International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-9 Issue-1, October, 2019

Performance of a Triple Cantilever Hybrid Energy Harvester (TCHEH) Based on the Triboelectric Surface Modification

M K Azwan, H Salleh, S Rao

***Abstract:** The aim of this study is to characterise the performance of a Triple Cantilever Hybrid Energy Harvester (TCHEH) based on the triboelectric surface modification. The application is to harvest sufficient amount of power for low power sensor node. The whole system comprises of three separated generators being put together into one prototype with the design of triple cantilever beam. The triple cantilever consists of top and bottom triboelectric energy harvester (TEH) and middle section piezoelectric energy harvester (PEH). The top and bottom section is the Polytetrafluoroethylene (PTFE). The testing for TEH consists of pairing the highest negative charged material which is Polytetrafluoroethylene (PTFE) with few other positively charged materials. The best pair was used for further testing by modifying the triboelectricsurface in order to increase the power output. At the frequency of 13Hz and acceleration at 0.27gms^{-2}, the ideal opened-circuit voltage, V_{OC} produced for top TEHwas 2.23V and for the bottom TEHwas 2.24V, while for the PEHwas 9.27V. The final prototype of TCHEHproduced an optimum power of 7.29mW at a resistance of 9kΩ. The power density obtained from the prototype was7.36Wm^{-2} which enable the low power sensor node to power up.*

***Keywords:** Piezoelectric, Triboelectric, Electrochemical, Generator, Hybrid, Cantilever, Contact Mode, Surface Modification, Energy Harvester.*

I.INTRODUCTION

Research on the energy harvester specifically TEH and PEH has increased significantly in the recent years. This is due to the advancement in the Internet of Things (IoT) technology and industrial revolution 4.0 where the application of electronics demands a sustainable power source to power up low power electronic devices and wireless sensors, as in [1]. However, there are challenges that need to be overcome before it can be implemented in various applications. Among the challenges of the TEH device are the relatively low power output compared to more conventional renewable energy sources; the durability and output stability of the device as in [2]. Increasing the power output will extend its application to a much broader range, applicable to many more industries. Some work on piezoelectric, triboelectric and hybrid energy harvesters are reported in [3]-[7].

Revised Manuscript Received on October 30, 2019.

* Correspondence Author

M K Azwan*, Department of Mechanical Engineering,Universiti TenagaNasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.

H Salleh, Institute of Sustainable Energy, Universiti TenagaNasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.

S Rao, Institute of Sustainable Energy, Universiti TenagaNasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.

In order to overcome these challenges, there is a need to investigate the effect of triboelectric surface modification of the device, as in [8]. Yang et al. proposed triple cantilever triboelectric energy harvester as in [9]. However, none of the literature focuses on using a hybrid piezoelectric and triboelectricenergy harvester in a triple cantilever approach. Thus, the objectives of this work are to investigate the effect of triboelectric surface modification techniques for different materials; as well as to characterise the optimum parameters of the TCHEH design.

This work focuses on the triboelectric surface modification of contact-separation mode of hybrid TEH and PEH. The energy harvesterconsists of two electrodes of different materials in the triboelectric series connected to PEH in a triple cantilever configuration as in [9]. The methodology includes identifying key parameters as well as experimental validation. The final output will be the characterisation of an optimumTCHEH. This has a significant contribution to the energy harvesting technology globally with wide range potential application from human body movement to aviation industry. The application is in tandem with the IoT, and Industrial Revolution 4.0 initiatives. This paper consists of five sections. The fundamentals of triboelectrification is presented in the second section, followed by the methodology, results, discussion and conclusion.

II.FUNDAMENTALS OF TRIBOELECTRIFICATION

Technically, two different materials can produce charges when come into contact with each other. Some parts of the two materials' surfaces formed chemical bonds, called adhesion and to equalize the electrochemical potential, the charges move from one material to the other. The transferred charges can be either ions or molecules. When both materials rubbing together, some of the ion can produce extra charges and some may be less.

