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DESIGN OF COMPOSITE NANOGENERATOR FOR ENVIRONMENTAL ENERGY COLLECTION

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Abstract - With the increase of renewable energy utilization and the demand for high-efficiency energy system, the research on compound generator is becoming more and more important. Based on the principle of micro-energy collection technology, this paper combines electromagnetic power generation, friction power generation, piezoelectric power generation, photovoltaic power generation and temperature difference power generation to construct a composite nano-generator, which realizes the conversion of energy sources such as wind energy and solar energy into electric energy in the natural environment. By building a physical model test system, the output performance of the composite nano-generator is studied. It is found that the rectified load voltage increases with the increase of wind speed in the environment, and the maximum load voltage can reach 15V at the speed of 120rpm. In addition, the prepared composite nano-generator can continuously supply power to commercial temperature and humidity sensors when connected to the circuit in normal environment. Compared with the traditional generator, the composite nano-generator is suitable for the energy supply of self-powered sensors and small electrical equipment.

Keywords: Energy collection, Micro-energy, Nano-generator, Self-powered sensor, Structural design.

1. Introduction

In recent years, with the growth of energy demand, various environmental pollution problems caused by the use of fossil energy have become increasingly serious. Therefore, finding and using renewable energy has become the key to solve the energy crisis and environmental problems[1]. Due to abundant wind energy resources in nature, reasonable utilization of wind energy can not only reduce environmental pollution, but also alleviate the phenomenon of energy shortage. On the basis of wind power generation, more new energy power generation methods have also been developed, such as photovoltaic power generation and composite power generation.

In 2006, Wang et al.[2] first proposed the concept of the nanogenerator, and the world's first PNG is also developed. It uses nano-materials and nano-technology to collect mechanical energy from the environment and convert it into electrical energy. Since then, researchers have proposed and experimented with various design concepts and structures of composite nano-generators, such as in 2019, Qian Shuo et al. [3]at North University of China proposed a maglev electromagnetic-piezoelectric hybrid high-efficiency energy harvester, which is expected to be used for harvesting various types of mechanical energy. In 2024, Bai Q.[4]proposed a triboelectric-piezoelectric-electromagnetic composite wind energy collector based on buckling bistable mechanism as a sustainable power supply and a self-powered wind speed sensor. At the same time Wei Zusheng et al. [5] designed a spatially multiplexed dual-resonance piezoelectric-triboelectric hybrid vibration energy harvester to address the issues of low energy harvesting efficiency of single-shaped piezoelectric energy harvesters in broadband vibration environments and the large space occupied by hybrid energy collecters. The application research of this kind of generator in new energy power generation system, sensor network and other aspects is gradually expanding, showing a good application prospect.

However, despite the great progress in research, the composite nano-generator still faces some challenges

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in practical application. For example, the nano-generator has some problems, such as poor compounding, balance and optimization of various energy conversion efficiencies, long-term stability of the system and economic feasibility of large-scale application[6]. Especially in structural design, further in-depth exploration is urgently needed.

Aiming at the above problems, this paper puts forward a design scheme of composite nano-generator. By combining wind power generation, friction power generation, photovoltaic power generation and temperature difference power generation, the generator converts natural energy in the environment into electric energy to power commercial temperature and humidity sensors to make them work continuously, which has great potential in energy supply of self-powered systems and small electrical equipment.

2. Scheme Design and Working Principle

The overall structure of the composite nano-generator mentioned in this paper is shown in Figure 1:

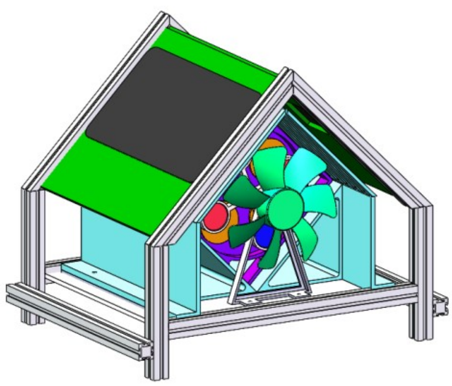
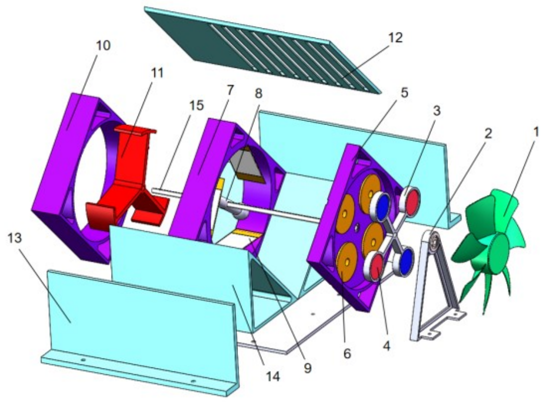


