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The Effect of Surface Texture on Teflon as Electrification Layer of 360° Lateral-Sliding Mode Triboelectric Generator

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ABSTRACT

Harvesting neglected mechanical energy from daily activities and converting it into electrical energy is a crucial start towards clean, low-cost, and sustainable energy. In this work, we report a development of a Teflon-based rotating triboelectric generator (TEG) and its relationship with rotational speed. The texture on Teflon was modified by uni-directionally rubbing the sandpaper with three different grit numbers; 500, 1000, and 1500 respectively, 50 times each. The surface roughness of the Teflon was measured using Mitutoyo Surface Roughness Machine SJ-310 before and after undergoing the 360° lateral sliding mode TEG test. The highest surface roughness was from 500 grit sandpaper, forming a Ra of 1.550 µm. Moreover, this surface of Teflon generated the highest output voltage of 25.3 mV at 1500 rpm with a calculated power density of 0.37 mW/m2. This simple technique gives an overview of how the surface texture may improve the electrical output of TEG by integrating the electrification contact area of TEG.

1. Introduction

Day by day, the energy demand is increasing with modern technology. The world most utilised energy, fossil fuels diminished over time. For that reason, it is necessary to find out new sources of renewable energy. To date, researchers are working hard to find new sources of energy that are naturally replenishing but flow-limited, clean, cost-effective, and sustainable to overcome such issues. In 2022, a group of researchers suggested a critical approach to solar energy for Malaysia due to the deliberation of carbon production over the other four renewable energy resources available in Malaysia: biomass, energy-from-waste, wind, and hydro energy cause of five criteria: carbon production, operational costs, location characteristics, energy, and availability of renewable energy resources [1].

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Zhong Lin Wang and his team from Georgia Institute of Technology USA in the year 2012 discovered a new source of energy harvesting from which two materials have frictional contact, and patented it as a Triboelectric Generator (TEG) [2,3]. TEG transforms mechanical energy into electrical energy. TEG works on the principle of the triboelectric effect and electrostatic effect [4-6]. The TEG follows a mechanism when two different tribo-materials (having opposite polarities) come in contact and then separate or slide against each other. Electrons were transferred from one material to the other, and electrostatic charges of opposite polarities were developed on the surfaces of the electrification layer of TEG [7,8]. TEG has two main motions; the sliding motion and the vertical contact-separation motion. In sliding type TEG, rotating and freestanding designs are frequently applied, whereas, in vertical contact-separation, pressure and vibrations are the most adapted [9]. This technology generates high output power and efficiency along with the low cost of fabrication and materials. TEG should therefore be taken into account as a trustworthy potential energy harvesting system in Malaysia due to its zero-carbon production.

The new generation of TEG is developing, both on a macroscopic scale (ie: wind in the air and wave in the ocean) and microscopic scale (ie: body movement, muscular contractions, and blood flow). Hence, creating a vast scope of potential for energy generation. TEG has the high potential to become one of the solutions for a greener and more sustainable future in the energy generation sector. Especially for wearable devices and Internet of Things (IoT) applications [10]. In recent years, numerous studies have been carried out to enhance the output power of TEG. The previous research approaches for TEG improvement can be classified into three categories: i) surface modification [11,12], ii) device structure [13,14] and iii) type of materia l[15-17].

This study implemented surface modification as TEG enhancement. The purposes of the surface modification process are to improve the wear resistance against degradation, biocompatibility, surface wettability, and electroconductivity. There are numerous techniques of surface modifications, such as electrical discharge machining (EDM), thermal spraying, physical vapour deposition (PVD), chemical vapour deposition (CVD), electroplating, laser coating, electron-beam irradiation, and sputtering [18]. However, in this preliminary study on TEG, the surface of negative tribo-material was modified by texturing with different sandpaper grit numbers.

On the whole, this paper reported the development of a 360° lateral-sliding(rotating) mode TEG system and the investigation of the effect of surface roughness of negative tribo-material (electrification layer) on electrical power generation. Aluminum was used as the positive tribo-material not just because it is a strong alloy and lightweight; but yet due to its excellent electrical conductivity, outstanding thermal conductivity, chemical stability (due to its passive oxide layer), and high efficiency of electron transfer to polymers like Teflon [19,20]. On the other hand, Teflon was used as the negative tribo-material due to being placed at the highest rank of negatively charged material in the triboelectric series. Teflon also has a very high melting point (around 327°C, rarely damaged by heat). Moreover, Teflon is a hydrophobic material (resistant to water). It is also chemically inert (other solvents and chemicals will not damage Teflon). It has a low coefficient of friction (easy to slide). And it has high flexural strength (ability to bend and flex, even at low temperatures, and is easy to apply to a variety of surfaces without losing its integrity) [21]. This perspective study is a cornerstone for establishing next-generation energy applications consisting of TEG from portable devices to power industries.