For dielectric-to dielectric case in contact mode, the working principle can be described by the coupling of contact charging and electrostatic induction as in [10]. The TEH result can be improved by taking advantage of the different affinity charges of the different materials. The best one would be from the highest positive to the lowest negative charges of the materials and paired them together, as in [11]-[12]. In this work, since PTFE is having the most negative charges, other materials were paired to the PTFE to achieve highest output from the pairs.

The relationship between three parameters: the voltage,Vbetween the two electrodes, the separation distance, x between the two triboelectric layers, and the amount of transferred charge, Qin between, is important and gives out the following equation as in [13]:

$$V = -\frac{Q}{S\varepsilon_0}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} + x(t)\right) + \frac{\sigma x(t)}{\varepsilon_0} \qquad (1)$$

Where d is the thickness of triboelectric layer, $\varepsilon_r$is the relative permittivity, σ is the surface charge density, S is the area size and ε_0 is the vacuum permittivity.
For PEH part as in [14], the absolute displacement of the beam is denoted by $w(x,t)$. If the beam is assumed to be undamped, the equation of motion for free vibrations can be written as:

$$EI\frac{\delta^4 w(x,t)}{\delta x^4} + m\frac{\delta^2 w(x,t)}{\delta t^2} = 0 \qquad (2)$$

Where EI is the flexural stiffness, E is the Young's modulus and $I$is the cross-sectional area moment of inertiaand m is the mass per unit length of the beam.

III.METHODOLOGY

This prototype uses the dielectric-to-dielectric arrangement type with tapping mechanism. The whole system comprises of three separated energy harvesters being put together into one prototype with the design of triple cantilever beam. Thus, there are three sections, top and bottom (TEH) and middle section (PEH). The top and bottom section is the Polytetrafluoroethylene (PTFE). They were curved to be closer to thePEH.Piezoceramic is extended and a mass was attached at the end for better effectiveness of the vibration. On both surfaces of the piezoelectric were attached with the copper film follows with a thin layer of un-inked paper. Meanwhile, on the outer surfaces of both PTFE are attached with the copper films.

The copper films in this prototype function as the electrode. Once the whole prototype undergoes certain frequency of vibration using a shaker that matched with its natural resonance frequency, the prototype will start to vibrate efficiently. The PEH will oscillates up and down creating pressure in its own body resulting in the output voltage and at the same time the paper layer on both surfaces of the PEH will be having contact back and forth with the top and bottom PTFE board also creating output voltage as shown in Fig. 1 below.

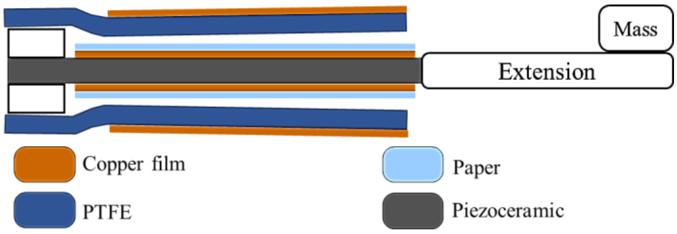

Fig.1 Schematic diagram of the prototype

Testing Setup

The testingswereconducted in the laboratory by using few reliable equipment. This is to get consistent input into the prototype in term of vibration motion in a more accurate adjustable frequency and acceleration.

