SAVUNMA BİLİMLERİ DERGİSİ
The Journal of Defense Sciences
https://dergipark.org.tr/tr/pub/khosbd

Comparative Investigation of Triboelectric Energy Harvesting Modes: A Simulation Study

Triboelektrik Enerji Hasat Modlarının Karşılaştırmalı İncelenmesi: Bir Simülasyon Çalışması

Ali Ekber ÖZDEMİR [1] Sibel AKKAYA OY [1*]

[1]*Ordu University, Fatsa Faculty of Marine Sciences, Marine Sciences and Technology Engineering Department, Ordu, TÜRKİYE*

Makale Bilgisi

Araştırma makalesi
Başvuru: 02.10.2024
Düzeltme: 18.10.2024
Kabul: 21.10.2024

Keywords

Triboelectricity
Nanogenerator
Simulation
Modelling
Renewable energy

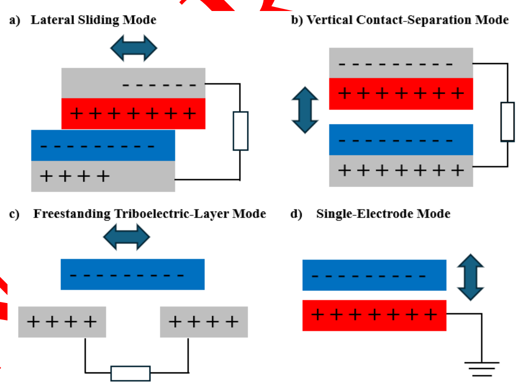
Anahtar Kelimeler

Triboelektrik
Nanojeneratör
Simülasyon
Modelleme
Yenilenebilir enerji

Highlights

Triboelectric energy conversion can be a promising and very inexpensive method for low-power systems. Friction between two different materials can generate free electric charges, and these electric charges can provide power for low-power systems such as wireless sensor nodes. In this paper the open and short circuit conditions of a triboelectric system for four working modes have been investigated.

Graphical Abstract



Abstract

This study presents a comparative analysis focused on simulating the operational modes of a triboelectric nanogenerator (TENG) using simulation-based method. Simulation modelling was performed using a demo version of the Comsol Multiphysics software. The simulations were conducted under both open circuit and short circuit conditions. The study provides the voltages across the surface of the electrodes under open circuit conditions and the transferred electrical charges under short circuit conditions, along with their respective graphs. The study examines the four main operating modes of a TENG—Vertical Contact-Separation Mode, Lateral Sliding Mode, Single-Electrode Mode, and Freestanding Mode—simulated under specific parameter sets. These results hold significant importance in the design stage of a Triboelectric Nanogenerator (TENG), as each working mode necessitates a specific interface circuit to harvest energy efficiently.

Özet

Bu çalışma, simülasyon tabanlı yöntem kullanılarak bir triboelektrik nanojeneratörün (TENG) çalışma modlarının simüle edilmesine odaklanan karşılaştırmalı bir analiz sunmaktadır. Simülasyon modellemesi Comsol Multiphysics yazılımının demo versiyonu kullanılarak yapıldı. Simülasyonlar hem açık devre hem de kısa devre koşullarında gerçekleştirilmiştir. Çalışma, açık devre koşulları altında elektrotların yüzeyindeki voltajları ve kısa devre koşulları altında aktarılan elektrik yüklerini ilgili grafikleriyle birlikte sağlar. Çalışma, belirli parametre setleri altında simüle edilen bir TENG'in dört ana çalışma modunu (Dikey Kontak Ayırma Modu, Yanal Kayma Modu, Tek Elektrot Modu ve Bağımsız Mod) inceliyor. Bu sonuçlar, Triboelektrik Nanojeneratörün (TENG) tasarım aşamasında büyük önem taşıyor çünkü her çalışma modu, enerjiyi verimli bir şekilde toplamak için özel bir arayüz devresi gerektiriyor.

*Corresponding author, e-mail:sibelakkaya@odu.edu.tr

DOI: 10.17134/khosbd.1559922

Elektronik/Online ISSN: 2148-1776
Basılı/Printed ISSN: 1303-6831

1. INTRODUCTION

It is expected that the human population will reach 8.6 billion by 2030, with 61% of the population living in cities [1, 2]. This means that the energy demand of human civilization will be on the rise across all scales, spanning from nanowatts to gigawatts, driven by growing population and advancements in technology and industry. There is a correlation between energy demand and CO_2 emissions. Due to the energy demand of the population, the annual CO_2 emission rate is increasing by 2% [3]. Global warming and climate change are the biggest problems threatening humanity. To address this problem, alternative and clean energy technologies should be developed and implemented across all scales, not only at a very large scale but also at the smallest scales, within a short time frame.