Figure 1: Three-dimensional design of composite nano-generator

The design of the composite nano-generator is divided into friction-piezoelectric-electromagnetic power generation and photovoltaic-temperature difference power generation, which are described in two parts below.

2.1 Friction-Piezoelectric-Electromagnetic Power Generation Structure and Principle

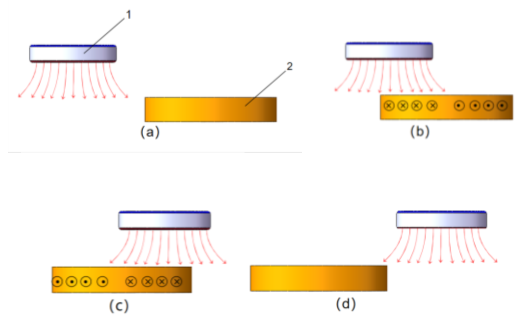
As shown in Figure 2, the friction-piezoelectric-electromagnetic power generation structure consists of a fan, a fan bracket, an electromagnetic rotor, an electromagnetic stator, a piezoelectric stator, a wiping stator, a wiping rotor, a radiating plate, an L-shaped support frame, a triangular support frame and a rotating shaft.



1-Fan blade2-Fan blade bracket 3-Electromagnetic rotor 4-Magnet 5-Electromagnetic stator 6-Copper coil 7-Piezoelectric stator 8-Piezoelectric rotor 9-Piezoelectric sheet 10-Erasing stator 11-Erasing rotor 12-Radiating plate 13-L-shaped support 14-Triangular support 15-Rotating shaft.

Figure 2: Schematic diagram of friction-piezoelectric-electromagnetic power generation structure

As shown in Figure 3, the electromagnetic rotor is equipped with four circular magnets with a diameter of 12mm in turn according to opposite poles, and four copper coils with the same size and an outer diameter of 38mm and 3710 turns are fixed in the electromagnetic stator, and copper wires between each copper coil are connected in series to form a passage. The fan blades drive the rotating shaft to make the electromagnetic rotor rotate. Because the electromagnetic rotor is equipped with magnets with opposite poles, the copper coil in the electromagnetic stator is in a constantly changing magnetic field. According to the principle of magnetoelectric conversion[7], the changing magnetic field will make the electrons of the conductor move in one direction, and the charges in the copper coil begin to move directionally to form an induced current. Figure 3 (a), (b), (c) and (d) shows the change of current in the copper coil when the magnet passes through the copper coil by rotating.



1-Magnet 2-Copper coil

Figure 3: Schematic diagram of electromagnetic power generation

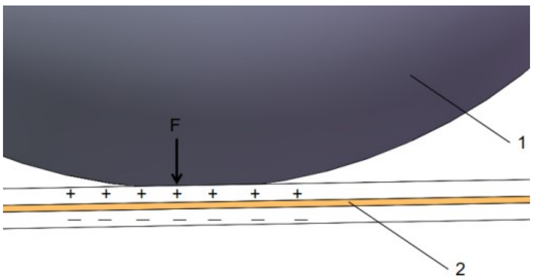
This trend can be explained by Formula (1) and Formula (2):

$$V_{OC} = -N\frac{\Delta\phi}{\Delta t} \quad (1)$$

$$I_{SC} = \frac{V_{OC}}{R} \quad (2)$$

Where V_{OC} and I_{SC} is the open-circuit voltage and short-circuit current of electromagnetic power generation respectively, n is the number of turns of the coil, $\Delta\phi$ is the change amount of magnetic flux, Δt is the time taken for the magnetic flux to change, and R is the resistance of the coil. With the increase of rotating speed, the change of magnetic flux per unit time increases, which will lead to the linear increase of voltage and current[8].