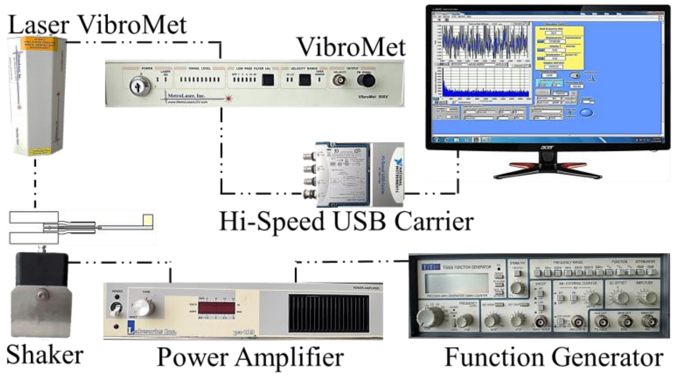

Fig. 2Testing setup

Fig. 2 shows the testing setup. The laser vibrometer system, *MetroLaserVibroMet* was used to obtainthe prototype's acceleration. The function generator was used to control and adjust the frequency of the shaker after the prototype was mounted on the shaker in order to find the prototype's resonance frequency. After the shaker's frequency has been set, the laser was used to identify the prototype's acceleration. To adjust the acceleration gain of the shaker, power amplifier was used. Theacceleration was set to 0.27gms^{-2}and the frequency was set to 13 Hz throughout the testing to achieve results with consistent input.

Experimental Testing

Three stages of testings were conducted. The first testing was conducted to obtain the baseline data for the most common triboelectric configuration layer. The configuration consists of copper with kapton as the electrode-to-dielectric configuration of the prototype'striboelectricenergy harvester along with the piezoceramic as the piezoelectric energy harvester.

The second testing was conducted to obtain the best pair of triboelectric layers. The best result from this testing was used to develop the final prototype. It isdone by using the dielectric-to-dielectric configuration with copper as the main electrode of the system. To improve the first testing data, it is possible to cater the triboelectric layers.Thesecond testing was done,and it shows that the paper with PTFE produced the highest output voltage.

A more accurate and consistent result can be achieved by using the shaker machine to induce vibration onto the prototype at the same frequency as the resonance frequency of the prototype as shown in Fig. 3.

The best result from this testing were then implemented and the output were compared with the first testing.

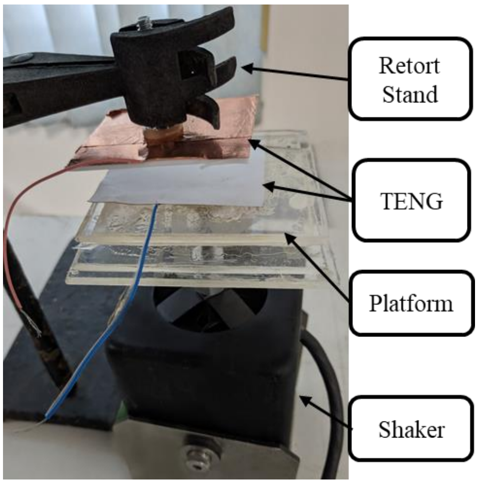

Fig. 3 Setup of the triboelectric layer testing

In order to further improve the outcome, the third testing was conducted on the final prototype in order to compare its performance with the first testing data. The surface modification was done on the PTFE's surface using three methods namely, debossed, heat treated and sandpapered.Fig. 4-6 show the changes of different type modified surface after different treatments.

Results which induces high output will be implemented to the prototype. These will determine that the hybrid prototype have vast tendency to achieve higher results and efficiency.

Fig. 4Modification of PTFE surface after debossed a) Original surface b) Debossedusing 18 punches.

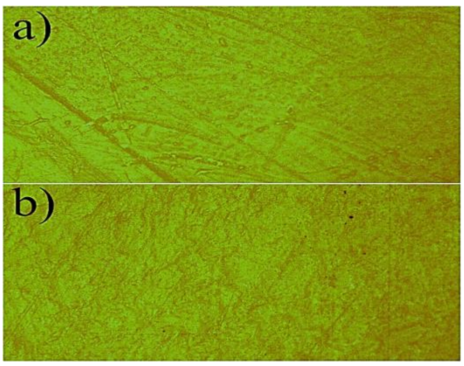

Fig. 5Modification of PTFE surface after heat treatment a) Original surface b) Heated at 150° C