2. Experiment Details

2.1 The 360° Lateral-Sliding TEG

The 360° lateral-sliding mode TEG was made of a 10 radially-arrayed sectors aluminum rotator with a 5 cm diameter and 2 mm thick, and 3 layers of a stator. The first layer of the stator was acrylic, then coated with a thin copper layer as the electrodes (10 complementary patterns separated by fine gaps in between), and finally, the Teflon sheet as the electrification layer of TEG.

The 360° lateral-sliding mode TEG setup was involved with ISOTECH DC power supply to provide power to the DC motor. For the purpose of this research study, the DC motor was used to rotate the aluminum rotator (positive tribo-material) instead of using natural source of mechanical energy. Then, the aluminum rotator was frictionally rotated with Teflon stator (negative tribo-material/electrification layer). Two lead wires were soldered on the positive and negative copper electrodes to connect with 220 Ω load resistor. The other two lead wires were then connected to the oscilloscope to measure the voltage generated from the 360° lateral-sliding mode TEG. V_{rms} were measured from the Tektronix DPO2002B oscilloscope in Figure 5 because this type of TEG generates alternate output voltage and current. Generally, the RMS value is applied for all kinds of alternate signals (positive and negative) by taking the square root of the sum of their squares. Besides that, the power density of the highest generated V_{rms} output was calculated using Eq. (1) below

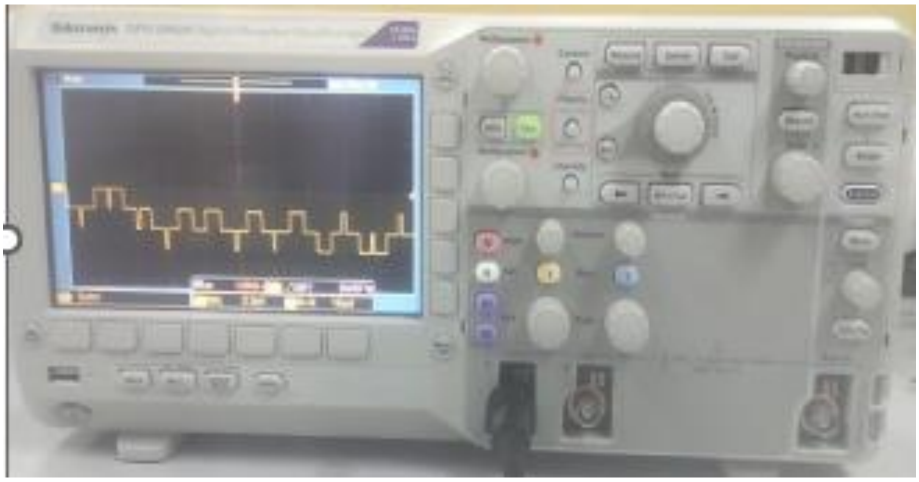

Fig. 1. The waveform captured from the oscilloscope. The Vrms was selected for the output voltage generated from the 360° lateral-sliding mode TEG

$$\text{Power Density} = \frac{Vrms \times I}{A} \tag{1}$$

where, V_{rms} is refer to the output voltage measure from the oscilloscope, *I* is short circuit current calculated across the 220 Ω resistor, and A is the surface area of the Teflon in m^2.

The rotational time for a sample to rotate was fixed to 20 seconds. The experiment was carried out in a confined room at 26°C temperature at fixed humidity. Only one person in the room was allowed to conduct the experiment since noise from individuals may affect the results. The 2D-illustration of the 360° lateral-sliding mode TEG setup was shown in Figure 2. Figure 3-5 show the design of the aluminum rotator and the copper electrodes in details.

