

Wave-driven Friction Nanogenerator Based on PDMS/Fe₃O₄ Composite Nanomaterials

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Abstract: Wave energy is a widely available renewable energy source with a lot of potential for self-powered sensing applications. However, wave energy density is low, and most wave sources in the natural environment are low- to medium-frequency wave sources. In order to improve the collection efficiency of wave energy in low and medium frequency bands, a wave-driven overlapping cube friction nanogenerator (OC-TENG) based on polydimethylsiloxane/ triiron tetroxide (PDMS/Fe₃O₄) composite nanofilm materials is designed. PDMS/Fe₃O₄ composite nanomaterials as the negative friction layer, polyamide 11 (PA11) as the positive friction layer, and copper foil (Cu) as the electrode, combined with the overlapping cube structure. With varying wave frequencies, the OC-TENG can produce peak voltages between 57.35 and 86.32 volts as well as short-circuit currents between 4.61 and 9.83 μ A, significant improvement over pure PDMS-based TENG at the same wave frequency. Due to its extremely effective wave-to-electricity conversion properties in the low and medium frequency ranges, the OC-TENG might be used as a low-power device power source.

Keywords: Wave energy, friction nanogenerator, PDMS/Fe₃O₄, overlapping cubic structure.

1. Introduction

As human beings continue to explore and develop new types of clean energy [1], many new types of clean energy, such as solar energy, wind energy, geothermal energy and wave energy, have been developed rapidly [2]. Among them, the ocean occupies about 71% of the total area of the earth, and the total area of China's sea is about 4.73×10^7 km², which contains a large amount of blue clean energy - wave energy, and the development and utilization of wave energy in the ocean is of great significance to promote economic development, reduce carbon emissions and protect the ecological environment [3]. Compared with wind power, solar power and other research progress is relatively slow, so there are many technical difficulties in utilizing ocean energy to generate electricity [4]. At the moment, electromagnetic generators are the primary tool used in conventional ocean energy collection techniques. Electromagnetic generators, hydraulic systems, and wave capture devices are examples of conventional methods for harvesting ocean wave energy [10,11]. The device is large and bulky, usually requires a floating platform for support, and can only collect the kinetic energy of waves in one or two specific directions, which has certain limitations in collecting ocean energy.

The friction nanogenerator (TENG) prepared by friction nanotechnology, which was firstly proposed by Academician Zhonglin Wang in 2012, provides a new way of collecting low-frequency ocean wave energy [5]. The friction nanogenerator converts the low-frequency wave energy in the ocean into mechanical energy, which is converted into electrical energy and utilized through the principles of friction initiation and electrostatic induction [6]. Compared with the

traditional electromagnetic generator to collect ocean wave energy, TENG not only has the advantages of small size and low cost, but also greatly improves the efficiency of collecting low-frequency wave energy [7]. Compared with other large-scale energy harvesting devices that focus on output power, friction nanogenerators focus more on self-drive and convenience. Existing friction nanogenerators have been able to collect mechanical energy from the environment to be converted into electrical energy to sustain small devices [8], and they have great potential for development in the field of self-drive [9].

Therefore, in this paper, in accordance with the ranking of electronegativity of common materials by DK Davie et al [12], as shown in Fig. 1, an overlapping cube friction nanogenerator (OC-TENG) based on polydimethylsiloxane (PDMS) blended with iron tetraoxide nanoparticles (Fe₃O₄) as the material of the negative friction layer, polyamide-11 (PA11) with a strong ability to lose electrons as the material of the positive friction layer, and Cu as the electrode layer, is constructed to improve the efficiency of capturing the energy of low-frequency waves. Generator (OC-TENG) to improve the efficiency of capturing the energy of low and medium frequency ocean waves, and combined with the unique overlapping cube structure to increase the working efficiency of TENG. At various water wave frequencies, the OC-TENG produced an open-circuit voltage between 57.35 and 86.32 V as well as a short-circuit current between 4.61 and 9.83 μ A. This high-performance acoustic energy harvesting device offers a novel approach to self-powered sensing, which is crucial in many domains like artificial intelligence and the Internet of Things, as well as a straightforward and affordable way to convert ambient acoustic energy into electrical energy.