Thanks to advancements in integrated circuit (IC) technologies, it has become possible to produce smarter and smaller devices that consume ultra-low energy [4]. The development of devices with ultra-low energy consumption has sparked increased interest in battery-free device technologies [5]. Main characteristics of this kinds of devices is to be needed an energy harvester which generates energy from ambiance.

The operational efficacy of energy harvesters' hinges upon a multitude of variables, encompassing the energy conversion mechanism, constituent materials, operational modes, and physical dimensions of the device [6].

The design of an efficient harvester necessitates meticulous consideration of all pertinent parameters influencing its functionality. Frequently, the optimal values for these parameters must be discerned during the design phase, as the fabrication stage typically lacks the requisite conditions for their optimization. This investigation delves into the meticulous analysis of specific parameters crucial to the performance of a triboelectric energy harvester across four main working operational modes, employing the Comsol Multiphysics software for comprehensive analysis.

The article is structured as follows: Information regarding triboelectric energy converters will be provided in the subsequent section. Following that, the performances of energy harvesters under different parameters for four distinct operating modes will be evaluated using COMSOL models.

2. TRIBOELECTRICITY

Triboelectricity is a partially novel method of energy generation intended to power ultra-low power devices, characterized by the connection and separation continuously of two dissimilar materials [7]. The mathematical background of this phenomenon can be explained by Maxwell's equations, which can be found in more detail in [8, 9].

The triboelectric effect has been known for over 2000 years [10], and nowadays, this effect has been utilized not only for energy harvesting but also in sensing applications [11]. The first TENG was proposed in 2012 [12]. While the effect can be readily employed in various applications, this phenomenon exhibits a complex nature attributed to the following reasons [10]: (1) Even on a surface with high charge density, the charge density can only reach 1 electron unit per ~105 surface atoms. This implies that irrespective of the degree of surface charging, the resulting charge per surface atom remains relatively low, thus leading to a notably modest charging rate. (2) Fundamental questions such as determining which surface will acquire a positive charge and which will become negatively charged upon contact remain challenging to answer definitively. Additionally, exceptions, such as those observed in cyclic triboelectric series from different theories, appear to be mutually exclusive. Various factors can influence the same triboelectric process, thereby complicating the comprehensive analysis by isolating each dominant parameter for modelling the triboelectric effect. Considering these intricate aspects of the triboelectric effect, numerous experiments have been undertaken. While these findings are commendable, their significance is significantly diminished due to the absence of more robust theoretical deductions to interpret the phenomena observed in the triboelectric process. Despite the utilization of numerous simulation and modelling methods to elucidate the phenomena, the lack of sufficient physical laws and mathematical descriptions further compounds the difficulty [10, 13, 14]. Nevertheless, these simulations and models are valuable for the development of practical applications.

2.1.TENG Structures

A TENG can be operated in four working modes [15-20] as shown with Figure 1.

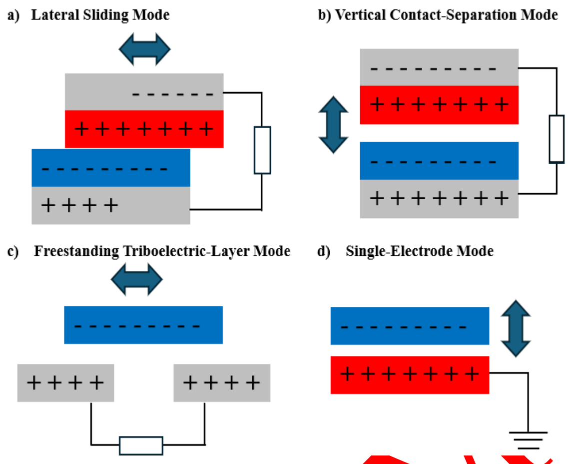


Figure 1: Operation modes of a TENG.

Lateral Sliding Mode (LSM): In this operational mode, friction between two dissimilar materials is used to generate free electrical charges. The direction of movement is lateral. The main applications of this mode can be summarized as wearable electronics, self-powered sensors, human-machine interfaces, energy harvesting from mechanical vibrations, and Internet of Things (IoT) devices [19].