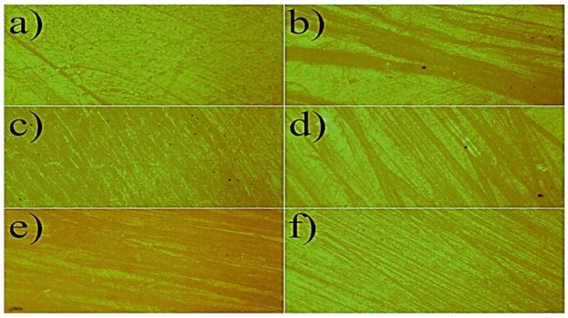

Fig. 6 Modification of PTFE surface by using sandpaper a) Original surface of PTFE b) Roughed surface using 80 grit c) Roughed surface using 240 grit d) Roughed surface using 360 grit e) Roughed surface using 600 grit f) Roughed surface using 1500 grit

IV.RESULTS AND DISCUSSION

Parameters Result

The first testing result is shown in Table 1 below. This test was done to get the baseline data and compare later with the modified one in this work.

Table. 1 First Testing

Energy harvester	Voltage (V)
Piezoelectric	8.86
Top Triboelectric	0.25
Bottom Triboelectric	0.27

The implementation produced decent yet very low output. Thus, some improvement is needed to heighten the result. Second testing was done in order to achieve a better result. The result is shown below in Fig. 7.

The triboelectric layers can be catered by pairing the highest negative charged material, PTFE with other more positively charged materials. The result shows that the pair between the PTFE and the paper, produces higher result than the other materials, as in [11]-[12]. This can be explained by the affinity charges of each of the materials, the higher the difference between positive and negative charges, will produce higher voltage difference across the charges gap as in [15].

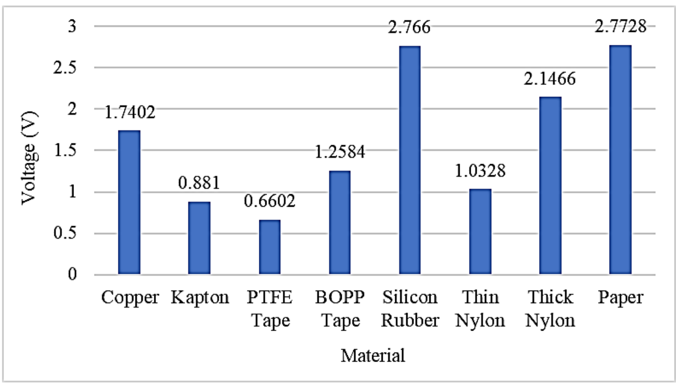

Fig. 7Output comparison between triboelectric layers with PTFE

Retrieval Number: A2662109119/2019©BEIESP
DOI: 10.35940/ijeat.A2662.109119
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Next, from second testing, the paper layer will be implemented into the prototype to see changes from the first testing result. The latest value is shown in Table 2.

Table. 2 Second Testing

Energy harvester	Voltage (V)	Average (V)
Top Triboelectric	1.43	1.47
	1.41	
	1.39	
	1.50	
	1.61	
Piezoelectric	8.60	9.15
	9.01	
	9.68	
	8.96	
	9.53	
Bottom Triboelectric	1.68	1.64
	1.63	
	1.59	
	1.61	
	1.71	

Significant changes can be spotted by comparing the first testing result to the second testing result. The increment achieved nearly 4.8 times from the first testing result.
Since the paper is a better pair with the PTFE, the need of improving the prototype is still in the open, thus third testing will bethe surface modification.