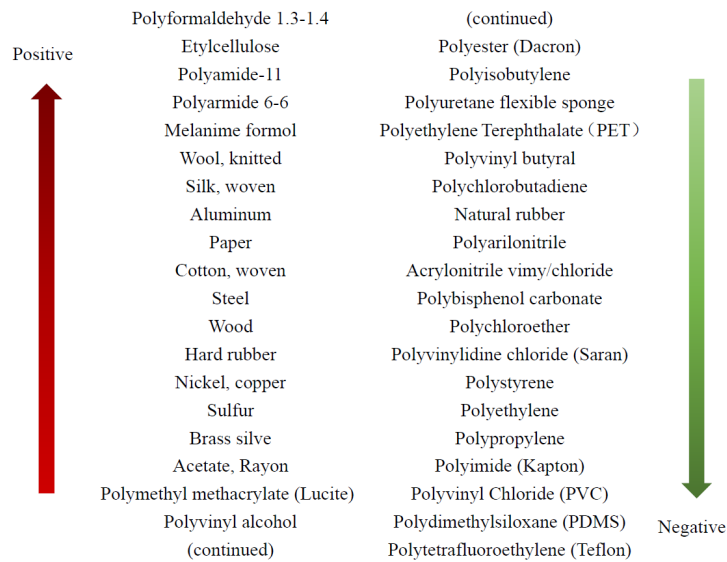


Figure 1. Electronegativity ranking of some common materials

2. Experimental Methods

2.1. Preparation of OC-TENG electrode layer

Due to the properties of high electrical conductivity, affordable price and easy availability of materials, copper foil metal material is often used as the conductive material of mechanical devices with the electrode layer of friction nanogenerators. According to the fact that copper foil is located in the higher left of the friction electric sequence table, it can be seen that copper foil has a strong ability to lose electrons and is easy to be positively charged, so copper foil is used as the electrode layer material of OC-TENG in this experiment.

The copper foil was cut into several 20 cm×10 cm sizes, ultrasonically cleaned to remove surface impurities, dried at room temperature, repeatedly rolled by a roller machine until the surface was wrinkle-free, rinsed with anhydrous ethanol, and then dried at room temperature to complete the preparation of the electrode layer material of the OC-TENG and set aside.

2.2. Preparation of pure PDMS friction layer films

The fabrication process of PDMS films is shown in Fig. 2.

Firstly, the main agent of PDMS was mixed with the curing agent in the ratio of 10:1 using a pipette gun, and the mixture was placed in a magnetic stirrer for 30 min to fully mix the two. After mixing, the mixture was put into a centrifugal mixer with a rotational speed of 500 r/min under vacuum conditions for 20 min, in which all air bubbles were discharged, and the fully integrated mixture of PDMS and curing agent was poured into a dispenser dish. Then place the copper foil of the selected metal electrode on the plate coating machine, set the temperature at 60 °C and turn on the vacuum, place a scraper on the edge of the electrode, adjust the scraper to 0.3 mm, pour the mixture in the dispenser dish uniformly in the vicinity of the scraper, start the coating machine, so that the scraper moves uniformly from one end of the copper foil to the other, and then carry out several coats of coating after the return of the scraper to the position, so that the mixture is evenly spread on the copper foil of the electrode. The mixture is evenly spread on the electrode copper foil. Finally, the copper foil and the mixture were put into a constant temperature drying oven and dried at 70°C for 20 min to complete the preparation of PDMS dielectric film.

