Development of a hybrid raindrop generator based on tribo-nanotechnology

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Abstract. With the rapid development of modern industrial society, the energy crisis has become one of the urgent problems to be solved in modern society. Electric energy is one of the indispensable energy sources in the current society, and its production has always been concerned by more and more people. Based on the existing raindrop generators, a new raindrop generator, which can make full use of raindrop energy to generate electricity by means of triboelectric nanogenerators and cutting the magnetic line of force, is proposed to solve the current renewable energy power generation problem. Its brief construction model and its application prospects are given by this generator. Preliminary calculations show that the energy conversion efficiency of the hybrid system is about 50%, which improves the conversion efficiency of raindrop energy to electric energy and has good practical value.

1 Introduction

In the past ten years, with the continuous increase of energy demand in social development, more and more people have paid attention to the problem of non-renewable and rare energy, and they have been committed to maintaining the huge energy consumption required by modern society. The reduction of non-renewable energy and the sustainable development of energy have become an urgent problem that people need to solve. Solar energy and water droplet energy have been attracting attention as an important part of the main renewable energy sources. Since the rise of the solar energy industry in 2007, the Chinese market has been quickly swept away. Up to now, China's photovoltaic power generation ranks first in the world, and it has become one of the necessary power generation facilities for domestic households and enterprises. However, due to the frequent changes in the intensity of natural light and the rainy regions of southern China, solar energy cannot meet people's daily electricity needs. There is not much clean energy available in China's rainy areas at present. Therefore, reducing the use of rare energy and increasing the use of renewable energy in the rainy southern areas is still a big problem.

In view of the rainy climate conditions in southern China, it is considered to convert raindrops into electricity, so as to utilize raindrops as a clean energy. Raindrops can be used

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as a tiny energy source and have been collected by foreign countries in the form of triboelectric nanogenerators. The application of triboelectric nanogenerators (TENGs) [1] in raindrop energy harvesting is mainly to use the impact force brought by falling raindrops to make the contact-separated TENG generate a potential difference, thereby causing the electrons to be driven to generate alternating current. Based on TENG, this design combines it with electromagnetic induction technology to design a hybrid TENG, which makes the power generation efficiency of electromagnetic induction technology higher than that of triboelectric nanogenerators. The power generation efficiency of the system is convenient to implement its application in real life.

2 Literature review

The conversion of raindrop energy to electrical energy comes from the generation of triboelectric nano-power technology. Since triboelectric nanogenerators (TENGs) [1] were invented in 2012, they have played a powerful role in harvesting tiny amounts of energy due to their light weight, low cost, and high efficiency. There are two main ways to apply triboelectric nanogenerators in raindrop power generation. The first way is to collect the electrostatic energy carried by raindrops with sliding triboelectric nanogenerators, and the second way is to use contact-separated triboelectric nanogenerators to collect raindrops energy while mechanical energy carried when falling. In 2014, a rotary triboelectric nanogenerator (SR-TENG) was invented at the Georgia Institute of Technology in response to the problem of collecting kinetic energy from rotating tires, which completed the conversion of kinetic energy and wind energy into electrical energy [2]. In 2015, a transparent and self-cleaning superhydrophobic contact-separated triboelectric nanogenerator that can be combined with solar cells was fabricated by Jeon et al. by using PDMS materials [3]. The experimental data proves that the designed load resistance is 25MΩ, and the average instantaneous power can reach 0.27w. It is indicated that the output efficiency of the superhydrophobic coating is about 7.5 times that of the non-coating. When photovoltaic panels and triboelectric was combined by this design, nanogenerator films are highly recyclable and can harvest solar or raindrop energy alone [3].

A moth-eye triboelectric nanogenerator (MM-TENG) was proposed by Yoo et al. in 2018. The TENG proposed in this experiment uses materials with more optical properties than solar cell protection glass sheets [4]. The SWT is 89.41%, which is 0.01% higher than that of the protective glass plate. At the same time, the material has self-cleaning ability as a superhydrophobic material, which prolongs the service life of the generator. The design shows that the system reaches the optimal value when the drop height of raindrops is 50cm and = 45◦. When the drop height is greater than 50cm, the generated power gradually decreases. After the experiment, the influence of design parameters on the output power, such as the relationship between C_I and C_M, and the influence on the voltage difference should also be considered. A grid TENG that designs the TENG film in the form of a grid was proposed by Cheng et al. in 2021. This design reduces the regional interference problem caused by excessive film area and excessive raindrop falling density [5]. However, in this design, an incoming wire needs to be connected to each fence electrode respectively, which also leads to a relatively complicated manufacturing process of the entire generator, which makes its application in real life more difficult.