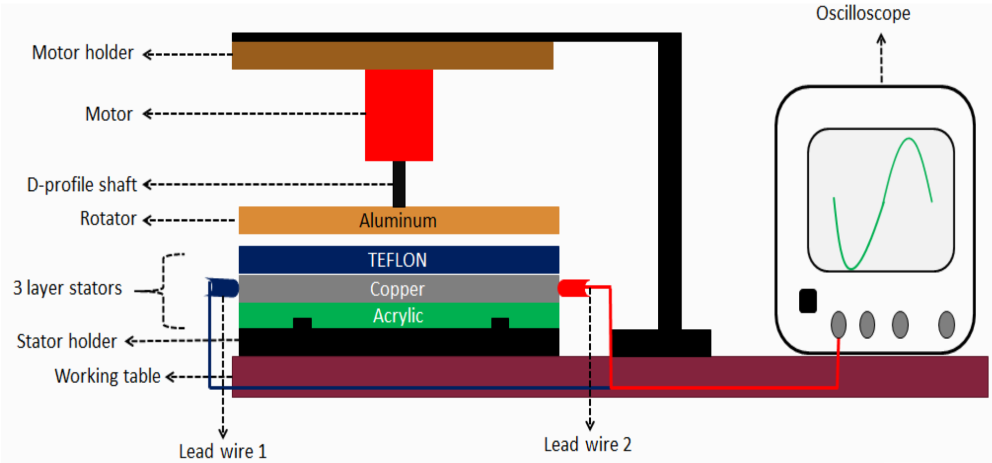

Fig. 2. The 360° lateral-sliding mode TEG setup

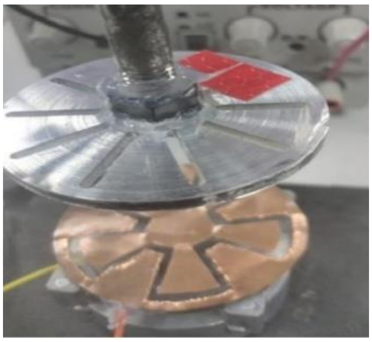

Fig. 3. The aluminum rotator and the copper electrodes orientation in the setup

Fig. 4. The 10 radially-arrayed sectors of aluminum rotator

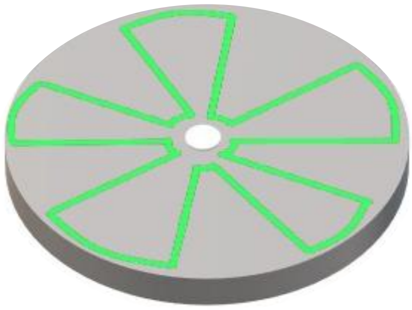

Fig. 5. The 10 complimentary sectors of copper electrodes separated by fine gaps in between

2.2 Surface Texturing on Teflon Surface

The 0.2 mm thick Teflon sheet was cut into 12 pieces with 50 cm diameter disc-shaped. Then, 3 pieces of Teflon sheet were remained as raw Teflon, the other 9 pieces were rubbed with different grit number sandpapers, 500, 1000, and 1500 respectively (3 pieces each). Each sample was unidirectionally rubbed 50 times. Teflon was then cleaned with a 1:1 mixture of acetone and hydrochloric acid and left dried for one day in the chamber.

2.3 Surface Roughness Test of Modified Teflon Surfaces

The surface roughness of the Teflon surface was measured by using Mitutoyo Surface Roughness Machine at Metrology Lab, MJIIT. The needle of the machine was horizontally moved in a straight line for 4 mm distance. The Ra value of Teflon was measured before and after the rotational test.

2.4 Rotational Test

Each Teflon sample was rotated with three different rotational speeds, 500 rpm, 1000 rpm, and 1500 rpm. The output voltage was measured using the Tektronix DPO2002B Digital Oscilloscope, and the current was calculated across the 220 Ω resistor. The samples were labelled as per Table 1.

Table 1
The rotational speed parameter

Rotational Speed (rpm)	Sand Paper Grit Number			
	Raw Teflon [A]	#500 [B]	#1000 [C]	#1500 [D]
500	A_1	B_1	C_1	D_1
1000	A_2	B_2	C_2	D_2
1500	A_3	B_3	C_3	D3

3. Results and Discussion
3.1 Surface Roughness

Figure 6 shows the surface roughness Ra of modified Teflon surfaces before and after the rotational test at 500 rpm, 1000 rpm, and 1500 rpm, respectively. The Ra of all samples at initial state are lower than the Ra after undergone the rotational test. At initial state (blue line), the lowest Ra is 0.516 µm, which is from group A sample. Meanwhile, the highest Ra at initial state is 1.55 µm, from group B sample. Group A sample is the raw Teflon surface; group B, group C and group D samples are the Teflon surfaces that have been rubbed with sandpaper grit numbers 500, 1000, and 1500, respectively. Thus, Figure 6 clearly shows that as the sandpaper grit number increases, the Ra decreases, and the surface becomes smooth.

