed articles.

Acknowledgements

FRGS, MOE and MMU supports this research project with the Grant entitled: Formulating the Figure-of-Merits (FOM) for Optimizing the Output Power of Direct Current

Triboelectric Nanogenerator (Project No: FRGS/1/2021/TK0/MMU/02/3). The research project is also devoted to those who have helped us.

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