High Performance Multiaxis Triboelectric Nanogenerator for Blue Energy Harvesting

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***Abstract*—In order to attain Net-zero by 2050, renewable energy has been deemed as the best alternative to end the current global reliance on fossil fuels, thus it is crucial to search for sustainable energy sources. Among various clean energy sources, blue energy from the ocean presents a promising renewable-source in the form of tidal wave, tidal current as well as thermal energy. In this work, an omnidirectional spherical TENG based on multi-layered TENGs and LS-TENGs was fabricated for ocean energy harvesting. This device was able to generate a peak open-circuit voltage of 100V when being stimulated by a mechanical shaker in a single axis at 1.8Hz, the same peak voltage was also consistently achieved when displaced in the other 2 axis. Moreover, several combinations of LS-TENG tubes were evaluated by rotating them by 180 ° at 1Hz. It was demonstrated that as more LS-TENGs are combined together, the peak open-circuit voltage produced also increased nearly linearly. Furthermore, the structure of the multilayer TENG was also validated using COMSOL to analyze the electric potential distribution between the Cu and FEP.**

I. Introduction

Rapid development of the human economy and society also leads to increasing global energy demands. Currently, this high energy demand is being satisfied mainly by burning fossil fuels, which in turn, contributes greatly to environmental pollution hence it is crucial to utilize as well as search for more clean and renewable energy sources. Blue energy from the ocean presents a promising renewable source in the form of tidal waves, tidal currents as well as thermal energy. However, the current development of blue energy extraction is restricted by the lack of economical energy harvesting technologies. At present, numerous ambient environmental energy harvesters based on either electromagnetic or piezoelectric have been developed but they possess low energy-conversion efficiency or complex structure.

The emergence of triboelectric nano-generator (TENG) presents a new way to convert low-frequency mechanical energy into electricity based on the coupling of triboelectrification and electrostatic induction. TENGs are especially useful in capturing omnipresent energies that are usually wasted in one's everyday life, including human motions, vibrations, and ocean waves. Different from normal Electromagnetic generators (EMG), TENGs operate on a mechanism driven by Maxwell's displacement current instead [1]. TENGs are lightweight, low-cost, and flexible, making them suitable for harvesting water waves.

A. Ocean wave energy generation

At the moment, the majority of ocean wave energy extraction schemes utilize EMGs with various mechanical structures. Nonetheless, they still face plenty of challenges, ranging from possessing low scalability to high cost, so they are not often deployed in the ocean. Moreover, unlike other renewable energy sources like solar power where photovoltaic (PV) panels can generate energy as long as there is light available between the infrared and ultra-violet range in the visible spectrum, to effectively capture energy from tidal waves, a device capable of harvesting low-frequency mechanical energy is necessary. EMGs typically require at least 50Hz to generate a practical output, though the water waves have an extensive motion range and it depends on the weather (e.g. frequency increases as wind speed increases), an oceanic energy harvester should also be able to harvest waves in tranquil seas where wave movements are irregular and are of low frequencies (0.1 to 6Hz), hence EMG is impractical for this environment. TENG has already been able to achieve optimal energy output in rough seas but has yet to adapt to calm seas, thus it is important to expand the application of TENGs in small water waves and other similar water bodies.

B. Mission statement

- Design and fabricate an individual buoyant structure that can generate electricity from ambient mechanical energy using TENG.
- Incorporate another TENG structure operating based on a different mechanism to increase the device's overall energy generation
- Perform theoretical analysis of the electromagnetic behavior of the multilayered TENG

Among various TENG structures, current shapes for blue energy harvesting are limited to spheres, cylinders, and cuboids. Spherical structures have been employed the most but the output performances of the previous rolling spherical TENGs were relatively low [1] and were usually unidirectional. Therefore, a novel spherical TENG device with high sensitivity omnidirectional energy generation capability is required to increase the feasibility of using TENG for blue energy harvesting.

C. Related Works

At the moment, TENG ocean energy harvesting systems include liquid-solid contact TENGs, fully enclosed TENGs, bionic structure TENGs, composite TENGs and TENG networks. This work utilizes both liquid-solid contact TENGs as well as fully enclosed TENGs.