As shown in above Figure 2, the piezoelectric stator is fixed with three 60mm×30mm PZT ceramic piezoelectric pieces connected in series and evenly distributed inside the casing through springs. The piezoelectric rotor consists of a short shaft with a length of 72mm and two round iron balls with a diameter of 18 mm. With the rotation of the rotating shaft, the piezoelectric rotor constantly hits the ceramic piezoelectric sheet, and the piezoelectric material of the ceramic piezoelectric sheet is deformed by the external force, and the upper and lower surfaces of the piezoelectric material generate charges as shown in Figure 4, thus realizing the conversion from mechanical energy to electrical energy[9].



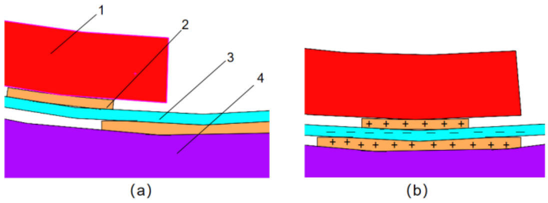
1-Round iron ball 2-Ceramic piezoelectric sheet
Figure 4: Schematic diagram of piezoelectric power generation

According to the equivalent circuit model, the electric energy stored in the piezoelectric element under the open circuit when the piezoelectric ceramic is acted by external force can be calculated:

$$E = \frac{1}{2}C_P V_S^2 = \frac{1}{2}\left(\frac{d_{31}^2}{\varepsilon_{33}^T}\right)\varphi\left(T_a\right)^2 \quad (3)$$

Open-circuit electric energy E is the maximum electric energy that can be provided by piezoelectric sheet, and it is an important index of piezoelectric ceramics. According to formula (3), E is proportional to the volume φ and average stress $\left(T_a\right)^2$ of piezoelectric ceramics, in which improving the average stress of piezoelectric ceramics is the key point of structural design, but when the external force is too large, it will lead to the rupture of piezoelectric plates, so we should pay attention to the relationship between structure and stress[10].

Copper foil is evenly distributed at a distance of 3mm on the inner side of the brush stator, and a circle of copper foil is attached to one side to form a passage. A layer of PTFE film with a width of 30mm is covered on the copper foil, and copper foil is evenly distributed at a distance of 2mm on the outer side of the brush rotor. As the wiping rotor rotates, the copper foil outside the wiping rotor begins to rub the PTFE film inside the wiping stator. As shown in Figure 5, Figure 5(a) shows that the copper foil on the wiping rotor is not in contact with the copper foil on the wiping stator through the PTFE film, and Figure 5(b) shows that the copper foil on the wiping rotor is in contact with the copper foil on the wiping stator through the PTFE film. According to the different electron-obtaining abilities of different materials, triboelectrification will lead to a positive electrostatic charge on the surface of copper foil, while a negative electrostatic charge equal to its charge density will be carried on the PTFE film, and a potential difference will be formed along with the continuous sliding of copper foil, thus generating current.



(a)Unexposed situation (b)Exposed situation
1-Wipe the rotor 2-Copper foil 3-PTFE film 4-Wipe the stator
Figure 5: Schematic diagram of friction power generation

This phenomenon can be explained by Formula (4) and Formula (5):

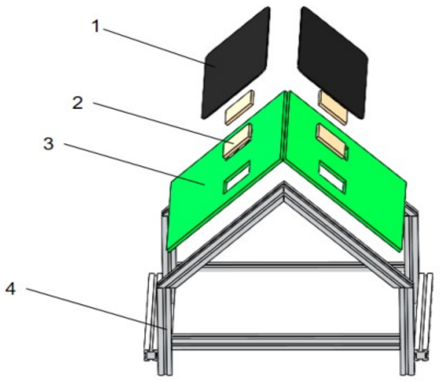
$$I = n\frac{\Delta Q}{\Delta t} \quad (4)$$

$$I = \frac{U}{R} \quad (5)$$

Where n is the number of segments of the friction film and $\Delta Q / \Delta t$ is the transmission rate of charges in the friction film, U is the voltage, I is the current and R is the internal resistance. The increase of rotating speed increases the charge transfer rate $\Delta Q / \Delta t$, so the current increases[11].

