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Research and Analysis of the Droplet-Based Electricity Generator Based on a Rotating Structure

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Abstract: With the development of science and technology, the social demand for energy is also increasing. However, the traditional method of energy supply primarily relies on non-renewable resources for energy conversion. While this conventional approach can expedite the energy conversion process, it also results in irreversible ecological hazards. To solve the above problems, the use of renewable clean energy is proposed. In this paper, a droplet generator is proposed to integrate the rotating structure with the body effect power generation for the tiny energy of raindrops. This droplet generator can increase the speed of droplets leaving the dielectric layer and reduce the effect of continuously falling droplets on the droplet-based electricity generator (DEG). It is demonstrated that the instantaneous power of the generator can reach 0.9 mW, which can be a good solution to the power supply needs of some small power supply equipment, and thereafter is beneficial to the self-powering of the equipment in rainy days.

Keywords: Bulk effect power generation; Droplet power generator; Friction nanopower generation; Renewable energy sources

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1. Introduction

The modern energy field is facing the problem of depletion of non-renewable energy due to industrial development, forcing the world to pay attention to the study of renewable energy. The more widely used renewable energy sources in today's society include solar energy, wind energy, tidal energy, etc [1–9]. Despite the immense energy generated by natural phenomena, the various small sources of energy in the world seem insignificant in comparison. However, many of these tiny energy sources, as forms of renewable energy, are relatively easy to harness. This has made the utilization of such energies a key focus for scientists. With ongoing advancements in the study of ultrafine particles in modern industry, researchers have discovered that nanomaterials can serve as effective tools for converting small energy into electricity. This development has opened up new possibilities for energy conversion in current generator systems. In recent years, due to the continuous development of nanotechnology, the research in the direction of man-made materials has also seen a leap forward, which has led to the emergence of man-made materials in recent years with special optical, electrical, infiltration, adhesion, heat and mass transfer properties beyond those of living beings. Currently, the applications of the triboelectric nanogenerator (TENG) have been covered in research fields such as smart medicine, self-powered sensors, smart furniture, artificial intelligence, and droplet power generation.

In recent years, a method to increase the frictional charge density by coupling the surface polarization of the triboelectric nanogenerator and the hysteretic dielectric polarization of the material under vacuum conditions was reported by Wang *et al.* [10–12]. In 2018, Zhang *et al.* proposed a novel triboelectric nanogenerator design based on a Pelamis serpentine energy harvester [13]. In the same year Wang *et al.* reported an ultra-low friction electric-electromagnetic hybrid nanogenerator (NG) [14]. Meanwhile, a washable touch-driven textile TENG based on triboelectric nanogeneration technology was proposed by Xiong *et al.* [15]. This technology can be applied to harvest voluntary and involuntary mechanical energy from body movements.

Inspired by the historical development of electromagnetic generators, a self-charging excitation triboelectric nanogenerator system similar to the principle of conventional magnetically-excited generators was proposed and realised by Liu *et al.* in 2019 to achieve a highly stable output [16]. In the same year, Ouyang *et al.* demonstrated a fully implantable symbiotic pacemaker based on an implantable friction nanogenerator for energy harvesting and storage as well as cardiac pacing in large animals [17]. In 2019, Nie *et al.* also proposed a triboelectric nanogenerator, which can work based on the interaction between two pure liquids [18]. However, the energy harvesting effect shown on the use of TENG for harvesting droplet energy tends to have large drawbacks due to its limitations in energy output. Volume effect droplet power generation (DEG) solves this problem well as a high instantaneous output power generation method [19]. In contrast, the use of bulk effect power generation often has a large impact on the power generation efficiency of continuously falling droplets due to problems such as the droplets not slipping off the dielectric layer in a timely enough manner.

Here, a droplet generator that integrates a rotating structure with body-effect power generation is proposed. The droplet generator can increase the speed of droplets leaving the dielectric layer and reduce the effect of continuously falling droplets on the bulk effect power generation. Experiments have shown that the instantaneous power of the generator can reach 17.14 mW, which is a good solution for the energy collection of continuously falling droplets, and therefore can be a good solution for the power supply of some small power supply equipment, which is conducive to the self-powering of the equipment in rainy days.