1) Fully-enclosed TENGs: The majority of previous blue energy harvesting TENG researches explored the idea of fully enclosed TENGs. The marine environment's humidity affects the output performance of the solid-solid contact TENGs greatly, hence a fully enclosed structure is the most common way to overcome the harsh marine environment's hindrance on the TENG's energy generation process. As mentioned above, there are 3 main fully enclosed structures: spherical structure TENGs, multilayer structure TENGs, and the spring-assisted structure. It is also worth mentioning that currently, most fully-enclosed TENGs contain solid-solid contact TENGs to exploit the motion of floating bodies in ocean waves.

2) Spring-assisted structure: Usually, the majority of the shock potential energy from the ocean waves is dissipated into sound or mechanical energy and the energy collected by TENGs in this short time period is very limited. By adding springs to the structure, the shock potential energy can be stored as elastic potential energy and can later be converted into kinetic energy. In addition, the energy conversion efficiency can be improved with springs, by converting the low-frequency oscillation of waves into high-frequency oscillations of the TENG by reaching resonance.

Xu. et al [2] reported an integrated TENG array device based on an air-driven membrane structure, which exploited the low-frequency wave movements to control air pressure inside its structure. As shown in figure 1 Below, The oscillator case was connected to the outer shell with elastic bands (both made from acrylic), then inside the oscillator case contained a TENG array of max TENG gap size of 6mm, soft membranes (20% nylon, 80% polyethylene) were used as the air chamber walls. The electrodes in a single TENG unit were Cu foils covered with 50um polytetrafluoroethylene (PTFE) film and Al foils respectively.

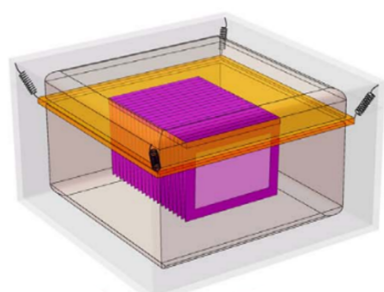

Fig. 1: TENG array based on air-pressure membrane [2].

When water waves push the water shell upwards, the inner oscillator case goes down relative to the shell, this compresses the lower air chamber, driving the TENG unit to induce electrification. While operating at a frequency of 2.9 Hz, the high-density array of TENG units was able to generate a short-circuit current of 187μA and outputs transferred charges per cycle of 15uC. However, the main disadvantage of this structure was its limitation in capturing wave motion in 1 direction. Moreover, the TENG unit may be vulnerable to temperature change, as air pressure varies according to temperature, and the air pressure within the air chamber may be affected which in turn, may not allow for ideal contact separation of TENGs.

3) Spherical Structure: Spherical structure TENG is the most widely adopted structure for ocean energy harvesting, mainly because of its ease of manufacturing and it being lightweight. [3] Additionally, its circular shape allows for low motion resistance/inertia in water waves, meaning it can easily respond to the motion of the waves. Moreover, its symmetrical spherical design implies that it has the capacity to collect the mechanical energy of the waves from all directions.

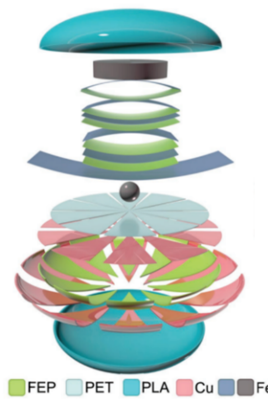

Fig. 2: Oblate spheroidal TENG (OS-TENG) [4].