2.2 Photovoltaic - Thermoelectric Power Generation Structure and Principle

The photovoltaic-thermoelectric power generation structure is shown in Figure 6. The photovoltaic power generation and thermoelectric power generation parts are composed of photovoltaic panels, a top plate, thermoelectric power generation pieces and a frame, wherein the photovoltaic panels are installed above the top plate, and the thermoelectric power generation pieces are placed in grooves in the top plate.



1-Photovoltaic panels, 2-Thermoelectric panels, 3-Roof 4-Frame
Figure 6: Schematic diagram of photovoltaic-thermoelectric power generation structure

The basic structure of photovoltaic cell is a semiconductor diode, and the PN junction is formed by the mutual contact between the P region and the N region of the semiconductor. Because there are different numbers of carriers on both sides, there will be the phenomenon of carrier recombination and carrier diffusion, thus destroying the electrically neutral nature of the PN junction, and a depletion region will be formed where the PN junction contacts, resulting in an internal electric field.

The principle of thermoelectric power generation is based on the movement of charge carriers by using the Seebeck effect of materials. When there is a certain temperature difference between the two sides of thermoelectric battery, the number ratio of holes and electrons generated on the higher temperature side is much higher than that on the lower temperature side. Because of the large difference in the number ratio of holes and electrons generated on both sides, both holes and electrons move to the lower temperature side, so a single PN junction generates a potential difference. A plurality of PN junction modules are connected in an orderly arrangement to form a thermoelectric battery which can output a higher voltage value, and the thermoelectric battery can realize the conversion of heat energy and electric energy only by having a certain temperature difference between the cold and hot ends[12].

Therefore, in the composite nano-generator structure in this paper, the upper end of the thermoelectric generator is located on one side of the photovoltaic panel, and the temperature is higher due to illumination, while the lower end of the thermoelectric generator is lower due to the rotation of the lower fan, thus generating electricity by temperature difference. The power generation principle is shown in Figure 7.

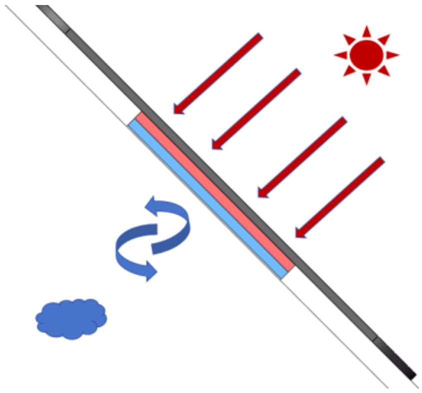


Figure 7: Schematic diagram of photovoltaic-thermoelectric power generation

3. Results and Discussion

Firstly, according to the designed prototype of the composite nano-generator, aluminum profiles with different lengths are used to build the frame, and acrylic plates and 3D printed structural parts are used as supporting parts and blades, as shown in Figure 8.

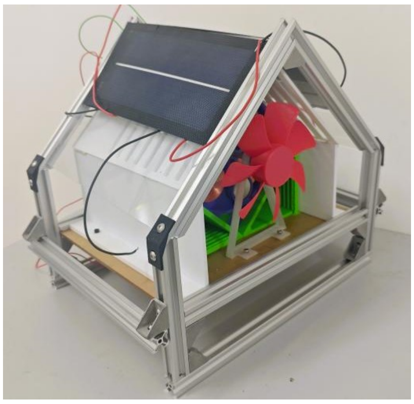
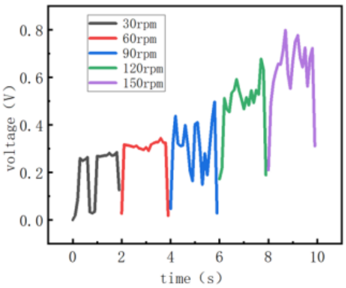


Figure 8: Preparation of Composite Nanogenerator

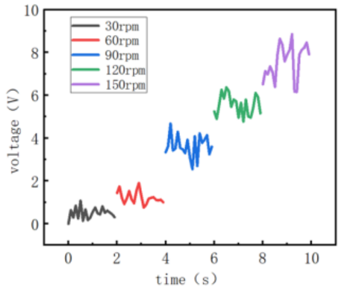
3.1 Output Performance of Friction-Piezoelectric-Electromagnetic Power Generation