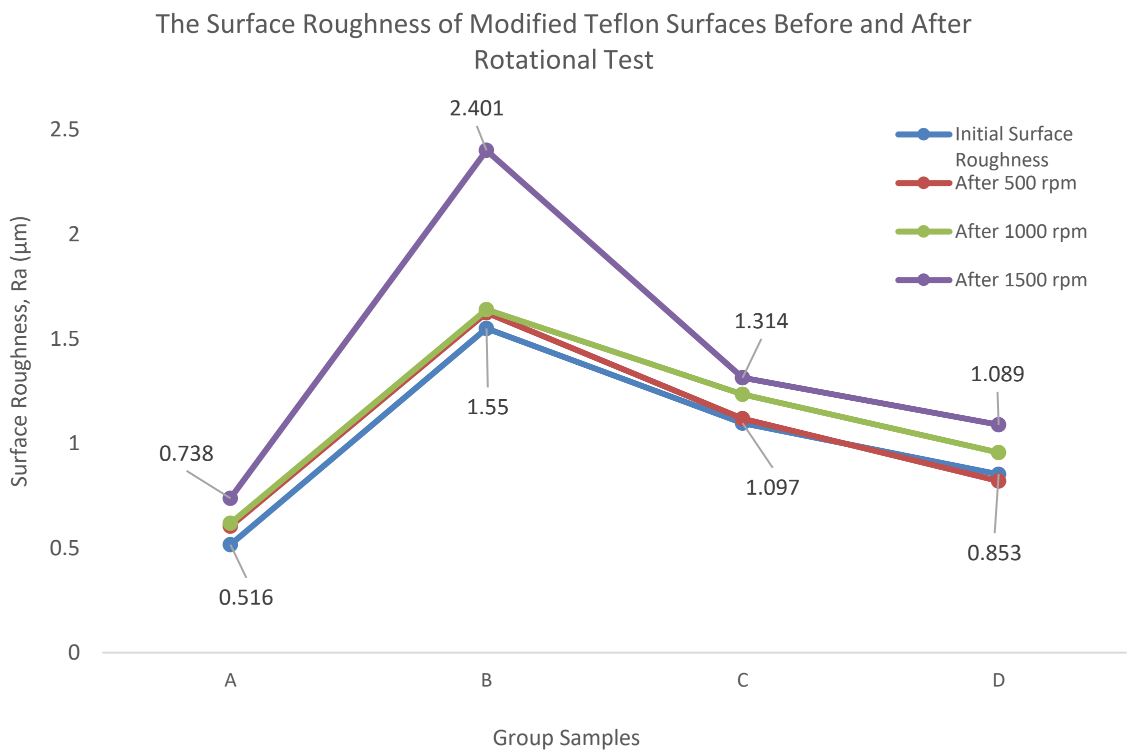

Fig. 6. Surface roughness of Teflon before and after rotational test.

Besides that, the Ra of all four group of Teflon surfaces is at the highest after rotating at 1500 rpm. The sample B_3 records the roughest surface among others, and the Ra of B_3 is three times higher than the Ra of A_3 (the smoothest surface). On the other side, the Ra increment percentage from initial state to the 1500 rpm test of sample A, B, C, and D are 43.02%, 54.90%, 19.78%, and 27.67%, respectively. Group B sample shows a significant difference, group A sample shows moderate increment, but group C and D show fairly low variance.

In other word, the surface of Teflon become rougher after frictionally rotated with aluminum rotator. This is because, Teflon has low hardening characteristics. When friction occurs between aluminum and Teflon, the surface of the Teflon becomes rougher.

3.2 Electrical Output

Figure 7 clearly shows that the output voltages of all group samples are directly proportional with the rotational speed. When the rotational speed rises, the voltage increases and thus the output current. This result can be explained by the change of charge transfer rate in the tribo-material surfaces. Due to:

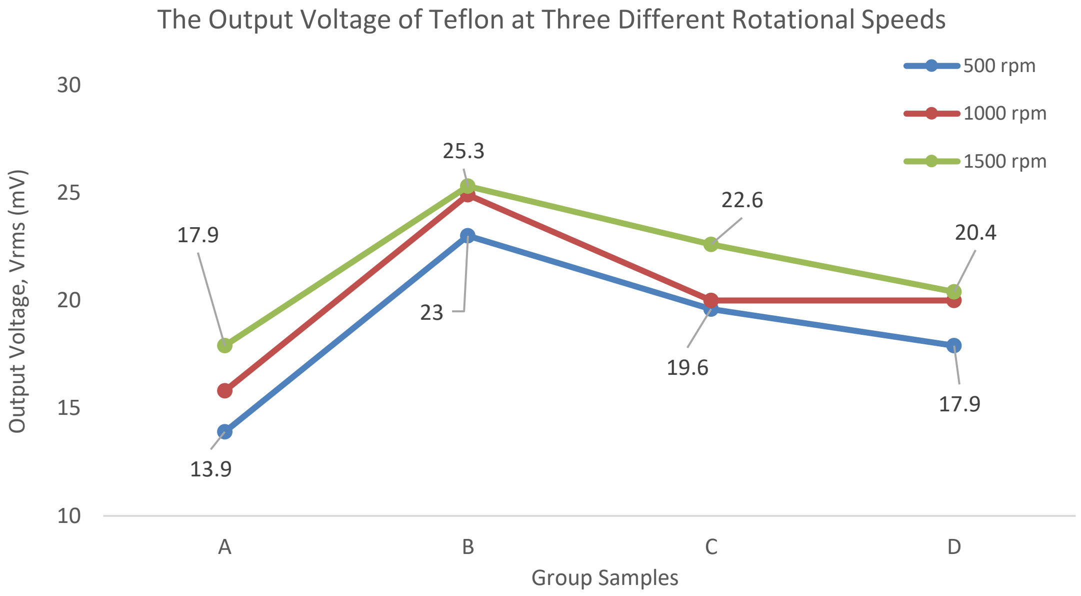

Fig. 7. The output voltage from each Teflon with three different rotational speed, 500 rpm, 1000 rpm, and 1500 rpm respectively

$$I = \frac{\Delta Q}{\Delta t} \quad (2)$$

where, I is the output current, Q is the electrostatic charges, and t is time. Hence, the higher the rotational speed is, the shorter the electrostatic charges transfer duration, which means a larger current and voltage is generated [9].

Refer Figure 7, at 500 rpm, the lowest output voltage is 13.9 mV by sample A_1. On the other side, sample B_1 generates output voltage 65.47% higher than A_1, and marks the highest output voltage at 500 rpm rotational test.

Other than that, samples A, B, C, and D generates largest output voltage at 1500 rpm rotational test. At 1500 rpm, sample B_3 generates 25.3 mV output voltage, which is 41.34% greater than sample A_3 (the lowest output voltage at 1500 rpm). These results correlate with the surface roughness results, where sample B (500 grit Teflon) has the highest surface roughness, making to largest contact electrification between Teflon and the aluminum. As a result, sample B generates the highest output voltage among others.

Meanwhile, the percentage increment of the output voltage from 500 rpm to 1500 rpm of samples A, B, C, and D are 28.78%, 10%, 15.31% and 13.98%, respectively. Hence, the output voltages of all the Teflon samples increases with the rotational speed. This is due to the frequency of contact electrification, the higher rotational speed means the more frequent contact electrification occurred between Teflon and aluminum, thus improving the output voltage.

If looks into more detail, even though sample A generates the lowest output voltage at 500 rpm, 1000 rpm, and 1500 rpm, but this sample records the highest voltage improvement of 28.78% compare to the other samples. On the contrary, although sample B generates the highest output voltage, yet this sample marks the least voltage improvement of 10%.

There are few theories can be deduced with the situation explained in previous paragraph. One of them is this may because of sample A is a raw material (un-modified surface), the surface is initially smooth but roughen during rotational test with aluminum rotator. Thus, this introduces the self-modified surface on Teflon, that lead to big improvement of output voltage. Further analysis also needs to be done to give a concrete reason of this situation.

Figure 8 deduces the relationship between the surface roughness of Teflon and the output voltage generated from Teflon-based 360 lateral-sliding TEG. It shows that the output voltages of TEG increase with the surface roughness of its electrification layer (tribo-material). This is because the higher the surface roughness is, the wider the actual surface area. To some extent, the concept of TEG is like a parallel plate capacitor.