Vertical Contact-Separation (VCS) Mode: This mode refers to a specific operational principle where two dissimilar materials are brought into contact and then separated vertically. This movement creates a cyclic process of contact and separation, which generates a triboelectric effect, leading to the generation of electricity. This mode is characterized by its ability to efficiently harvest mechanical energy from vertical motions, enabling the conversion of mechanical energy into electrical energy in various applications, such as energy harvesting from human motion, vibrations, or other mechanical sources [17].

Freestanding Triboelectric-Layer (FTL) Mode: In this operation mode, a configuration involves symmetric electrodes positioned beneath a dielectric film, where the width of the electrodes and the gaps between them are comparable to the dimensions of the moving object. As the object approaches and moves away from the electrodes, an asymmetric distribution of electric charges occurs on the material's surface, leading to the flow of electrons between the electrodes and the mitigation of local potential differences. This process generates an alternating current (AC) output due to the oscillation of electrons. Importantly, since there is no direct friction or contact between the moving object and the top dielectric layer of the electrodes, free rotation becomes feasible without mechanical contact, thereby minimizing abrasion of the dielectric layer. This innovative approach significantly enhances the durability and prolongs the service life of TENGs operating in rotation mode. Consequently, the harvesting of energy from human locomotion, automobiles, and other moving objects becomes both feasible and convenient [20].

Single-Electrode (SE) Mode: In contrast to the previously described operating modes, this mode does not involve the use of two electrodes interconnected by an external circuit. Instead, two dissimilar materials function freely. To harness mechanical energy in this mode, a single-electrode TENG is utilized, with the bottom electrode grounded. As the top object approaches or departs from the bottom film, the local electrical field distribution changes, prompting electron flow between the ground and the bottom electrode to match the potential change. This energy harvesting strategy has been applied in both contact-sliding and contact-separation modes [18].

TENGs are very useful tools to harvest energy from mechanical movements and vibrations like piezoelectric energy harvesters. While the power density of TENGs varies between 0.1 and 100, piezoelectric nanogenerators (PNGs) have a power density ranging from 0.001 to 30 [21]. Variation of electrical power output of a Triboelectric Nano Generator (TENG), the selection of materials holds significant importance. In this context, a table known as the triboelectric series presented in Table 1, is utilized [21,22].

Table 1: Qualitative triboelectric series of common materials.

Triboelectric series		
Most + charged	0	Styrene and polystyrene
Hair, oily skin	Steel (no charge)	Orlon
Nylon, dry skin	Wood (small negative charge)	Plastic wrap
Glass	Amber	Polyurethane
Acrylic, lucite	Sealing wax	Polyethylene (like Scotch tape)
Leather	Polystyrene	Polypropylene
Rabbit's fur	Rubber balloon	Polyvinylchloride (PVC)
Quartz	Resins	Silicon
Mica	Hard rubber	Tefon (PTFE)
Lead	Nickel, copper	Silicone rubber
Cat's fur	Sulfur	Ebonite
Silk	Brass, silver	Most − charged
Aluminium	Gold, platinum	
Paper	Acetate, rayon	
Wool (no charge)	Synthetic rubber	
0	Polyester	

3. SIMULATIONS FOR TENG STRUCTURES

All simulations were performed for open circuit voltage and short circuit current conditions. Efficient energy harvesting can be achieved by using external sophisticated interface circuit.

3.1. Lateral Sliding (LS) Simulations

For LS mode simulations (Open circuit and short circuit), the structure depicted in Figure 2 is employed.

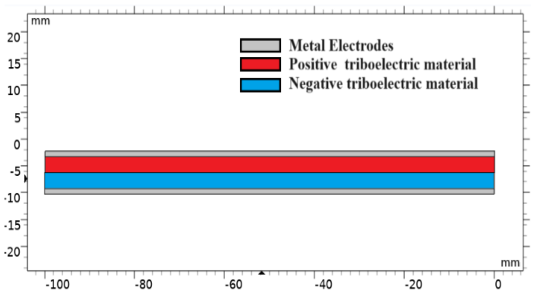


Figure 2: LS model used for simulation.

In these simulations, the bottom electrode and bottom triboelectric material are fixed, while the top electrode and top triboelectric materials are shifted by 1mm for each step. Selected parameters are listed for simulations in Table 2.

Table 2: Model Parameters for LS mode modelling.