In 2019, Liu et al [4]. have also designed an oblate spheroidal TENG (OS-TENG) assembled by two novel TENG subparts: the upper part based on a steel spring plate for rough seas and the lower part consisting of a rolling ball and two copper-coated polymer films. This TENG structure combined two triboelectric modes to flexibly respond to the random wave motions. The upper part is composed of a pie iron and 3 arched triboelectric basic units, each unit is made up of 2 jointed spring-based steel plates (good elasticity and fatigue-resistance), one of which is coated with fluorinated ethylene propylene (FEP) film. The upper part also utilizes rough sea conditions when the wavelengths are short and the amplitude is large, collecting energy with the TENG using single electrode mode. In the lower part, a radial patterned FEP film was coated with copper adhered on the internal surface of the oblate spheroidal shell, then another polyethylene terephthalate (PET) film coated with copper was placed above the inner FEP film so the 2 films come into contact whenever the iron shot overlapped them, initiating electrostatic induction. The most contributing factor for consistent ambient motion harvesting of the flat ball TENG structures was its ability to solve the imbalance of gravity center of the internal TENG under the water waves which in turn may have been its posture for optimal output performance. This robust TENG structure was able to produce a short-circuit current of 76μA and an open-circuit voltage of 281V at 4Hz of mechanical vertical stimulation. Nonetheless, this structure still relies on the vertical stimulation from the water waves, also if a tidal wave flips the whole sphere, the lower part of the TENG will not be able to operate normally.

In addition, Xu et al. [5] introduced an optimized ball-shell structured TENG with high responsivity to small agitations,

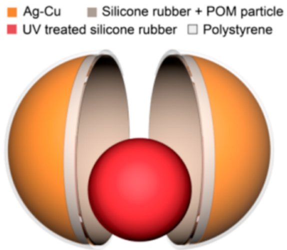

Fig. 3: Ball-shell TENG [5].

using silicone rubber as triboelectric material. Such structure may involve the ball rolling in a chaotic way, sometimes perpendicular to the agitation direction. This originates from the nonlinear dynamic system of the ball-shell system thus providing unpredictable harvesting in particular agitation ranges.

On the other hand, Xu et al [1] prepared a spherical TENG with a spring-assisted multi-layered structure for harvesting water wave energy from multiple triggering directions. As shown in figure 4, each multilayered TENG has five basic contact separation mode units, a total of 30 basic units inside the spherical structure. Each TENG unit is made with 50um-thick and 4.5cm-wide Kapton films as the substrate of the multilayered TENG in a zigzag shape. Foam blocks are placed on top of the Kapton as the base for the electrodes. Copper foils and FEP films bonded together were then adhered on both sides of the Kapton to form a single TENG unit. The multilayered TENG was then sandwiched in an acrylic plate which was supported by springs and copper balls were placed in the middle to compress the springs. The springs are also used to convert low-frequency oscillations from the wave to high internal vibrations.

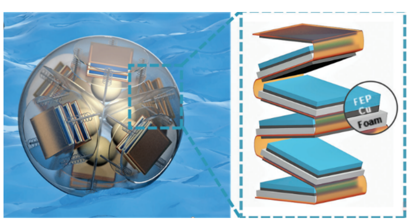

Fig. 4: Spherical TENG with a spring-assisted multi-layered TENG [1].

4) Liquid Solid contact TENG: Given that performance of solid-solid TENGs are sensitive to environmental factors, resulting output instability may be due to inefficient physical contact area between two abrasive surfaces. An alternative liquid dielectric such as water or other fluid dielectrics can serve as a favorable substitute for the contact in the friction layer of a TENG. Liquid-solid-based TENGs (LS-TENG), enlarge the contact surface area between dielectric mediums and avoid the wear and tear problem of solid-solid TENGs.

In liquid-solid contact, water often has a positive triboelectric charge after friction, so negative friction materials such as FEP are usually preferred as the friction layer. This was seen in [3] where an LS-TENG based on FEP films was fabricated, not to mention the nanowires were modified on the FEP film surface, resulting in even more surface area and electrical output efficiency was increased by 7.7%. This solves the traditional low surface charge density problem while the hydrophobicity assures durability.