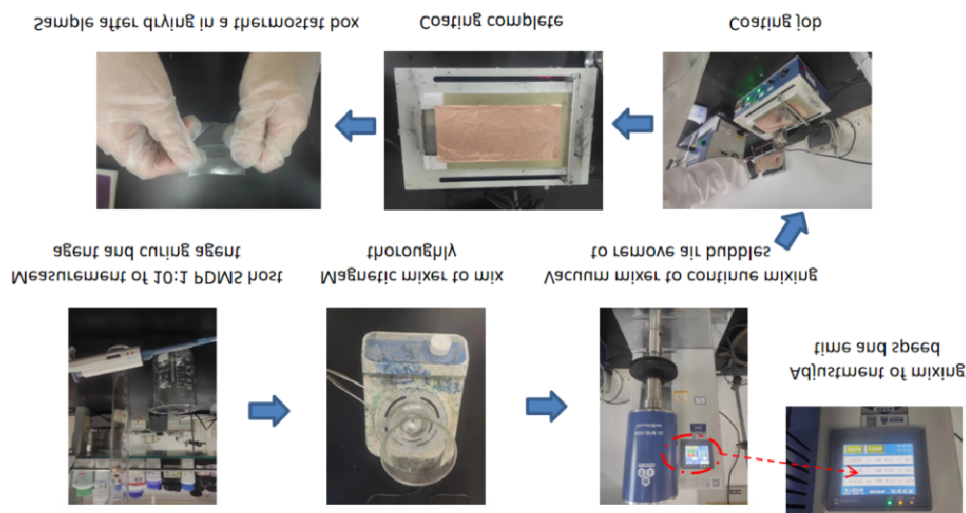


Figure 2. Preparation flow of PDMS film

2.3. Preparation of PDMS-based composite friction layers with different mass fractions of Fe₃O₄

Nanoscale iron tetraoxide (Fe₃O₄) powder was taken to the agate mortar for grinding, to be ground to a fine powder, which was placed in PDMS for mixing, the resulting mixture was placed in a vacuum stirrer for stirring, set the stirring time of 10 min, the rotation speed of 600 r/min, and repeat the stirring until the mixture was mixed uniformly and no fine

particles, repeat the steps of making PDMS friction layer. After that, the steps of making PDMS friction layer were repeated to obtain the PDMS/Fe₃O₄ composite dielectric layer made by adding different mass fractions of Fe₃O₄. In order to minimize the experimental error, in the experimental process, in addition to the addition of Fe₃O₄ mass fraction were set to 2.0 wt%, 4.0 wt%, 6.0 wt%, 8.0 wt%, respectively, the dosage of reagent materials, such as PDMS, and the amount of the production of the PDMS dielectric layer to keep the same, the preparation process of the PDMS/Fe₃O₄ composite dielectric layer is shown in Fig. 3.

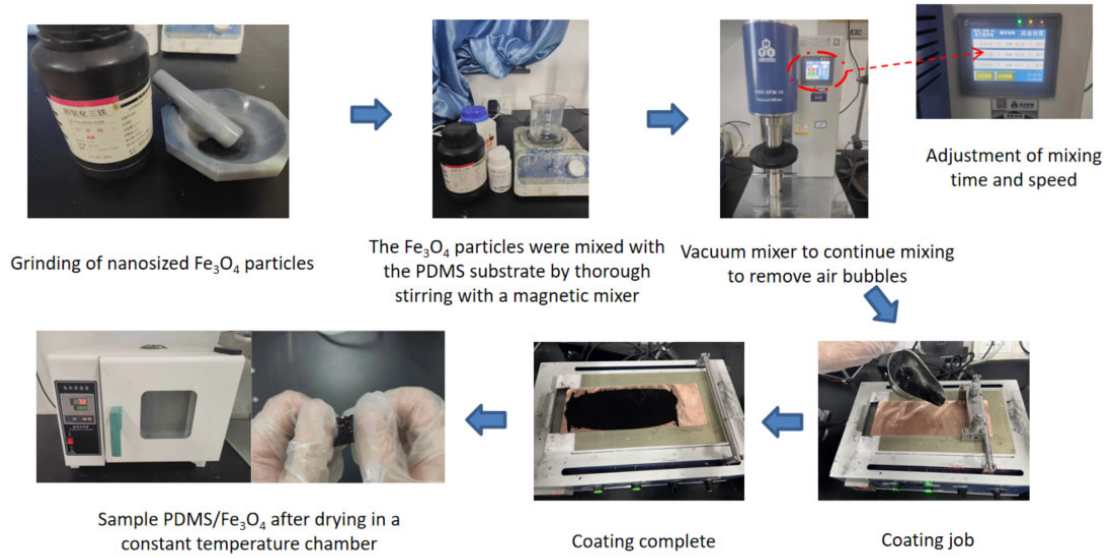


Figure 3. Preparation process of PDMS/Fe₃O₄ friction layer

2.4. Structure of the OC-TENG device

By analyzing the interaction between the floating body and waves, this paper designs a friction nanogenerator (OC-TENG) with overlapping cubic structure, which is schematically shown in Fig. 4. The device consists of two squares inside and outside, the eight vertices of the small square inside and the eight vertices of the large square are