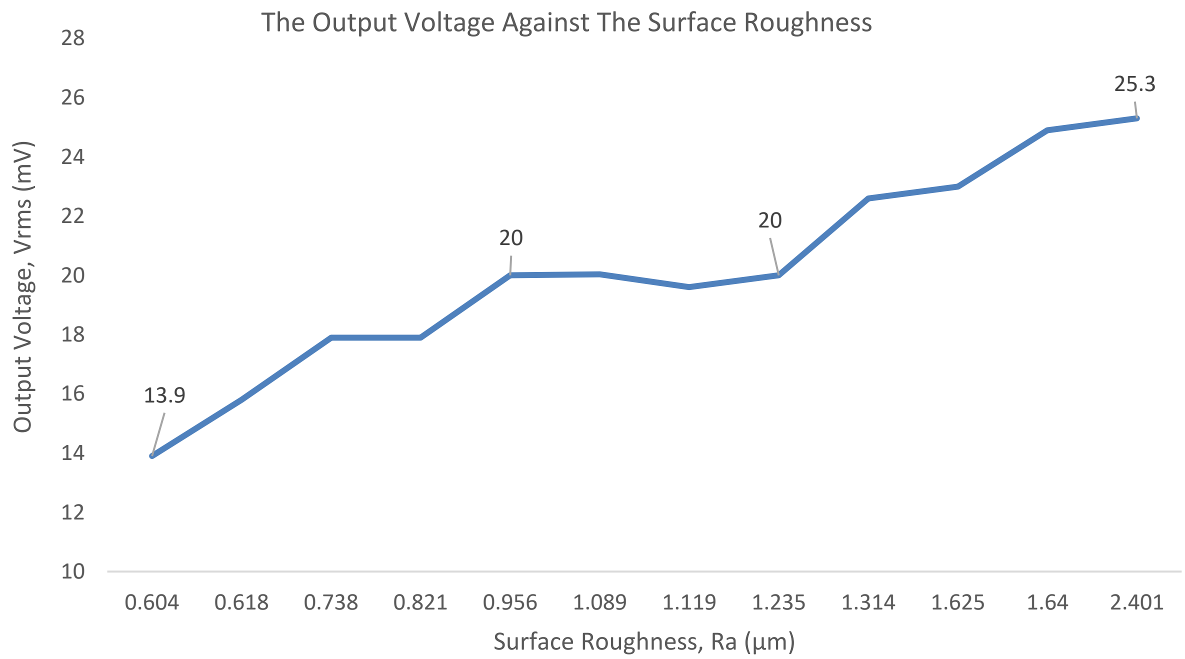

Fig. 8. The relationship between the output voltage and the surface roughness of Teflon based 360 lateral-sliding TEG

$$C = \frac{\varepsilon_0 \, \varepsilon_r \, A}{d} \tag{3}$$

$$Q = C\,V \tag{4}$$

From Eq. (3) C is the capacitance, ε_0 is the permittivity of free air, ε_r relative permittivity of dielectric, A is the surface area, and d is the gap in between two dielectrics (tribo-material). Hence, by increasing the surface area, the capacitance also increases and directly improves the charge, Q (Eq. (4)).

On the other hand, the highest power density (calculated using Eq. (1)) generated from this 360° lateral-sliding mode TEG is 0.359 mW/m2 from sample B3. The power density is low if compared with 8.49 W/m2 reported by Shuang Yang Kuang and his team [19] using the same TEG design but different tribo-materials, rotator, and stator's sector numbers. The proper fabrication of the structural setup may help to improve the electrical output generation. And yet, this low-generated power also can be boosted by adding a power management circuit [22-24] to demonstrate the practicability of using TEG for everyday power needs.

4. Conclusions

In conclusion, we have established a 360° lateral sliding mode TEG test system. We successfully tested the system with Teflon as the electrification layer at three different rotational speeds, 500 rpm, 1000 rpm, and 1500 rpm. The output voltage generation of TEG increases as the rotational speed increases. Furthermore, the surface roughness of Teflon has also varied with four different grit sandpapers, no grit, 500 grit, 1000 grit, and 1500 grit. The surface roughness of the Teflon was measured using Mitutoyo Surface Roughness Machine SJ-310 before and after the rotational test. The lower sandpaper grit number results in the highest surface roughness, Ra and thus, generate the highest output voltage. We also reported that the surface roughness of Teflon increased after the rotational test, making it a self-modified surface tribo-material that escalates the output voltage of TEG. Even though this work reported the low power density, it may amplify by adding a power management circuit at the output of the TEG system. The cost-effective and broad sources of mechanical motion harvesting, the presented TEG in this paper is a practical approach to convert mechanical motions for small electronic devices to industry usage.

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