A superhydrophobic magnetoelectric generator based on the Faraday electromagnetic induction phenomenon was designed and fabricated by Ma et al. in 2020, which can generate electricity by changing the magnetic flux to harvest the energy of raindrops as shown in Figure 1 [6]. On the one hand, the design uses a permanent magnet material as the magnetic induction line generating device, and copper coils are used as the material for cutting the magnetic induction line, and on the other hand, a superhydrophobic coating is added to the design to make the device function stably in the continuously falling raindrop environment. However, this design faces the problem of large flow of raindrops and too fast falling time. Because if the raindrop discharge time is longer than the spring recovery time, the change speed of the magnetic flux will be slower, regardless of the raindrop not falling vertically but falling in an oblique direction. And the design does not consider whether the drop of the blade will cause the copper coil to tilt, thereby affecting the output power. There has been some progress in the research of water droplet power generation at home and abroad. In research, triboelectric nanogenerators are often used as power generation devices for the conversion of raindrops to solar energy. Triboelectric nanogenerators commonly used in research include two-electrode contact-separated TENG, single-electrode contact-separated TENG, sliding TENG and spaced TENG, among which the contact-separated TENG is the most widely used. Since the triboelectric nanogenerators was invented, people's research on them has continued to deepen, and it has been widely used in the collection of micro-energy, and its energy conversion efficiency can reach about 14.9%. Most of the current designs used for raindrop power generation are based on contact-separated TENGs [7]. In addition, there are also magnetoelectric generators that use raindrops to complete the electromagnetic induction phenomenon. However, the energy conversion efficiency generated by the contact-separated TENG is low, and the utilization of raindrop energy is not high enough. And a generator that converts raindrop energy through the magnetoelectric effect can turn on an LED light within 700 seconds. It can be seen that the efficiency of using these two designs alone is not ideal, and the power generation is low. Therefore, a hybrid raindrop generator based on magnetic induction and TENG is designed and studied in this paper to improve the conversion efficiency of raindrop energy to electricity. In the design of raindrop power generation, the movement of cutting magnetic lines of force in the phenomenon of electromagnetic induction is used to realize the partial conversion of raindrops into electric energy. At the same time, combining it with a triboelectric nanogenerator improves the conversion efficiency of raindrop energy. A superhydrophobic coating is applied around the magnet throughout the design to achieve self- cleaning of the device and prolong the service life of the device.

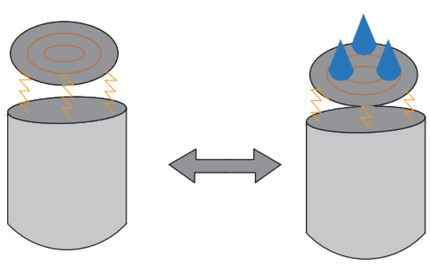

Fig. 1. Superhydrophobic permanent magnet electric generator.

3 Principle introduction

Building on Ma et al. , this design combines the motion of cutting magnetic field lines with a triboelectric nanogenerator to form a form similar to a windmill, as shown in Fig. 2a, and designs a hybrid[6]. The two raindrop power generation methods used in this design can improve the conversion efficiency of raindrop energy. At the same time, a super-hydrophobic coating is used on the blades. The uniform magnet with super-hydrophobic coating makes the system longer life. Such a design can achieve a good power generation effect, and can have a good energy conversion effect in the face of raindrops falling in both oblique and vertical directions.

3.1 Cutting magnetic field line motion

Since the phenomenon of electromagnetic induction was discovered by Faraday in 1831, the phenomenon of electromagnetic induction has been studied and applied by scholars. The principle of the electromagnetic induction phenomenon refers to the process in which some conductors in the closed loop cut the magnetic eld lines in the magnetic eld generated by the magnet and generate an induced current. This design uses the structure of the rotating blade to realize the motion of the cutting magnetic eld line. In this design, there are 12 rotating blades in total, each of which is an isosceles triangle of equal size. The shape of the blades is fixed by circular copper wires connecting the feet of adjacent blades to avoid deformation of the blades in the initial state.