Thickness of electrodes	0.1mm
Thickness of triboelectric materials	1mm
Length of the system	100mm
Amount of sliding	1mm
Relative permittivity of negative triboelectric material (ε_0)	2
Relative permittivity of positive triboelectric material (ε_0)	4
Initial surface charge density of negative triboelectric material	- 7e-6 C/m^2
Initial surface charge density of positive triboelectric material	7e-6 C/m^2
With of the system	100mm

The Surface electric potential distribution of the TENG operated in LS mode under the parameter set given in Table 2 is shown in Figure 3.

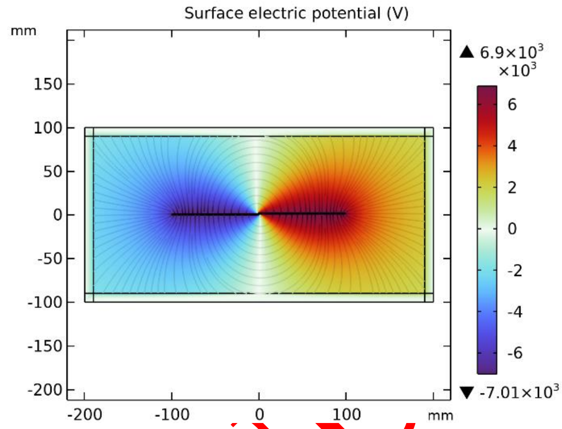


Figure 3: The change in surface electric potential in LS mode.

Electric potential distribution across the electrodes for open circuit condition is given with Figure 4 and the transferred charge amount to the electrodes has been provided in Figure 5 for the short circuit condition. Under the short circuit condition, boundary conditions were redefined as follows: the top of the electrodes was grounded, and the transferred charge amount was calculated in the simulation.

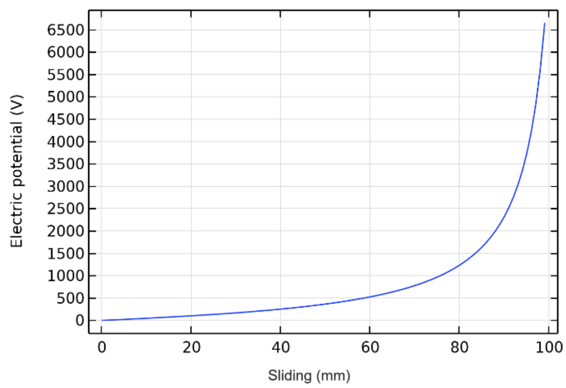


Figure 4: Electric potential of electrodes for open circuit condition in LS mode simulation.

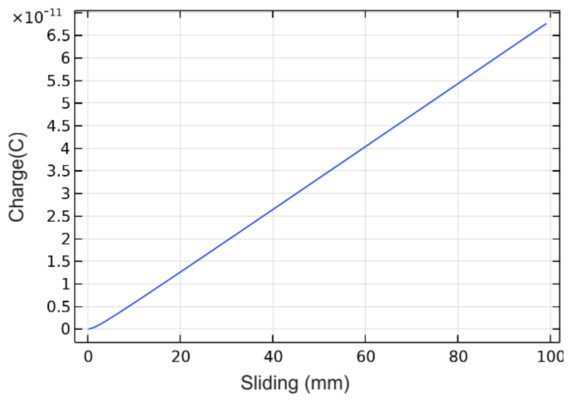


Figure 5: Transferred electric charge to the electrodes under short circuit conditions.

3.2.Vertical Contact-Separation (VCS) Simulations

For these simulations, the parameters listed in Table 3 were utilized. The same structure depicted in Figure 1 was employed, albeit at a different scale to reduce computational costs of simulation.

Table3: Model parameters for VCS mode modelling.

Thickness of electrodes	0.01mm
Thickness of triboelectric materials	0.1mm
Length of the system	5 mm
Amount of vertical sliding	1mm
Relative permittivity of negative triboelectric material (ε_0)	2
Relative permittivity of positive triboelectric material (ε_0)	4
Initial surface charge density of negative triboelectric material	- 7e-6 C/m^2
Initial surface charge density of positive triboelectric material	7e-6 C/m^2
With of the system	5 mm

The surface electric potential distribution of the TENG operated in VCS mode at the end of the simulation is shown in Figure 6.