The DC motor is used to simulate the rotation of the rotating shaft at different wind speeds, and the open circuit voltage of the friction-piezoelectric-electromagnetic power generation part is measured by DHO802 digital oscilloscope. According to the open circuit voltage observed in Figure 9, the output performance of friction-piezoelectric-electromagnetic power generation can be judged. Figure 9(a) shows the change of open circuit voltage with the increase of rotating speed. As shown in the figure, the maximum voltage can reach 0.8V ; when the rotating speed is 150rpm. Figure 9(b) shows the change of open circuit voltage of piezoelectric power generation with the increase of rotating speed. As shown in the figure, the maximum voltage can reach 8.85 V when the rotating speed is 150rpm.

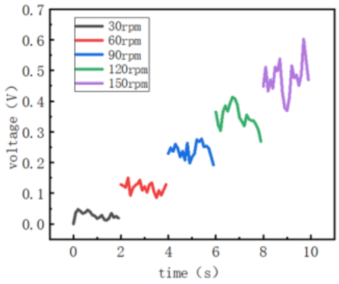
Figure 9(c) shows the change of open circuit voltage of electromagnetic power generation with the increase of rotating speed. As shown in the figure, the maximum voltage can reach 0.6V ; when the rotating speed is 150rpm. Figure 9(d) shows the change of open-circuit voltage of friction-piezoelectric-electromagnetic power generation with the increase of rotating speed. As shown in the figure, the maximum voltage can reach 10.14V when the rotating speed is 150rpm.

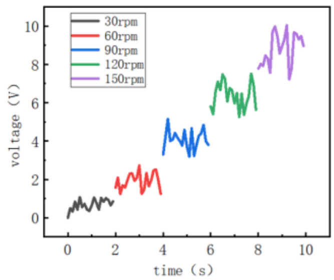


(a) Wiping



(b) Piezoelectric





(c) Magnetoelectric *(d) Combination*

Figure 9: Open-circuit voltage

Using digital source meter Keithley2611B, the short-circuit current of friction-piezoelectric-electromagnetic power generation part of DC motor at 120rpm is measured, and the test result is shown in Figure 10. The short-circuit current of the friction-piezoelectric-electromagnetic power generation part reaches 5mA at 120rpm.

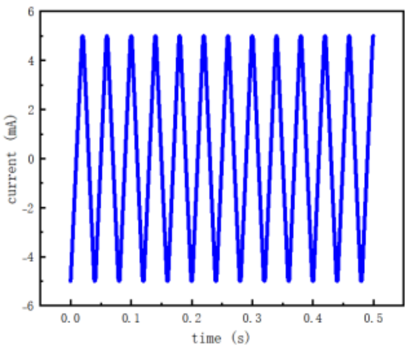
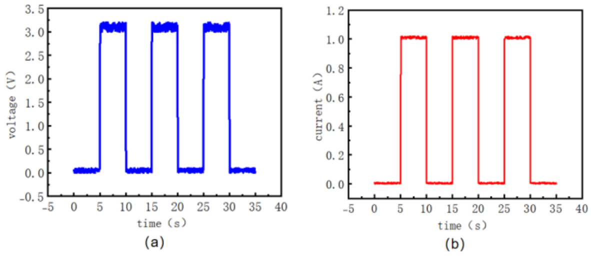


Figure 10: Short-circuit current of friction-piezoelectric-electromagnetic power generation part

3.2 Output Performance of Photovoltaic-Thermoelectric Power Generation

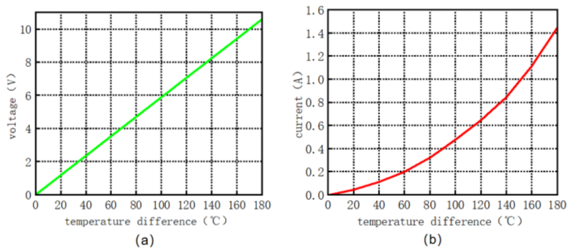
After testing, the photovoltaic panel in this paper finally adopts a flexible solar panel with a certain hydrophobicity, which has an output voltage of 3V and an output current of nearly 1 A. The output waveform is shown in fig. 11. In figure 11(a), the maximum voltage generated by the solar panel is 3V, and in figure 11(b), the maximum current generated by the solar panel is 1A. The output characteristics of the solar panel cannot offset the output performance of the friction-piezoelectric-electromagnetic generator, but also make up for the disadvantage of small output current of the friction nano-generator[13].