In the whole design, after the raindrops fall on the blades of the runner, the gravitational potential energy of the raindrops on a certain area is converted into the kinetic energy of the blades, thereby driving the rotation of the entire runner. Two concave magnets are placed on both sides of the entire runner to generate magnetic induction lines, and the conductors that cut the magnetic induction lines are composed of copper wires for the entire fan blade skeleton of the windmill. In the selection of magnets, a magnet that can generate a uniform magnetic field is selected. Because the superhydrophobic layer has the characteristics of self-cleaning and strong hydrophobicity, the magnet is chosen to coat with a superhydrophobic coating. Adding a superhydrophobic coating to the magnet is beneficial to the self-cleaning of the magnet surface, to prolong the service life of the magnet, and to achieve better practical value.

3.2 Single-electrode triboelectric nanogenerator

The triboelectric nanogenerator (TENG) was proposed in 2012 by Dr. Fan and others in the research group of Professor Wang Zhonglin of the Zuozhi Institute of Technology to combine the principle of triboelectric electrification with the principle of electrostatic induction [1]. TENG has been attracting attention as a discovery that can harvest tiny energy and convert it into electricity. The main principle of the triboelectric nanogenerator is to use two materials with different electrical polarities, so that the two are contacted and charged through a certain motion. As far as the current research progress is concerned, TENGs are usually classified into two categories, one is sliding triboelectric nanogenerators, and the other is sliding triboelectric nanogenerators. The sliding triboelectric nanogenerator mainly relies on the force parallel to the friction surface to generate triboelectricity, while the contact-separated triboelectric nanogenerator mainly relies on the force perpendicular to the friction surface to generate triboelectricity. In this design, contact-separated triboelectric nanogenerators are used, with polytetrafluoroethylene (PTFE) as the cathode material of the triboelectric nanogenerator, Al as the cathode material of the TENG, and Cu as the cathode material, as shown in Fig. 2b.

The working principle is shown in Fig.2c，the whole triboelectric nanogenerator uses positive and negative electrode materials as its two friction layers, and an electrode is attached to the friction layer as the negative electrode material. When the electrodes are not in contact with raindrops, the entire TENG is in the initial state, which is electrically neutral. When the raindrop falls, the two friction layers with different charges are in contact with each other due to the gravitational potential energy of the raindrop. After the contact, the system is still in an electrically neutral state until the pressure on the electrode 1 disappears, and the two friction electrodes are separated from each other. At this time, the direction of the space electric field becomes the opposite direction to that of the initial state, so that the electrodes induce a charge opposite to the initial state, thereby forming a potential difference and causing the ow of electrons between the two electrodes. When the whole system works, the TENG will cycle between the three states, so that the whole TENG system generates an alternating current, thus completing the partial conversion of raindrops to electrical energy. In order to output the current better, for better output current, this design connects a rectified current to the output circuit of TENG to complete the rectification of the circuit. At the same time, a superhydrophobic coating is added to the entire surface of the triboelectric nanogenerator, which enables the surface of the TENG to drain in time, reducing the problem that the triboelectric nanogenerator cannot recover its shape due to a large number of raindrops.

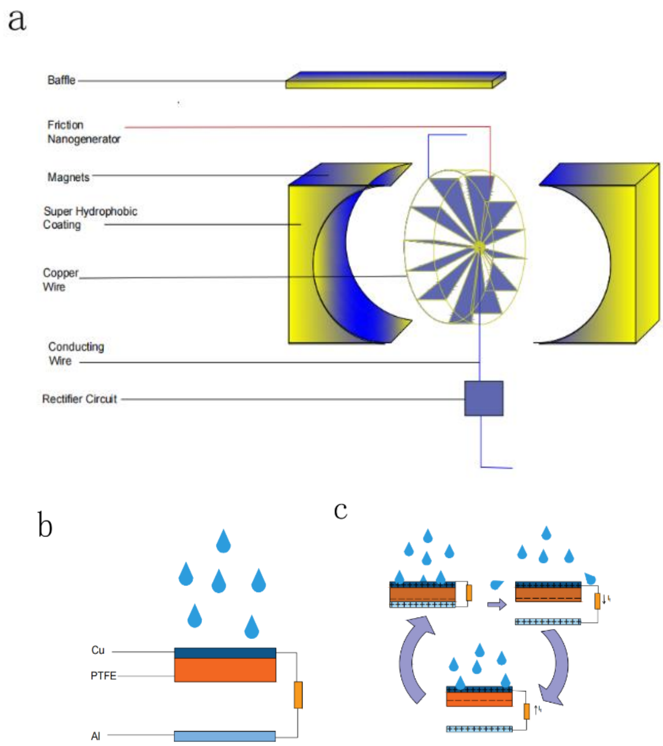

Fig. 2. System principle analysis. (a) System design diagram. (b) Single-electrode triboelectric nanogenerator. (c) Triboelectric nanogenerator power generation process.