Based on Fig. 8-10, the debossing increases the triboelectric output. Surface modification proved to be effective in increases the output of TEH as in [16]. Debossing the triboelectric layer shows the increase in the area of effectiveness thus resulting in the increment of the result. Meanwhile, treating the surface with high temperature decreases the output. PTFE's relative permittivity reduces when the temperature increases, as in [17]. Referring to the equation 1, as relative permittivity decreases, the voltage will decrease. As for the modification by sandpaper, no significant changes for the first three grit hardness. The outcome differs greatly from 360 grit to 600 grit, this shows that as the surface is being smoothed instead of roughed the output increases.

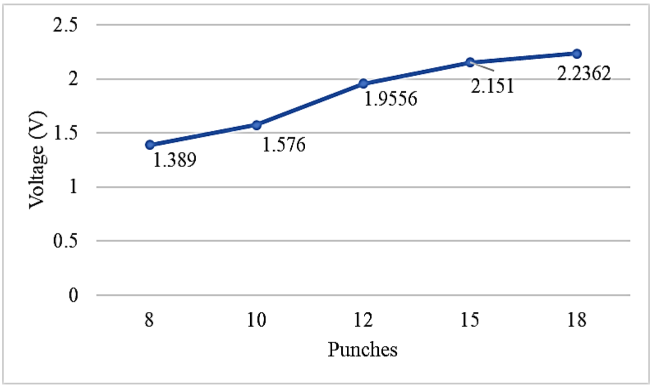

Fig. 8 Effect of debossing on the output

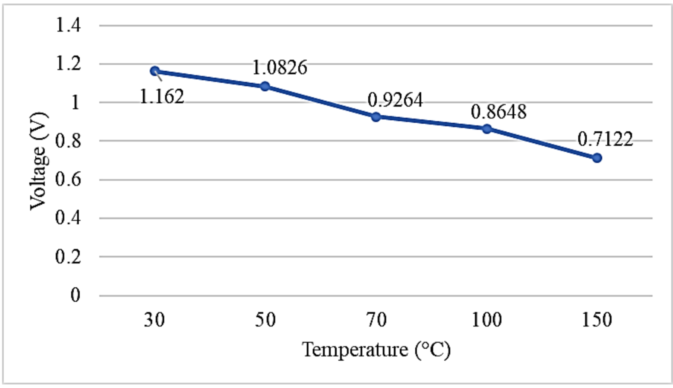

Fig. 9 Effect of heat on the output

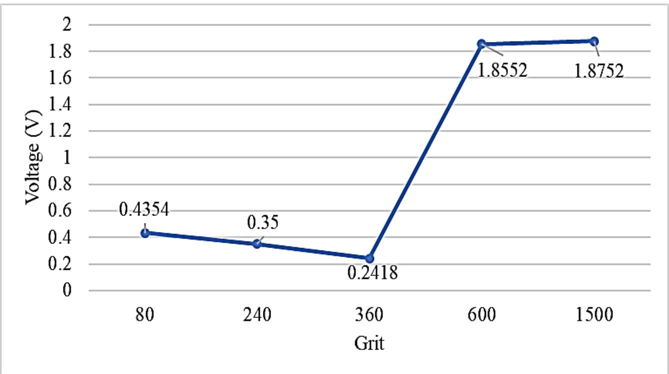

Fig. 10 Effect of roughness on the output

The modified PTFE's surface was used onto the final prototype and expected outcome is to have this third testing result to be better than the last one. The difference in result shows about 44% of increment from the second testing, as shown in Table 3.

Table. 3 Final Testing

Energy harvester	Voltage (V)	Average (V)
Top Triboelectric	2.14	2.23
	2.36	
	2.21	
	2.34	
	2.11	
Piezoelectric	9.36	9.27
	9.26	
	9.14	
	9.33	
	9.25	
Bottom Triboelectric	2.47	2.24
	2.31	
	2.12	
	2.19	
	2.09	

Fig. 11 shows the varied values of load resistance with its corresponding voltage and power values. Theoretically, the optimum power occurred when the load resistance is equivalent with the internal resistance of the source as in [18].