2. Power generation system design

2.1. Body effect power generation principle

As a solid-liquid droplet generator based on the body effect, the dielectric material used in DEG is usually characterized by a high surface charge density, so it is easy to form a volume effect when a continuous droplet impacts the surface spreading and contracting, and completes the conversion between potential energy of the droplet and electrical energy. Taking FEP as the dielectric layer and copper foil as the top electrode and bottom electrode as an example, when the droplet falls on the blade and spreads, the originally disconnected components (FEP and top/bottom copper electrode) are connected into a complete electrical system, and the whole DEG is in the working state, and the generation, coupling, and transfer of charges in the circuit are formed inside the whole droplet interface in the whole spreading and contraction of droplets, and the principle is as shown in **Figure 1** below:

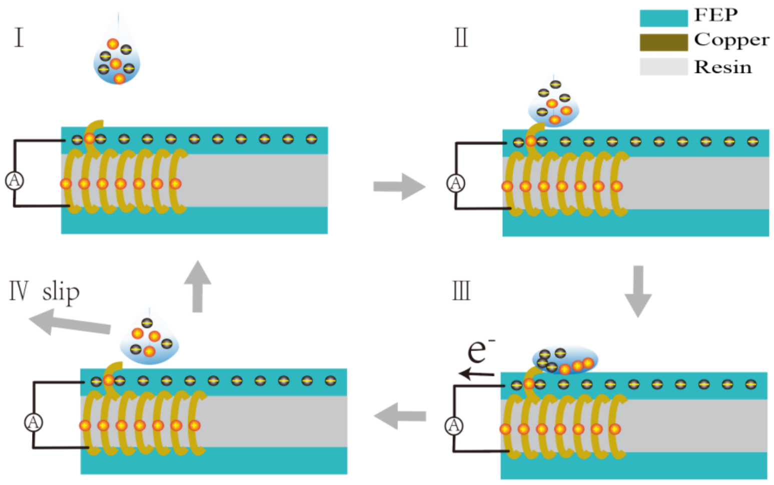

Figure 1. Schematic diagram of body effect power generation

When the droplets are not dropped onto the surface of the blade, the entire DEG system is in electrostatic equilibrium, and the electrons are uniformly distributed within the droplets, as shown in **Figure 2(I)**. Once the droplets are dropped onto the surface of the FEP, electrostatic induction occurs, with the negative charge in the FEP being induced by the positive charge in the droplets, as illustrated in **Figure 2(II)**. When the droplets come into contact with both the FEP film and the top electrode, the previously disconnected components are linked, completing a closed-loop electrical system. The positive charge in the droplet is attracted to the negative charge on the FEP surface, while the negative charge is drawn to the positive charge on the top electrode. This interaction causes electrons to move from the top electrode to the bottom electrode, generating a current that flows from the bottom to the top, as illustrated in **Figure 2(III)**. Subsequently, as the droplet contracts and slides down, some of the electrons in the bottom electrode flow back to the top electrode, completing the power generation cycle, as shown in **Figure 2(IV)**. Therefore, when the droplets keep falling and dropping on different blades, voltage signals of different sizes and directions are generated.

2.2. Introduction to the system architecture

Figure 2 shows a 3D schematic of the overall system structure, with the overall system composition consisting of five fixed-size acrylic panels, a system skeleton based on 3D printing completion, and corresponding materials. The device consists of a blade and a solid support, which were fabricated using 3D printing. The copper foil, which was originally used as the electrode at the bottom of the DEG, was replaced with a copper wire that surrounded the solid support. In addition, water droplet bearings are added at both ends of the rotating shaft to achieve smooth rotation of the blades and reduce friction loss. For the energy export of the system, two copper rings are inserted into the spindle to export the energy generated by the two types of power generation, and conductive silver needles are used instead of brushes to contact the silver needles with the conductive copper to achieve the power output of the system.