4 Efficiency analysis calculation

4.1 Magnetic induction

Assuming that the entire system is in an ideal state (the daily rainfall is constant, the air resistance is 0, and the resistance between the materials when the blades rotate is 0), the entire blade will first move at a variable speed after receiving raindrops, and then move at a uniform speed. In the initial state (the external force is 0), the whole system is in a static equilibrium state, the whole system is supported by gravity and the support force. Assuming that the whole system is in a daily precipitation of x milliliters, the density of rainwater is 1kg/m^3. Therefore, the gravity of the raindrops falling on the area per square centimeter per second can be expressed as:

$$\mathrm{mg} = \frac{\mathrm{x}}{10} \times 3600^{-1} \times \frac{1}{1000} \times 10\mathrm{N} \tag{1}$$

The blade angle changes during the operation of the whole system are regarded as four parts, namely blades A, B, C and D, as shown in Fig. 3a, are: 0°-30°, 30°-60°, 60°-90°, 90°-120°, the energy conversion under the four angle change states is analysed separately as follows:

0°-30° state of motion: 0°-30° state of motion: Let the side lengths of the entire blade be: *L*, *L*, *R* respectively, and the included angle is α, as shown in Fig.3b, when the blade A is at 0°-30°. In this motion state, its force analysis is shown in Fig.3c. When the blade A is in the motion state of 0°-30° degrees, the entire blade is subject to its own gravity mg, raindrop gravity $M_A g$, and supporting forces N_1 and N_2 to perform variable-speed motion. Then when the blade A is at 0° to 30°. When rotated, the area that receives raindrops can be expressed as:

$$S_A = \int_{\frac{\pi}{3}}^{\frac{\pi}{2}} L^2 \sin\alpha \cos\alpha \cos\theta \, d\theta \tag{2}$$

The area that accepts raindrops is expressed as:

$$M_A g = mg \times S_A = 3.6x \times \frac{\sqrt{3}-1}{2} \times 10^{-6} \times L^2 \sin\alpha \cos\alpha \tag{3}$$

Therefore, there is the law of conservation of energy to calculate that the blade A is at 0° -30° The work done by gravity during rotation is:

$$W_A = M_A g \times \left(\frac{1}{2} - \frac{1}{2} \times \cos\frac{\pi}{6} L\right) = \frac{2-\sqrt{3}}{4} M_A g L \tag{4}$$

30°-60° state of motion: When blade B is in this motion at 30°, it can also be obtained that the gravity of raindrops on blade B can be expressed as:

$$M_B g = 1.8x \times 10^{-6} \times L \sin\alpha \times \left[\left(\frac{2\pi}{3} + 1 - \frac{\sqrt{3}}{2}\right)L^2 \times (\cos\alpha)^2 + \left(\frac{\sqrt{3}\pi}{3} - \frac{\sqrt{3}-3}{2}\right)L - ln\frac{3}{2\sqrt{3}+3}\right) + \frac{\sqrt{3}-2}{2}\right] \tag{5}$$

Therefore, the blade B is calculated at 30° by the law of conservation of energy to 60° the work done by gravity during rotation is:

$$W_B = \frac{\sqrt{3}-1}{4} M_B g L \tag{6}$$

Similarly, when the state of 60° -90° is acceptable: From the force analysis of blade C, the same can be obtained by the raindrop gravity and the gravitational work done by the blade C during the rotation process:

$$M_c g = 1.8x \times 10^{-6} \times L \sin\alpha \times \left(\frac{2\sqrt{3}\pi - 21}{12} L + \frac{1-3\sqrt{3}}{3} L^2 \times (\cos\alpha)^2 + 2\, ln\frac{\sqrt{3}}{2} - \frac{1}{2} ln\, 3 \right. \tag{7}$$

$$W_c = \frac{1}{4} M_C g L \tag{8}$$

90°-120° state of motion: Blade D is at 90°-120°. In this state of motion, since the entire system is an ideal system, the blade D deviates by 90°. The moment the raindrop falls, the gravity of the raindrop on the blade D during the whole process is 0, which can be ignored.