Wang et al. [6] developed a multifunctional liquid dielectric interface based on TENG with direct current output which can function not only as an energy harvester but also as a chemical sensor. This LS-TENG also utilized FEP but in the form of a tube instead and Cu electrodes were designed into a ring tube structure. In virtue of the electronegativity difference between the FEP tube and the liquid dielectric, liquid flowing in the inner surface of the tube separates the electrons and the positive charges in the FEP and liquids respectively. On the outer surface of the tube, the charges of Cu electrodes will be induced by the triboelectric charge on the FEP, thus generating an electric charge. This process can be initiated by rotating the tube as seen in figure 5 Below. This specific LS-TENG was able to produce an open-circuit voltage of up to 228V and a peak short-circuit current of 11.5uA. Additionally, these types of fluid-state dielectrics with flexible shapes can adapt to any design shapes of TENG, making them an ideal candidate for fitting TENG into tight spaces.

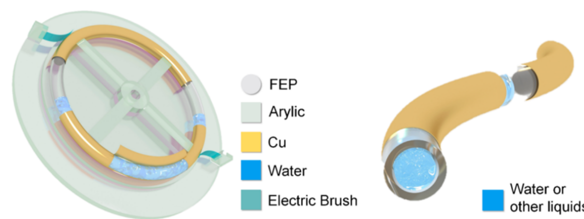

Fig. 5: Liquid dielectric interface based TENG [6].

II. Method

A. Design

In this work, a high-performance omnidirectional TENG device for all-weather blue energy harvesting is presented. The design is based on fully enclosed TENGs mainly due to their robustness to the negative impact of the harsh weather environment on the TENG. More specifically, this is a fully enclosed spherical case in order to make use of its ease of manufacturing allowing scalability in the future as well as its symmetrical shape to collect water energy from all directions.

Inside the spherical shell, contains 6 multilayered TENGs that are symmetrically located in different directions. Each multilayered TENGs has only two basic contact-separation modes, hence there are 12 total single contact-separation TENGs inside the structure. Each multilayered TENG is composed of a 25um thick Kapton and 4.5 cm wide Kapton strip as the foundation of the TENG unit and is arranged in a zigzag shape.(Kapton was used due to its High-temperature resistance, chemical resistance, and electrical insulation properties.) Each basic TENG unit inside 1 multilayered TENG is made up of the upper part consisting of a copper electrode and the lower part containing an FEP film bonded to a copper electrode via adhesion. In the center of the spherical case, a square-block mass is attached to all 6 multilayered TENGs.

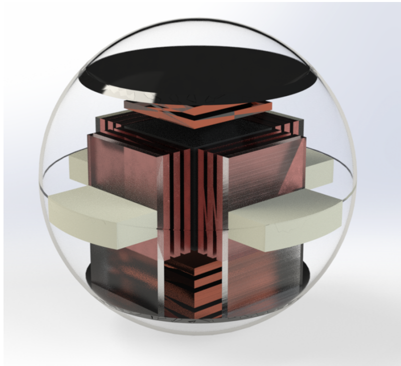

Fig. 6: Omni-directional energy harvester based TENG.

The mechanism of the TENG is triggered by the motion of the ocean waves, the movement of the spherical shell will displace the block mass in the center, leading to the block compressing the multilayered TENG. Subsequently, the Cu electrode comes into contact with the FEP film and opposite charges are generated on both surfaces. The change in the electrical potential difference between two electrodes drives free electrons to flow to the external circuit. As the wave continues to displace the block mass, the block mass moves in the other direction, not only separating both surfaces in this TENG but also compressing another multilayered TENG at the same time.

For the purpose of ensuring contact between the two surfaces of a TENG unit, acrylic plates are introduced as a flat platform to support the TENG. Thus, when the TENG is compressed, consistent contact is assured. The Kapton thickness allowed the multilayered TENG structure to also act as a spring that returns to its original state when not compressed, while not dampening the oscillation of the center block mass. Moreover, the multilayered TENGs from all 6 directions further act as a guide, to allow the center mass to oscillate in the correct direction.

The remaining empty spaces are preserved for LS-TENGs. The LS-TENG utilized here was in the shape of a cylinder. The cylinder tube was made from FEP and the dielectric liquid was H20. The tube was enclosed at both ends using plastic to prevent leakages. Copper electrodes were wrapped around both ends of the LS-TENG tube to enable electrons to flow to the external circuit.