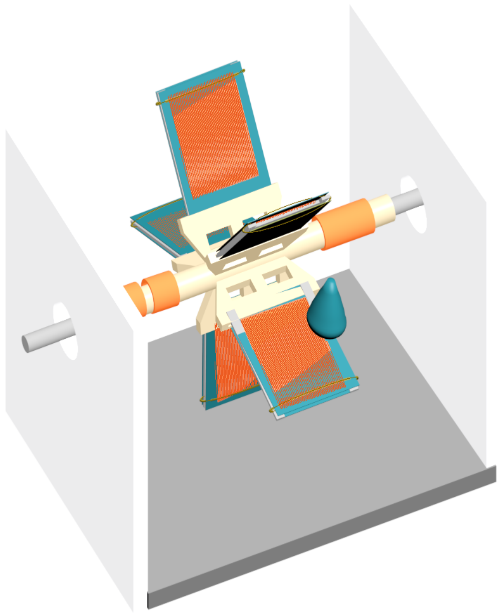

Figure 2. System architecture design diagram

Taking the blade (1) in 90° position as the initial state, the length of the blade, and the horizontal distance of the droplet generator from the origin, the whole system is analyzed to enter the next cycle after three states in the rotation process, as shown in **Figure 3**:

(a) When blade (1) rotates from its initial position to 108°, and the droplet generator is located between 0.95s < x < 1s, only blade (2) is impacted by the droplet. When the droplet generator is between 0.3s < x < 0.95s, only blade (2) is impacted. However, when the droplet generator is between 0s < x < 0.3s, both blades (1) and (2) may be impacted due to the rotation of the blades, as shown in **Figure 3(a)**.

(b) When blade (1) rotates from 108° to 144°, and the droplet generator is located between 0.8s < x < 1s, only blade (2) is impacted. When the droplet generator is between 0.3s < x < 0.8s, both blades (1) and (2) are impacted due to the blade rotation. When the droplet generator is between 0s < x < 0.3s, only blade (1) is impacted, as shown in **Figure 3(b)**.

(c) When blade (1) rotates from 144° to 180°, and the droplet generator is located between 0.95s < x < 1s, neither blade is impacted by the droplet. When the droplet generator is between 0.8s < x < 0.95s, only blade (1) is impacted by the droplet. Finally, when the droplet generator is between 0s < x < 0.8s, only blade (1) is impacted by the droplet, as shown in **Figure 3(c)**.