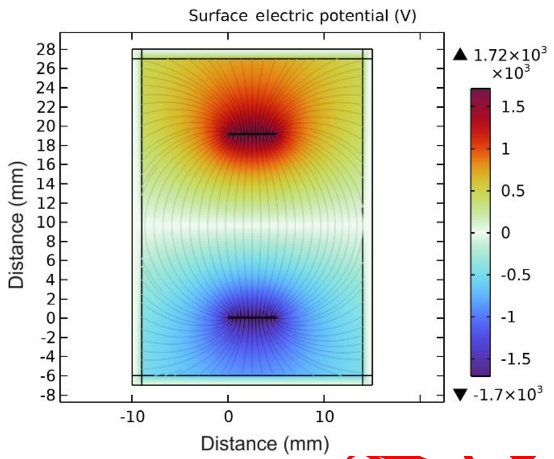


Figure 6: Surface electric potential distribution in VCS mode.

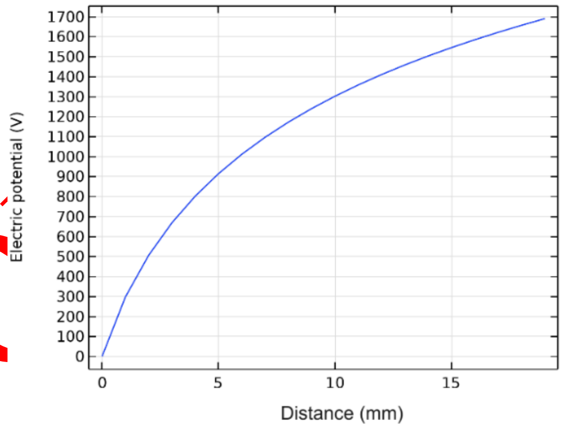


Figure 7: Electric potential of electrodes for open circuit condition in VCS mode simulation.

Transferred electrical charge on the short circuit condition to the electrodes has been given with Figure 8.

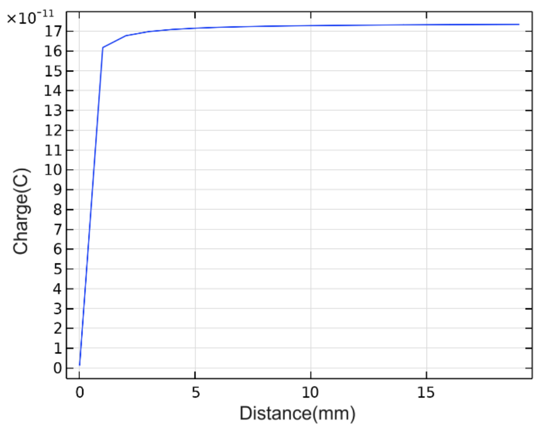


Figure 8: Transferred electric charge to the electrodes.

3.3.Freestanding Triboelectric-Layer (FTL) Simulations

In this stage, a configuration for FTL mode simulations given with Figure 9 is used.

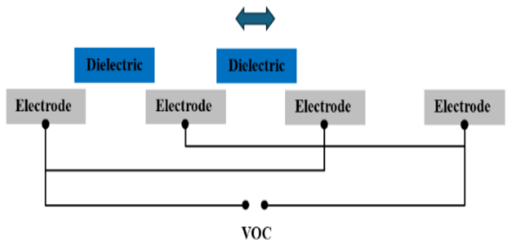


Figure 9: FTL mode model for simulations.

Parameter set has been used which is given by Table 4 in the simulations.

Table 4: Model Parameters for FTL mode modelling.

Thickness of electrodes	0.01mm
Thickness of triboelectric materials	0.1mm
Length of the electrodes and dielctrics	50 mm
Amount of vertical sliding	1mm
Relative permittivity of dielectric (ε_0)	2
Number of units	2
Surface charge density of dielectric	- 25e-5 C/m^2
Distances between electrodes	1mm
With of the system	5 mm
Gap between dielectric and electrode	0.0005mm

The surface electric potential distribution of the TENG operated in FTL mode at the end of the simulation is shown in Figure 10.

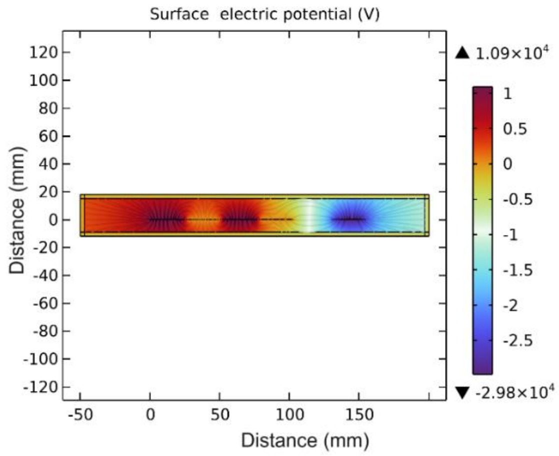


Figure 10: Surface electric potential distribution in FTL mode simulation.