Thus, the resistance of this prototype is 9kΩ for an optimum power of 7.29mW.The area of the prototype is 9.9 cm^2, thus the power density obtained from the prototype was 7.36 Wm^{-2}.

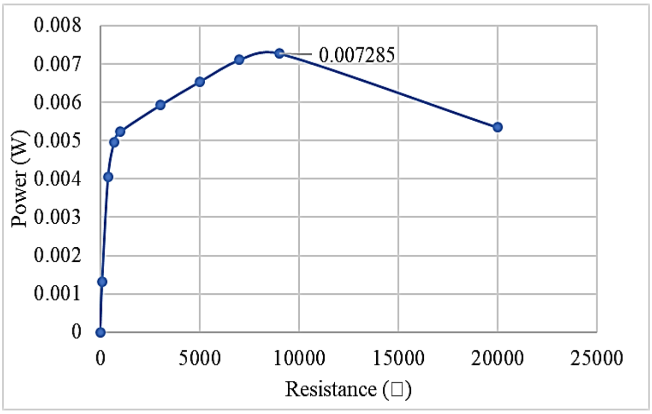

Fig. 11 Effect of resistance on power

Working Mechanism

Based on the working mechanism of the prototype in Fig. 1, there are three stages of load work. First, the top and bottom PTFE come into contact with the paper on both side of the piezoceramic. At this stage, the triboelectric charges produced on the surface due to its difference of polarity. No electron flows between the TEH. Then, as the piezoceramic oscillates up and down creating sudden gap in between the triboelectric layers and the electron started to flow. This is because the output voltage and current from the triboelectric were produced due to the electrostatic induction. On the third stage, while the piezoceramic swings, the pressure point produces electricity.

V.CONCLUSIONS

Thispaper discussed the performance of the triple cantilever housing two types of energy harvester,triboelectric and piezoelectric. Different materials of the triboelectric layers produce different outcome due to the difference in the polarity of the material's charges. It was found that TEH surface modification can boost up the output of the TEH by 44% showing that the relation between surface area ofeffectiveness and the output is very significant for the improvement of the triboelectricenergy harvesters. The objective of the result is achieved when the outcome of the project indicates that, the combination of paper and PTFE withdraw high output and even higher once the PTFE's surface is modified. This TCHEH has shown a significant increase in the peak power density of 7.36 Wm^{-2} when compared to the triple cantilever TEH from previous work as in [9], where the peak power density was 0.25 Wm^{-2}. Due to the past research states that only 100 µW is needed to operate a low power wireless sensor node as in [19], and since the result of the power output of this work is 7.29 mW, thus the objective to power up the low power wireless sensor node is achieved.

ACKNOWLEDGMENT

This research was supported by the Fundamental Research Grant Scheme (FRGS) 20140133FRGS from the Ministry of Education Malaysia and the UNITEN Internal Grant J510050869.