connected by an elastic rope, and the dielectric friction layer and the electrode layer are covered on the outer surface of the small square and the inner surface of the large square, so that the outer surface of the small square can be driven to collide with the inner surface of the large square by waves to produce a collision and thus a contact separation movement, and then realize the conversion from wave energy to electric energy and the wave energy can be converted into electrical energy.

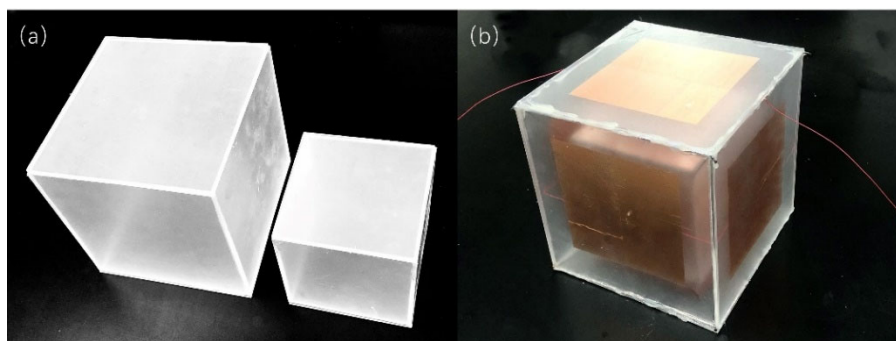


Figure 4. Schematic diagram of OC-TENG structure

3. Experimental Results and Discussion

3.1. Theoretical Output Modeling Principles of OC-TENG

The working mechanism of OC-TENG is the synergistic

action of contact charging and electrostatic induction. In this process, the voltage ($V_{OC-TENG}$) is formed as a result of the combined effect of the polarized charge generated during the contact charging between the two electrodes and the transferred charge (Q) generated by electrostatic induction. In this case, the voltage component generated by the polarized

friction charge can be expressed as $V_{OC}(x)$ and varies with the separation distance x , whereas the voltage component due to the transfer charge is $-Q/C(x)$, where $C(x)$ denotes the value of the capacitance between the electrodes. Therefore, the total potential difference between the two electrodes can be expressed as:

$$V_{OC-TENG} = -\frac{1}{C(x)}Q + V_{oc}(x) \quad (1)$$

That is the output equation of OC-TENG.

In a short-circuit state, the potential difference $V_{OC-TENG}$ of the OC-TENG vanishes. At this point, the polarized friction charge's voltage difference must be entirely neutralized by the transfer charge (Q_{SC}), which results in the equation that follows:

$$-\frac{1}{C(x)}Q_{SC}(x) + V_{oc}(x) = 0 \quad (2)$$

Following this, it is deduced that the basic relationship between Q_{SC} , $C(x)$, and VOC is:

$$Q_{SC}(x) = C(x)V_{oc}(x) \quad (3)$$

3.2. Comparison of the output performance of pure PDMS film and PDMS/Fe₃O₄ film

In order to evaluate the electrical output performance of PDMS/Fe₃O₄ nanocomposite films containing different mass fractions of Fe₃O₄ nanoparticles with TENGs of Cu foil and PA11, the electrical properties were tested, respectively. As shown in Fig. 5 and Fig. 6, it can be seen from the figures that the open-circuit voltage of the pure PDMS-based friction nanogenerator is 45.25 V and the short-circuit current is 5.35 μ A, and there is a significant enhancement in the output electrical performance of the doped Fe₃O₄ nanoparticles compared to the pure PDMS-based friction nanogenerator due to the fact that the relative permittivity of PDMS nanocomposite film will be increased by the addition of Fe₃O₄ nanoparticles, and thus the dielectric properties are effectively improved. However, with the increase of Fe₃O₄ nanoparticles doping concentration, the open-circuit voltage and short-circuit current of TENG show a trend of increasing and then decreasing, because the higher the content of Fe₃O₄ nanoparticles, the smaller the effective contact friction area of PDMS, which leads to a decreasing trend of the output performance after reaching a certain peak value. In the measured experiments, the electrical performance of the friction nanogenerator reaches the best when the doping mass fraction of Fe₃O₄ nanoparticles is 4 wt%, and its maximum open-circuit voltage can reach 72.85 V and the maximum short-circuit current is 7.89 μ A, which are 1.6 times and 1.8 times higher than the open-circuit voltage and short-circuit current of the undoped titanium dioxide nanoparticles of the pure PDMS film, respectively. Therefore, the PDMS/Fe₃O₄ nanocomposite membrane with a doping mass fraction of 4 wt% was selected for the performance study of the friction nanogenerator in the subsequent experiments.

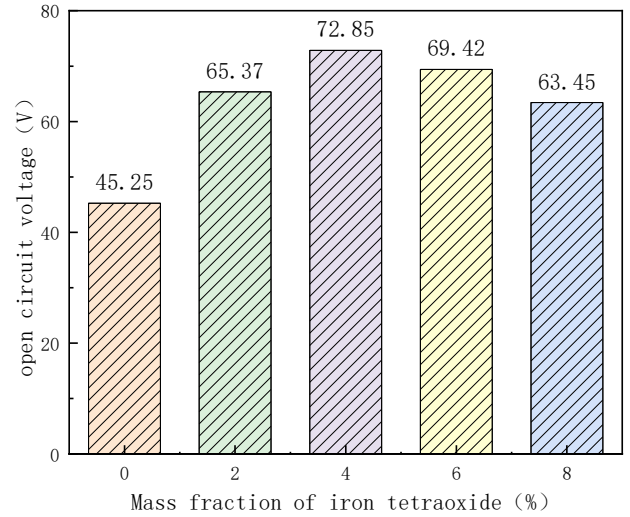


Figure 5. Output voltage for different Fe₃O₄ doping concentrations

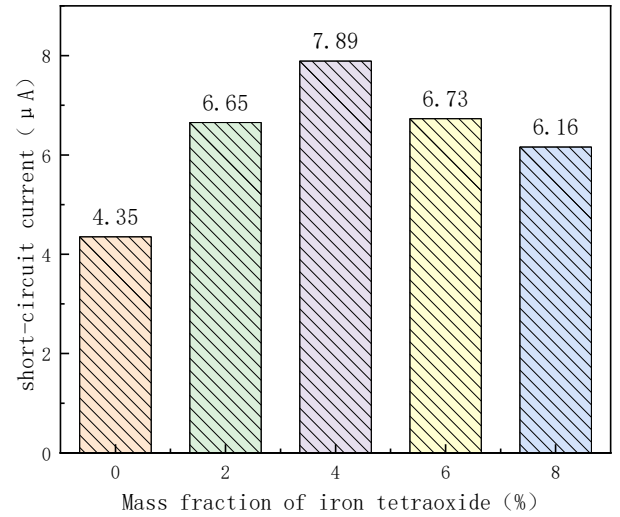


Figure 6. Output current for different Fe₃O₄ doping concentrations

3.3. Effect of wave frequency on OC-TENG output performance

Among the important sources of wave energy, frequency is one of the important monitoring information. Therefore, this section explores the effect of driving frequency on the power generation effect of OC-TENG, and evaluates its performance mainly based on the open-circuit voltage, V_{OC} , and short-circuit current, I_{SC} . Firstly, the simulated wave wavelength is fixed to 125 mm and wave height to 100 mm, and the effect of different frequencies on the output performance of OC-TENG is investigated by driving the wave with the linear motor with the frequencies of 0.4 Hz, 0.6 Hz, 0.8 Hz, 1.0 Hz, 1.2 Hz, 1.4 Hz, 1.6 Hz, and 1.8 Hz, which is because the common wave frequencies in nature are low frequencies, usually below 3 Hz.