Variation of the electrical potential on the electrodes for open circuit condition in FTL mode simulation under the parameter set given with Table 4 is given with Figure 11.

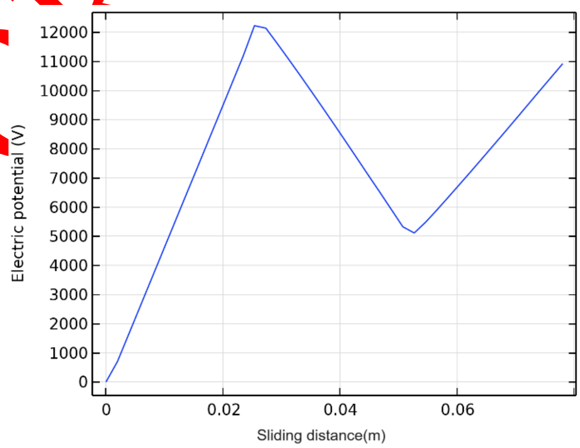


Figure 11: Electric potential of electrodes for open circuit condition in FTL mode simulation.

Another important case is the short circuit condition in FTL mode simulation. The charge transferred to the electrodes has been given by Figure 12 in short circuit condition in FTL mode simulation.

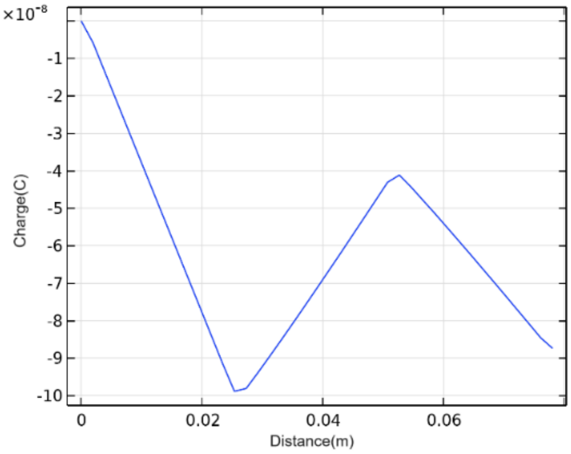


Figure 12: Transferred electric charge to the electrodes under short circuit conditions in FTL mode simulation.

3.4.Single - Electrode (SE) Simulations

The final operating mode in TENG structures is SE mode. For these simulations, a model depicted in Figure 1 (d) is utilized. A grounded metal and a dielectric are employed in the simulations. The simulations are conducted using the parameter set provided in Table 5.

Table 5: Model Parameters for SE mode modelling.

Thickness of electrode	1mm
Thickness of triboelectric materials	1mm
Length of the system	5 mm
Amount of vertical sliding	1mm
Relative permittivity of dielectric (ε_0)	2
Initial surface charge density of dielectric material	7e-6 C/m^2
With of the system	5 mm

Surface electric potential distribution for open circuit condition in SE mode simulation is given by Figure 13.

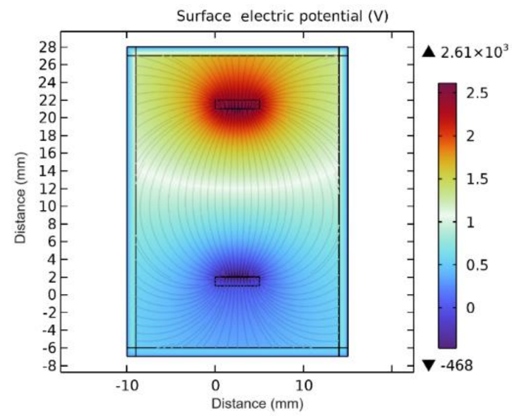


Figure 13: Surface electric potential distribution in SE mode simulation.

Open circuit voltage on the top of the dielectric material is shown in Figure 14.