According to the law of conservation of energy, during the rotation of the windmill, the gravitational potential energy of the raindrop is converted into the kinetic energy of the windmill, which can be expressed as:

$$\frac{2-\sqrt{3}}{4} M_A g L + \frac{\sqrt{3}-1}{4} M_B g L + \frac{1}{4} M_C g L = \frac{1}{2} M_{Total} V^2 \tag{9}$$

M_{Total} represents the total weight of the blade, and V represents the speed when the entire system is in a state of uniform motion. To sum up, there are two motion states during the operation of the system: (1) variable speed motion, (2) uniform motion. The electromotive force generated by its variable speed motion can be expressed as:

$$E = 2BL \int_0^{V_0} dV = 2BLV_0 \tag{10}$$

The electromotive force generated by its uniform motion can be expressed as:

$$E = BLV \tag{11}$$

Among them, when the system moves at a uniform speed, its speed $V=V_0$. In formula (10), B represents the magnetic field strength of the permanent magnet, and *L* represents the waist length of the windmill blade. It can be seen from the design diagram that when the whole system moves to cut the magnetic field line, the current is generated by the waist length of the blade. The copper wire with the bottom length is parallel to the direction of the magnetic field, so no current is generated. Through the above formula, it can be solved to obtain the output electromotive force of converting the gravitational potential energy of raindrops falling on the blades into electrical energy through the windmill under ideal conditions.

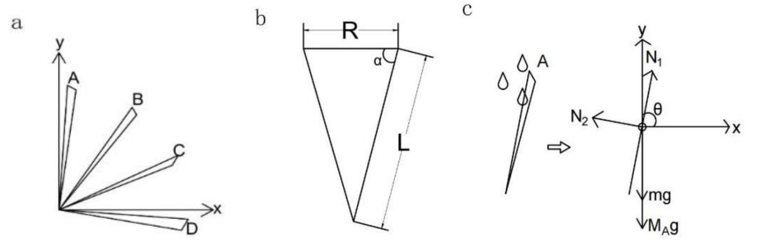

Fig. 3. Leaf Analysis. (a) Schematic diagram of blade movement. (b) Blade front view. (c) Force analysis of blade A.

4.2 Triboelectric nanogenerator

The triboelectric nanogenerator used in this design is a single-electrode triboelectric nanogenerator, copper and aluminium are used as the conductive materials of the generator, and aluminium is used as the dielectric material and conductive material in the single-electrode triboelectric nanogenerator pole. When the dielectric material of the triboelectric nanogenerator, PTFE is in contact with the Al film under the action of external force, an equal amount of heterogeneous charge, namely σ, will be generated between the two. When the two are separated, the potential difference created by friction drives electrons between the copper and aluminium. The amount of charge transferred is *Q*, creating a potential difference. In this design, the thickness of the dielectric material PTFE is d, the air gap distance between the two plates is *x(t)*, and the area of receiving raindrops is *S*. The change method is the same as the change of *S* with the blade angle in the previous section. The distinction is not repeated in this section. Typically, the area of a circuit board is much larger than the thickness of the dielectric and conductive materials. From this, Gauss's theorem can be obtained, and the electric field strength in the dielectric material can be expressed as:

$$E_1 = -\frac{Q}{s\varepsilon_0\varepsilon_r} \tag{12}$$

The electric eld strength in the air gap can be expressed as:

$$E_0 = -\frac{Q+\sigma s}{s\varepsilon_0} \tag{13}$$

The potential difference between the two plates can be expressed as:

$$V = E_0 x(t) + E_1 d = -\frac{[Q+\sigma s x(t)]}{s\varepsilon_0} - \frac{Qd}{s\varepsilon_0\varepsilon_r} \tag{14}$$

The resistance connected to the external circuit is *R*, then according to Ohm’s law, the current and voltage can be expressed as:

$$I = \frac{dQ}{dt} \tag{15}$$

$$V = IR = \frac{dQ}{dt} \times R = -\frac{[Q+\sigma s x(t)}{s\varepsilon_0} - \frac{Qd}{s\varepsilon_0\varepsilon_r} \tag{16}$$

According to the solution calculation of the first-order linear differential equation, can get:

$$\mathrm{Q}(t) = e^{\int_0^{t_0} \frac{\frac{d}{\varepsilon_r}+x(t)}{s\varepsilon_0 R} dt} \left[\int_0^{t_0} \frac{\sigma x(t)}{\varepsilon_0 R} e^{\int_0^{t_0} \frac{\frac{d}{\varepsilon_r}+x(t)}{s\varepsilon_0 R} dt} dt + C \right] \tag{17}$$