As can be seen in Fig. 7 and Fig. 8, the performance of the OC-TENG power generation, as reflected in the open-circuit voltage and short-circuit current, is generally enhanced as the driving frequency is increased. The experimental data show that the short-circuit current increases from 4.61 μ A to 9.83 μ A while the open-circuit voltage increases from 57.35 V to 86.32 V during the process of increasing the frequency from 0.4 Hz to 1.8 Hz. This result is due to the fact that the increase

in frequency leads to increase in acceleration of the OC-TENG, thus increasing the mechanical energy, as shown in Newton's second law while the amplitude of the external drive is kept constant. increase, which in turn increases the mechanical energy. The increased mechanical energy results in an increased contact force between the PA11-PDMS/Fe₃O₄ power generating units, which allows the friction layer to make more complete contact, thus improving the overall output performance of the OC-TENG.

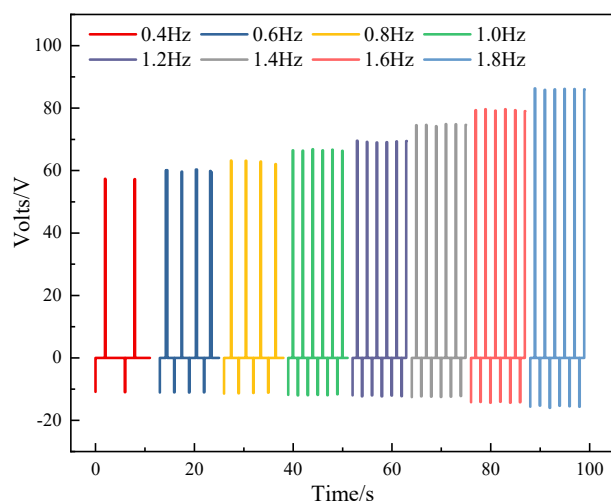


Figure 7. OC-TENG open circuit voltage at different frequencies

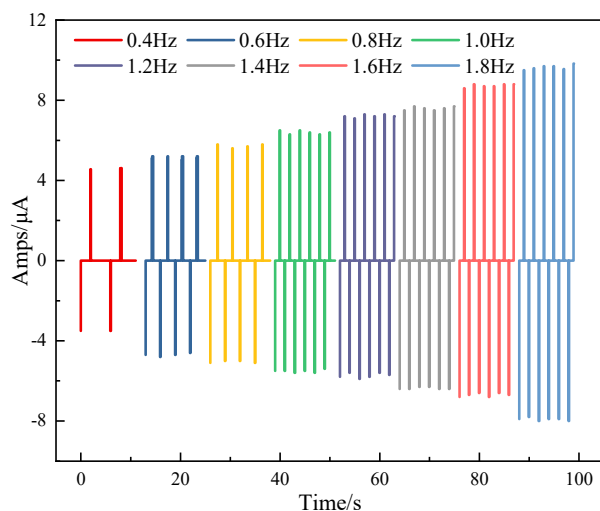


Figure 8. OC-TENG short-circuit current at different frequencies

4. Conclusion

In summary, a wave-driven friction nanogenerator (TENG) based on a PDMS/Fe₃O₄ composite film is developed in this paper, whose main structure includes a PDMS/Fe₃O₄ negative friction layer as the friction layer, a PA11 positive friction layer, a copper conductor foil as the electrode, and an overlapping cubic structure. Driven by waves at different

frequencies, the TENG can generate open-circuit voltages up to 57.35 V-86.32 V and short-circuit currents of 4.61 μA-9.83 μA. Compared with the conventional pure PDMS-based TENG, the PDMS/Fe₃O₄ nanocomposite-based OC-TENG shows significant improvement in output voltage and current, and at the same time provides a simple, cost-effective, and efficient method to fabricate high-performance wave-capture devices, which can be used to convert low-frequency wave energy in real-world environments into electricity to power self-powered sensing, which has great potential in different fields such as artificial intelligence and the Internet of Things. Internet and other different fields with great potential and usefulness.

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