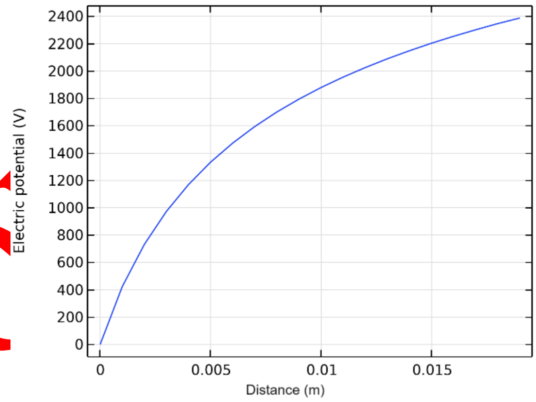


Figure 14: Electric potential of the top on the dielectric for SE mode simulation.

Other condition in SE mode modelling is the short circuit condition and amount of the transferred electrical charges to the grounded electrode has been shown in Figure 15.

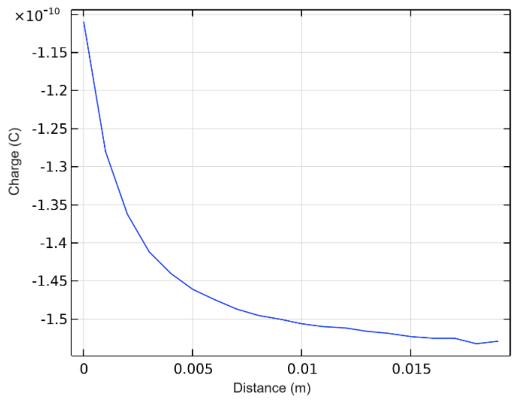


Figure 15: Transferred charge to the grounded electrode.

4.CONCLUSION

In this paper, four principles operation or working modes of a TENG have been investigated. Each mode has some advantages and disadvantages. Although TENGs have opportunities to supply energy for ultra-low power devices, some TENG structures need sophisticated interface circuits to harvest energy efficiently.

TENGs that work in the LS (Linear Sliding) mode have the capacity to produce energy even at lower speeds. Output voltage and current are relatively smoother and more stable in the LS mode compared to other modes, as depicted in Figures 4 and 5. However, this mode may not be suitable for higher speeds due to friction between materials.

In the VCS (Vertical Contact-Separation) mode, the maximum values of output voltage and current are restricted due to the nature of this mode. TENGs operating in this mode can generate relatively stable output voltage and current, as depicted in Figures 7 and 8. However, the working mechanism of this mode may produce unwanted sparks. Nevertheless, this mode is more suitable for operating at higher speeds compared to the LS (Linear Sliding) mode.

TENGs operating in the FTL mode require a rectifier circuit for energy harvesting applications due to the shape of the voltage and current waves. However, this mode is particularly suitable for high speeds. Additionally, the FTL mode enables the detection of very small movements, despite its more complex structure.

SE mode has very simple structure, but it has lowest energy output. In some cases, the SE mode may experience output fluctuations. This can result in instability and inefficiency in energy conversion.

TEŞEKKÜR (ACKNOWLEDGMENTS)

Bu araştırma hiçbir dış finansman almamıştır.

YAZAR KATKILARI

Ali Ekber ÖZDEMİR: Kavramsal tasarım, Veri düzenleme, Analiz, Denetim, Onaylama, Görselleştirme

Sibel AKKAYA OY: Metodoloji, Araştırma, Metodoloji, Yazma- Gözden geçirme ve Düzenleme

ÇIKAR ÇATIŞMALARI

Yazarlar, herhangi bir çıkar çatışması olmadığını beyan eder.

REFERENCES

[1] Q. He, F. Tapia, A. Reith, Quantifying the influence of nature-based solutions on building cooling and heating energy demand: A climate specific review, Renewable and Sustainable Energy Reviews, Volume 186, 2023, 113660, ISSN 1364-0321,

[2] S. Taslim, DM. Parapari, A. Shafaghat ,Urban design guidelines to mitigate urban heat island effects in hot-dry cities. Jurnal Teknologi, Volume 74, Issue 4, 2015.

[3] Y.H. Chen, Y.Z. Li, H. Jiang, Z. Huang, Research on household energy demand patterns, data acquisition and influencing factors: A review, Sustainable Cities and Society, Volume 99, 2023, 104916, ISSN 2210-6707

[4] M. -H. Chi, IC Technologies and Systems for Green Future, 2022 China Semiconductor Technology International Conference (CSTIC), Shanghai, China, 1-5, 2022. doi: 10.1109/CSTIC55103.2022.9856769.

[5] A. Torrisi, K. S. Yildirim and D. Brunelli, Low-Power Circuits and Energy-Aware Protocols for Connecting Batteryless Sensors, IEEE Communications Magazine, Volume. 61, No. 1, Pages 82-88, 2023. doi: 10.1109/MCOM.001.2200363.