REFERENCES

1. S. Roundy and P. K. Wright, *Smart Material Structure*, no. 13, p. 1131, 2004.
2. Z. L. Wang, "*Triboelectric Nanogenerators as New Energy Technology for Self-Powered Systems and as Active Mechanical and Chemical Sensors*," *American Chemical Society*, 2013.
3. M. H. Lam and H. Salleh, "*PZT Piezoelectric Energy Harvester Enhancement Using Slotted Aluminium Beam*," *Advanced Materials Research*, vol. 1051, pp. 932-936, 2014.
4. L. Dhakar, H. Liu, F. E. H. Tay and C. Lee, "A Wideband Triboelectric Energy Harvester," *Journal of Physics: Conference Series*, pp. 1-5, 2013.
5. G. Suo, Y. Yu, Z. Zhang, S. Wang, P. Zhao, J. Li and X. Wang, "Piezoelectric and Triboelectric Dual Effects in Mechanical Energy Harvesting Using BaTiO3/Polydimethylsiloxane Composite Film," *Applied Materials & Interfaces*, pp. 1-22, 2016.
6. J. Yu, X. Hou, M. Cui, S. Zhang, J. He, W. Geng, J. Mu and X. Chou, "*Highly skin-conformal wearable tactile sensor based on piezoelectric-enhanced triboelectricnanogenerator*," Nano Energy, vol. 64, pp. 2211-2855, 2019.
7. S. Lee, B. Yeom, Y. Kim and J. Cho, "*Layer-by-layer assembly for ultrathin energy-harvesting films: Piezoelectric and triboelectricnanocomposite films*," Nano Energy, vol. 56, no. 1-15, pp. 2211-2855, 2019.
8. L. Dhakar, S. Gudla, X. Shan, Z. Wang, F. E. Hock Tay, C.-H. Heng and C. Lee, "*Large Scale Triboelectric Nanogenerator and Self-powered Pressure Sensor Array Using Low Cost Roll-to-roll UV Embossing*," *Scientific Reports*, no. 6, p. 22253, 2016.
9. W. Q. Yang, J. Chen, G. Zhu, X. Wen, P. Bai, Y. Su, Y. Lin and Z. L. Wang, "*Harvesting vibration energy by a triple-cantilever based triboelectric nanogenerator*," *Nano Research*, vol. 6, no. 12, pp. 880 - 886, 2013.
10. G. Zhu, C. F. Pan, W. X. Guo, C. Y. Chen, Y. S. Zhou, R. M. Yu and Z. L. Wang, "*Triboelectric Generator Driven Pulse Electrodeposition for Micropatterning*," *Nano Lett*, no. 12, pp. 4960-495, 2012.
11. "*ECD Thermosphere Collective IQ*," ECD Quality Solutions, 10 April 2009. [Online]. Available: https://www.ecd.com/support/learning-center/resources/triboelectric-series-and-its-effect.aspx?Post=3917&tabid=371. [Accessed 25 June 2019].
12. F. Diaz and R. M. Felix-Navaro, "A Semi-quantitative Triboelectric Series for Polymeric Materials: The Influence of Chemical Structure and Properties," *J. Electrostat*, no. 62, pp. 277-290, 2004.
13. S. Niu, S. Wang, Y. Liu, Y. S. Zhou, Y. Hu and Z. L. Wang, "*Theoretical study of contact-mode triboelectric nanogenerators as an effective power source*," *Energy & Environmental Science*, vol. 6, pp. 3576 - 3583, 2013.
14. Erturk and D. J. Inman, "On Mechanical Modeling of Cantilevered Piezoelectric Vibration Energy Harvesters," *Journal of Intelligent Material Systems and Structures*, vol. 1311, no. 19, pp. 1311-1325, 2008.
15. W. Lee and D. E. Orr, " *The TriboElectric Series*," Alpha Lab Inc., 2018. [Online]. Available: https://www.alphalabinc.com/triboelectric-series/. [Accessed 26 June 2019].
16. G. Hassan, F. Khan, A. Hassan, S. Ali, J. Bae and C. H. Lee, "*Flat Panel Shaped Hybrid Piezo/Triboelectric Nanogenerator for Ambient Energy Harvesting*," *IOP Science Organization*, p. 1, 2017.
17. C. X. Lu, C. B. Han, G. Q. Gu, J. Chen, Z. W. Yang, T. Jian, C. He and Z. L. Wang, "Temperature Effect on Performance of Triboelectric Nanogenerator," *Advanced Engineering Materials*, vol. 1700275, no. 00, pp. 1-8, 2017.
18. "*Maximum Power Transfer Theorem*," Electronics Hub Organizations, 21 April 2015. [Online]. Available: https://www.electronicshub.org/maximum-power-transfer-theorem/. [Accessed 25 June 2019].
19. T. Y. K, *Analysis, Design and Implementation of Energy Harvesting Systems for Wireless Sensor Nodes, Singapore*, 2010.