Because when $t = 0$, the amount of transferred charge is 0, so $C = 0$ in formula (17) can be obtained. Since the whole system converts the kinetic energy of the falling raindrops into the kinetic energy of the TENG, suppose the moving electrode is in contact with the friction electrode at a constant speed, and the speed is V_{TENG}, then according to the kinematics formula:

$$x(t) = V_{TENG} \times t \tag{18}$$

To sum up, since the number of blades that can receive raindrops remains 4 during the whole system rotation of 30◦, the current and voltage generated when the triboelectric nanogenerator rotates for 30◦ degrees can be obtained.

4.3 Efficiency calculation analysis

The density of the copper wire used is 8.9g/cm^3, the radius of the copper wire used for the perimeter of the blade is r_1, and the radius of the copper wire connecting adjacent blades is r_2, the density of PTFE is 2.1g/cm^3. Since the side length of the blade is L, the total weight of copper wire required can be calculated as:

$$m_{cu} = [213.6L \times (1 + \cos\alpha) + 35.6\pi L] \times \pi r_{cu}^2 + 17.8\pi^2 r^2 L \quad (19)$$

The total weight of the PTFE film used was:

$$m_{PTFE} = 24L^2 \sin\alpha \cos\alpha \times d \times 2.1 = 50.4L^2 d \sin\alpha \cos\alpha \quad (20)$$

The total mass of the entire rotating system is:

$$M_{Total} = m_{PTFE} + m_{cu} = [213.6L \times (1 + \cos\alpha) + 35.6\pi L] \times \pi r_{cu}^2 + 17.8\pi^2 r^2 L + 50.4L^2 d \sin\alpha \cos\alpha \quad (21)$$

Bring equations (3), (5), (7), (19), (20), (21) into equations (9) can be calculated by:

$$V^2 = \{100.8L^2 d \sin\alpha \cos\alpha + 2[213.6L \times (1 + \cos\alpha) + 35.6\pi L] \times \pi r_{cu}^2 + 35.6\pi^2 r^2 L\}^{-1} \times (2 - \sqrt{3}) \times 3.6x \times \frac{\sqrt{3}-1}{2} \times 10^{-6} \times L^3 \sin\alpha \cos\alpha + (\sqrt{3} - 1) \times 1.8x \times 10^{-6} \times L \sin\alpha \times [(\frac{2\pi}{3} + 1 - \frac{\sqrt{3}}{2})L^2 \times (\cos\alpha)^2 + (\frac{\sqrt{3}\pi}{3} - \frac{\sqrt{3}-3}{2})L - \ln\frac{3}{2\sqrt{3}+3}) + \frac{\sqrt{3}-2}{2}] + 1.8x \times 10^{-6} \times L \sin\alpha \times (\frac{2\sqrt{3}\pi - 21}{12}L + \frac{1-3\sqrt{3}}{3}L^2 \times (\cos\alpha)^2 + 2\ln\frac{\sqrt{3}}{2} - \frac{1}{2}\ln 3 \quad (23)$$

Then, the induced electromotive force can be obtained by taking the formula (22) into the formula (10), and because for the electromagnetic induction phenomenon, the generated induced electromotive force is the generated voltage. As shown above, it can be seen that the amount of charge generated by the electromagnetic induction phenomenon is related to the side length L, the foot and the daily rainfall x of the isosceles triangle blade used. To sum up, after synthesizing the above formulas and considering the leakage flux, internal resistance loss, copper loss and other factors during the operation of the entire system, the efficiency of electromagnetic induction power generation alone is not less than 50%. At the same time, considering that the power conversion efficiency of a single TENG is about 50%, the efficiency of the entire system is preliminarily calculated in this design and the efficiency of this design is over 50% [8-13].

5 Conclusion and outlook

Clean energy power generation has long received public attention. With the gradual and proficient application of solar energy, wind energy, tidal energy, etc., the development of new energy has long been expected by people. Raindrops are ubiquitous in nature and can be used as clean energy. How to convert them into electricity has always attracted much attention. In this study, the triboelectric nanogenerator and the magnetoelectric phenomenon are combined in the form of windmills and applied to the conversion of raindrop energy. The energy conversion efficiency of the hybrid system is about 50%, which improves the conversion of raindrop energy to electric energy, so that the whole system can be Realize better practical value.

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