[6] M. Wajahat, AZ. Kouzani, SY. Khoo, M. Map. Comparative study and multi-parameter analysis to optimize device structure of triboelectric nanogenerators, Nanotechnology, Volume 34, No 42, 2023.

[7] M. Song, et al., Current amplification through deformable arch-shaped film based direct-current triboelectric nanogenerator for harvesting wind energy, APPl. Energy, Volume 344, Pages 121248, 2023. DOI: 10.1016/j.apenergy.2023.121248.

[8] A. E. Özdemir, Triboelectric-Based Wind-Driven Nano-Power Energy Generator, Electric Power Components and Systems, Volume 52, Issue 7, 1191-1199, 2024. DOI: 10.1080/15325008.2024.2317346

[9] N.D. Yılmaz, Energy Harvesting with Triboelectric Nanogenerators: Theoretical Roots, Working Principles and Working Modes, Konya Journal of Engineering Sciences, Volume 9, Issue 1, Pages 232 – 249, 2021.

[10] S. Pan, Z. ZhangFundamental theories and basic principles of triboelectric effect: A review, Friction, Volume 7, Pages 2–17, 2019. https://doi.org/10.1007/s40544-018-0217-7

[11] L. Dhakar, Study of Effect of Topography on Triboelectric Nanogenerator Performance Using Patterned Arrays. In: Triboelectric Devices for Power Generation and Self-Powered Sensing Applications, Springer Theses, Springer, 2017, Singapore. https://doi.org/10.1007/978-981-10-3815-0_3

[12] F.-R. Fan, Z. Q. Tian and Z. L. Wang, Flexible triboelectric generator, Nano Energy, Volume 1, No 2, 328–334, 2012. DOI: 10.1016/j.nanoen.2012.01.004.

[13] Y. Zhang, Shao, T. Effect of contact deformation on contact electrification: A first-principles calculation. J Phys Appl Phys 46: 235304, 2013.

[14] S. Lin, T. Shao, Bipolar charge transfer induced by water: Experimental and first-principles studies. Phys Chem Chem Phys 19: 29418–29423, 2017.

[15] X. Xiong, J. Liang and W. Wu, "Principle and recent progress of triboelectric pressure sensors for wearable applications," Nano Energy, vol. 113, 108542, 2023. DOI: 10.1016/j.nanoen.2023.108542.

[16] Q. Zheng, B. Shi, Z. Li and Z. L. Wang, "Recent progress on piezoelectric and triboelectric energy harvesters in biomedical systems," Adv. Sci., vol. 4, no. 7, 1–23, 2017. DOI: 10.1002/advs.201700029.

[17] Z. L. Wang, L. Lin, J. Chen, S. Niu and Y. Zi, 2016, Triboelectric nanogenerator: vertical contact-separation mode," In Triboelectric Nanogenerators. Green Energy and Technology. Cham: Springer. DOI: 10.1007/978-3-319-40039-6_2.

[18] Z. L. Wang, L. Lin, J. Chen, S. Niu and Y. Zi, 2016, "Triboelectric nanogenerator: single-electrode mode," In Triboelectric Nanogenerators. Green Energy and Technology. Cham: Springer. DOI: 10.1007/978-3-319-40039-6_4.

[19] Z. L. Wang, L. Lin, J. Chen, S. Niu and Y. Zi, 2016, "Triboelectric nanogenerator: lateral sliding mode," In Triboelectric Nanogenerators. Green Energy and Technology. Cham: Springer. DOI: 10.1007/978-3-319- 40039-6_3.

[20] Z. L. Wang, L. Lin, J. Chen, S. Niu and Y. Zi, 2016, "Triboelectric nanogenerator: freestanding triboelectric-layer mode," In Triboelectric Nanogenerators. Green Energy and Technology. Cham: Springer. DOI: 10.1007/978-3-319-40039-6_5.

[21] M. Davoudi, C.Y. An, DE. Kim, A Review on Triboelectric Nanogenerators, Recent Applications, and Challenges. Int. J. of Precis. Eng. and Manuf.-Green Tech. 2023. https://doi.org/10.1007/s40684-023-00569-6.

[22] A.F. Diaz, R.M. Felix-Navarro, A semi-quantitative tribo-electric series for polymeric materials: The infuence of chemical structure and properties. Journal of Electrostatics, 62(4), 277–290,2004. https://doi.org/10.1016/j.elstat.2004.05.005.