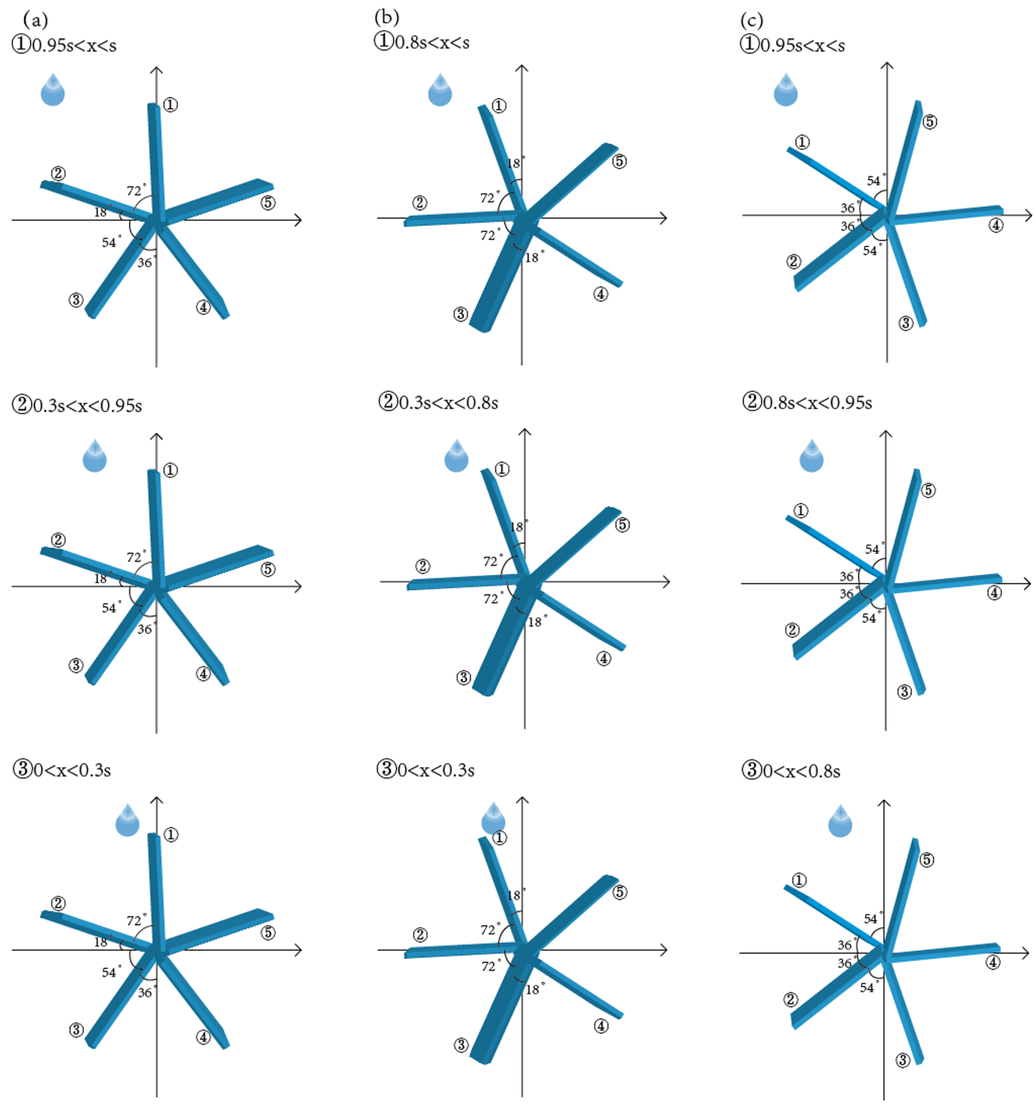

Figure 3. Analysis of blade motion state

After that, the blade (5) until blade (2) succeeds the movement process of blade (1) and completes the rotation of the blade, the blade maintains the cycle of the process during the operation of the system. Therefore, through the above study, it can be judged that the movement speed of the blade is not only related to the weight of the blade itself but also related to the droplet falling height *h*, droplet falling frequency *f*, droplet volume *V*, droplet falling position.

2.3. Experimental results

2.3.1. Effect of droplet drop height on DEG output

When the droplets were released at a frequency of 8 Hz (droplets were deionized water) at heights of 10 cm, 15 cm, 20 cm, 25 cm, and 30 cm, respectively, **Figure 4** shows the effect of droplet drop height on the DEG when acting alone in this configuration. The measured DEG output voltage and current characteristics fluctuate around 160 V for open circuit voltage and 5 μA for short circuit current as the droplet drop height increases from 10 cm to 30 cm. The amount of transferred charge generated by a single droplet drop did not change significantly in magnitude as the height increased, but the number of charge transfers generated in a given time period increased.

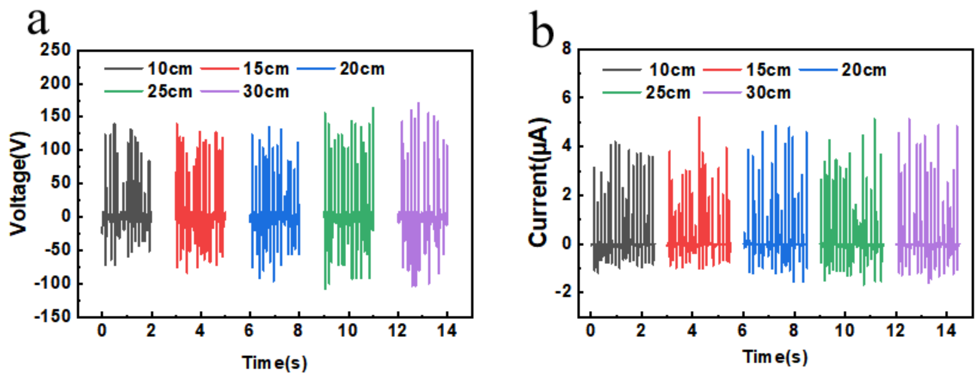

Figure 4. DEG output characteristics at different drop heights: (a) Output voltage diagram; (b) Output current diagram

The experimental results show that the change in output current and voltage due to the change in height is not particularly significant, and this phenomenon is quite different from the increase in output of the DEG in a stationary state with the increase in height of the droplet release. This is due to the designed structure. When the system is working, each DEG is rotating, which also leads to the increase of droplet height with the increase of potential energy to the kinetic energy of the system conversion more, to the body effect of power generation conversion is less. It has been experimentally demonstrated that as the height from which the droplet is released increases, the frequency of high-voltage and high-current pulse signals also increases. This is because the increased height, which is a result of the higher motion speed in the system, allows the droplet's fall time to more closely match the blade's rotation time. As a result, more droplets reach the maximum spreading area on the surface at just the right moment to contact the top electrode, thereby producing the maximum output.