In this project, practical tests, as well as simulations on both TENGs were carried out, capturing experimental data on the TENGs' performances.

B. *Experimental Procedure*

1) Data collection: The Structure was strapped to a mechanical shaker, and the mechanical shaker displaced the spherical TENG in 1 axis in order to mimic the motion experienced when floating on the surface of the ocean. The shaker induced oscillations within the spherical TENG and performances were retrieved using the 6514-system electrometer and captured using LabVIEW.

2) Theoretical Simulation: Numerical analysis on the multilayer TENG unit was performed using COMSOL Multiphysics, where the electric field and potential distribution were simulated. The software simulated the electric field using the finite-element method (FEM).

III. Result

A. *Experiment Data*

The shaker was set to induce an oscillation of 1.8-2.1Hz, in order to simulate tranquil sea wave motion with a wave amplitude of 2cm.

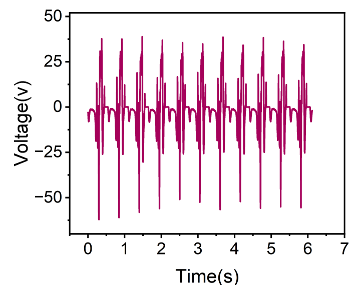

Fig. 7: TENG voltage plotted against time with 1.8Hz oscillation.

As seen in the graph above, a TENG comprised of Cu and FEP film, when experiencing 1.8Hz of oscillation was able to achieve a maximum voltage of 100V while being displaced in 1 direction. This also meant that only 2 multilayered TENGs were activated during this period. However, when only one multilayered TENG was utilized inside the spherical structure, an open-circuit voltage of 80V was generated, this may indicate that during the oscillation, one of the two TENGs did not fully contract, thus there was less contact area between the dielectrics, leading to less output than expected. Nonetheless, when oscillating in the other 2 axis, the spherical TENG was able to output similar values, therefore validating its consistency in multi-axial energy harvesting.

The same experiment was then repeated but in this iteration, the TENG was plugged into a Bridge rectifier and then into a capacitor. Again, using LabVIEW, the time taken to charge a 330uF capacitor up to 60V was timed.

As demonstrated in figure 8 below, the spherical TENG achieved an approximate transient period of 105 seconds and fully charged the capacitor at 110 seconds, then it rested at a steady state, again indicating its reliability in collecting as well as storing the energy from tranquil seas.

The LS-TENG structure was also tested by manually rotating the it 180° at 1Hz. This experiment was repeated by combining 3 then 5 identical LS-TENG cylinders.

The below figure 9 shows the voltage generated by each combination of LS-TENG. It can be seen that as more LS-TENG were combined together, the peak open-circuit voltage produced also increased nearly linearly. However, the LS-TENG cylinders were not bonded tightly together, thus the liquid dielectric motion inside the tube may not be in-sync, and perhaps more tightly spaced LS-TENG cylinders may have achieved better performance.

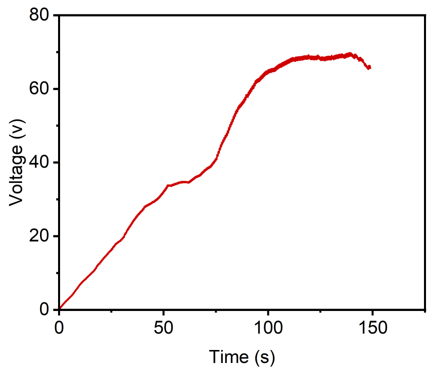

Fig. 8: Voltage of a 330uF capacitor plotted against time when being charged by the TENG.

Number of LS-TENG	Voltage (v)
1	15
3	48
5	102

Fig. 9: Voltage generated by each combination of LS-TENG.

1) Numerical Simulation: The distribution of the electric potential field of 1 layer within a single unit of TENG was simulated on COMSOL as presented below in figure 10 And figure 11.