2.3.2. Effect of droplet size on DEG output

The changes in the output current and voltage of the DEG were investigated separately as the droplet volume increased from 40 µL to 80 µL. When the droplet volume is 40 µL, the output voltage is approximately 100 V, and the current is around 3 µA. As the droplet volume increases to 60 µL, the output voltage rises to approximately 125 V, and the output current increases to 4 µA. With a further increase in droplet volume to 80 µL, both the output voltage and current continue to rise, with the output voltage reaching 250 V and the output current rising to 4.5 µA, as shown in **Figure 5**. The reason for this phenomenon is that when all other conditions are constant, the DEG output current and voltage change. The reason for this phenomenon is that when other conditions are certain, the increase in droplet volume will lead to an increase in the spreading area of the droplet when it falls on the blade, and due to the phenomenon of electrostatic induction, more charges are transferred and the amount of transferred charges increases from the initial 10 nC to 25 nC. Experiments have proved that the DEGs in the rotating state are the same as those in the stationary state, and the output current is the same as that of the DEGs in the stationary state, voltage magnitude will increase with the increase of droplet volume and will not be affected by the change of motion state on its output.

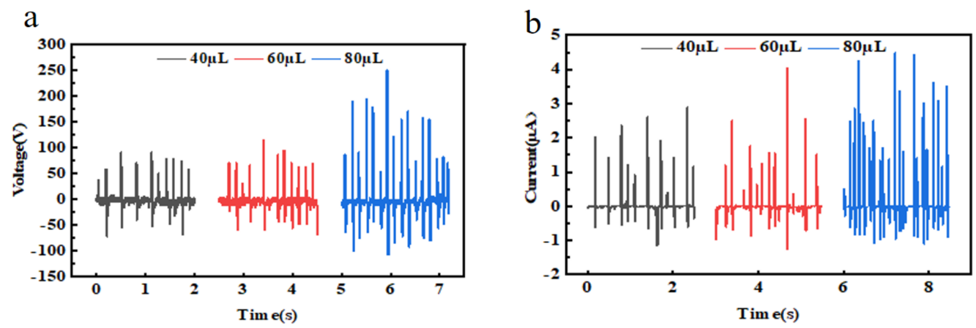

Figure 5. DEG output characteristics of different droplet sizes: (a) Output voltage diagram; (b) Output current diagram

2.3.3. Effect of bottom electrode copper wire on DEG output

The diameter of the copper wire as the bottom electrode was increased from 0.2 mm to 0.5 mm and the output state of the DEG during the process was measured. Experimentally, it was proved that the output voltage and current characteristics of the DEG in the rotating state did not change greatly with the increase of the diameter of the copper wire at the bottom electrode, but the frequency of the generated voltage and current was in the state of increasing and then decreasing, as shown in **Figure 6**. The reason for this phenomenon is that with the increase of the diameter of the copper wire, the weight of the whole rotating blade is increasing, and the rotating speed of the blade is then reduced. With a bottom electrode copper wire diameter of 0.2 mm and a lightweight rotating blade, if the rotation speed is too high, the liquid droplets cannot accurately make contact with both the top and bottom electrodes. As a result, the voltage and current output are reduced.

However, when the diameter of the copper wire at the bottom electrode is increased to 0.4 mm, the weight of the rotating blade also increases, leading to a decrease in the blade's rotational speed. As a result, the droplets are unable to make contact with both the top and bottom electrodes, which causes a reduction in the generated voltage and current frequency. In the experiment, it is found that when the diameter of the copper wire at the bottom electrode is 0.3 mm, the output voltage and current frequency are at the highest state. Therefore, it is considered that when the copper wire of the bottom electrode is at 0.3 mm, the rotational speed of the blade can better match the droplet's falling frequency of 8 Hz, and the optimal output conditions under a certain state are achieved.