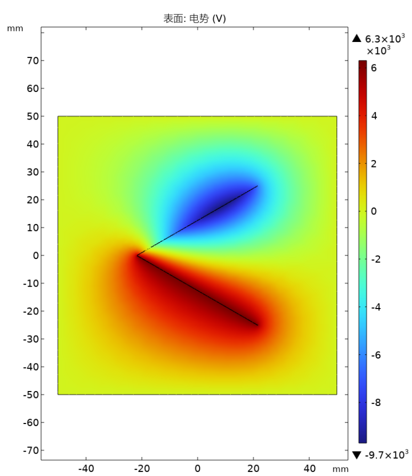

Fig. 10: Electric potential field distribution of 1 layer within a multilayered TENG.

Figure 10 displays the visualization of a single layer of TENG within the zigzag substrate when it was fully separated after initial contact. The upper plate represents the FEP and the lower plate denotes the Cu electrode. After the initial triboelectrification, the FEP became negatively charged whereas the Cu was positively charged as visualized by the electric potential distribution above. Another observation was that positive potential area actually covered the left end of the FEP. This may be explained by the metals such as Cu having an equipotential surface and since FEP is a non-metallic material, it may not be isopotential hence explaining the uneven distribution near the intersection of the 2 components.

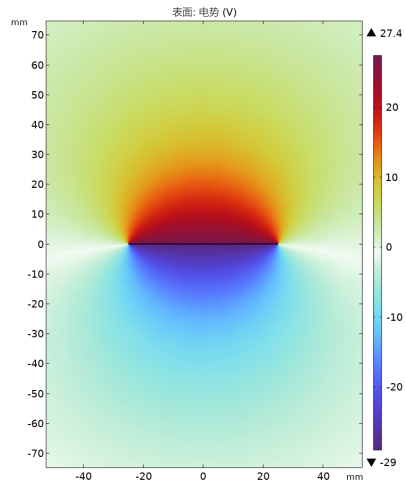

Fig. 11: Electric potential field distribution of the middle layer within a multilayered TENG.

On the other hand, Figure 11 above displays the electric potential field for the middle layer of a multilayered TENG, where one side was Cu and the other side was FEP. Since it denoted the middle layer, the Cu and FEP were separated with a layer of Kapton, which was demonstrated clearly in the simulation with a neutrally charged distribution in the middle. As expected, the electric potential distribution was fairly even on both sides with the Cu being positively charged and the FEP possessing a negatively charged electric potential. This solidified the triboelectric series assumptions, where it states that Cu has a higher tendency to lose electrons compared to FEP, therefore allowing FEP to become negatively charged after triboelectrification and demonstrating the reliability of the multilayered TENG mechanism for energy generation.

IV. Discussion

A. Conclusion

In Summary, a multi-directional based spherical TENG based on multilayered dielectric interfaces has been demonstrated for ocean energy harvesting. The multilayered TENG consisted of a Kapton substrate that housed an FEP film and a Cu electrode. This device was able to generate a peak open-circuit voltage of 100V when being stimulated by a mechanical shaker in a single axis at 1.8Hz, the same peak voltage was also consistently achieved when displaced in the other 2 axis. The structure of the multilayered TENG was also validated using COMSOL to analyze the electric potential distribution between Cu and FEP. Furthermore, LS-TENGs in the form of small cylinder tubes were incorporated into empty spaces within the spherical TENG to further leverage the blue energy harvesting of the device.

However, testing showed similar voltage output between a single TENG and 2 TENGs during oscillation, this may indicate that the second TENG unit may not have experienced consistent contact during the oscillation. Another issue encountered was the out-of-sync water liquid dielectric movements inside the LS-TENG, resulting in inaccurate measurements when measuring energy generated together by several LS-TENGs.

B. Future prospect

The material of the TENG will be further optimized such as alternating the nanostructure of the contact surfaces to possibly increase the multilayered TENG's performance, also Fermi levels will be further researched to explore possible useful information on the TENG materials. [7] In addition, the length of the Cu electrodes as well as the placement location for the LS-TENG should also be refined. Moreover, the effects of liquid inherent properties on the output performance of the LS-TENG will be further studied.

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