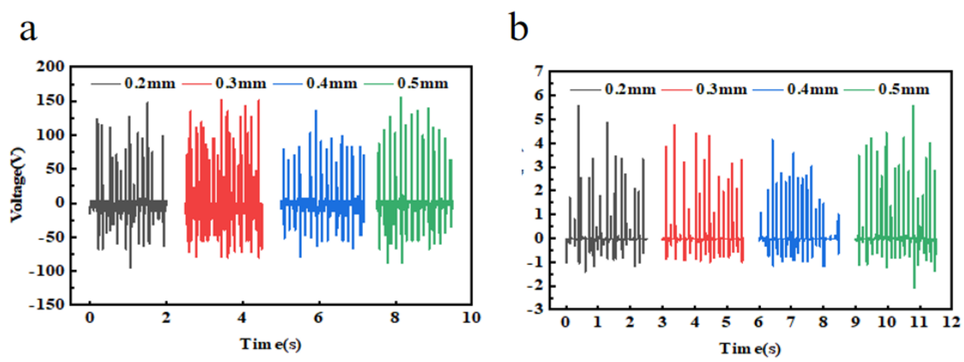

Figure 6. DEG output characteristics with different shared electrode diameters:(a) Output voltage diagram; (b) Output current diagram

2.4. DEG matching impedance and output power measurement

When the output of the DEG is guaranteed to be a high transient output, the size of the matching resistance is the key factor in determining the magnitude of the transient output power of the DEG, and the DEG can only produce the maximum transient output if the load resistance is the same as the internal resistance of the DEG. Therefore, to further illustrate the magnitude of the rotating DEG output power, the output power of the DEG in this state was explored based on the above study. The magnitude of the output power of the DEG under different loads is given by keeping the droplet falling frequency of 8 Hz, droplet size of 80 μL, falling height of 30 cm, diameter of the copper wire at the bottom electrode of 0.3 mm, and the number of turns of 60 and other relevant influencing factors. From **Figure 7**, it can be seen that the maximum output power of 0.9 mW can be obtained with an external resistance of 9 MΩ.

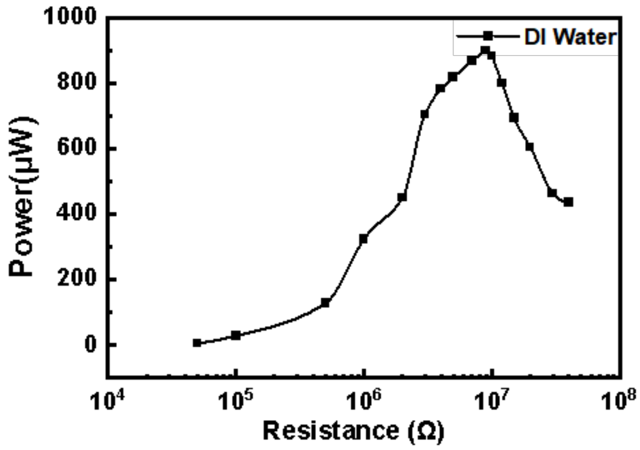

Figure 7. DEG output power curve

3. Conclusion

Droplet generators (DEGs) based on bulk effect power generation (BEP) have the advantages of high instantaneous output and ease of fabrication, and can be used to harvest energy from droplets at a low cost. However, the use of a planar stationary DEG is not conducive to the collection of continuously falling droplets. To address the above problems, a rotating droplet-based electricity generator (DEG) is proposed. It has been demonstrated that the instantaneous power of the generator can reach 17.14 mW, which differentiates it from the stationary DEG. The rotating DEG exhibits minimal variation in output due to changes in droplet size, release height, or release frequency. As a result, this structural design offers greater stability.. At the same time, due to the design of the rotating structure, the droplets falling on the dielectric layer can slide off the dielectric layer in time, which is conducive to the collection of energy from continuous droplets, and can also be a good solution to the power supply needs of some small power supply equipment, and thereafter, it is conducive to the self-power supply of the equipment in rainy days.

Disclosure statement

The authors declare no conflict of interest.

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