In this paper, the thermoelectric power generation adopts TEG1-199-3.5-6SEEBECK, which can generate an open circuit voltage of 10V when the temperature difference is 170℃.



(a) Open circuit voltage (b) Short circuit current
Figure 11: Open Circuit Voltage and Short Circuit Current of Flexible Solar Cell

The changes of output voltage and output current with temperature are shown in Figure 12. Figure 12(a) shows that the maximum voltage change can be more than 10V when the temperature difference is from 0 to 180°C, and Figure 12(b) shows that the temperature difference is from 0 to 10V.



(a) Output voltage (b) Output current
Figure 12: output voltage and output current of temperature difference plate

Although the output of photovoltaic panels and thermoelectric plates used in photovoltaic-thermoelectric power generation in this paper are both direct current, their power generation process is very easily affected by the environment, which leads to the constant change of current and voltage values output by the system[14]. Therefore, the photovoltaic-thermoelectric power generation in this paper needs to use DC-DC conversion circuit to stabilize the output voltage, and then the output electric energy can be stored in the battery or supplied to the load.

3.3 Output Performance of Composite Nanogenerator

Characterized by electricity[15] can be seen that the electrical signal generated by friction-piezoelectric-electromagnetic power generation is an alternating current signal, and alternating current cannot be directly used as energy to supply energy to small power units. Therefore, this paper adopts a management circuit flow of a composite nano-generator, as shown in Figure 13. It is necessary to rectify the alternating current signal by using a rectifier bridge composed of four diodes, so that the friction-piezoelectric-electromagnetic power generation part can be stored in the capacitor together with the photovoltaic-thermoelectric power generation part for use by electrical appliances.

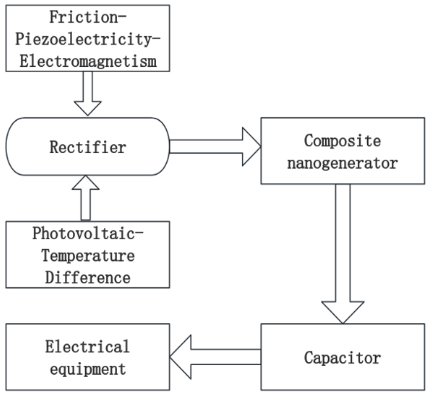


Figure 13: Management circuit of composite nano-generator

The waveform as shown in Figure 14 is obtained by the load test of the rectified composite nano-generator. From the figure, it can be seen that the maximum voltage can be generated at 120rpm, which shows that the voltage of the composite nano-generator can increase with the increase of wind speed in the natural environment.

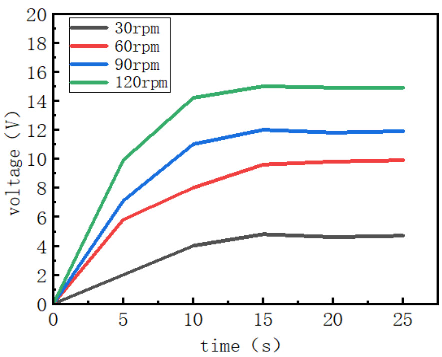


Figure 14: Voltage for supplying power to the load

The comparison of the output performance of different power generation units and their combinations is shown in Table 1. It can be seen that, under the same power generation duration, the output performance of the hybrid nanogenerator is superior.

Table 1. Performance Table of Output of Different Power Generation Units and Their Combinations

Combination	Voltage (V)	Current (mA)	Power (mW)
friction	0.72	0.35	0.252
Piezoelectric	8.5	0.4	3.4
Magnetoelectric	0.59	4.8	2.832
solar	2.9	0.65	1.885
thermoelectric	1.8	1.3	2.34
composite	12.7	5.2	66.3

3.4 Efficiency of Composite Nanogenerators

The hybrid nanogenerator proposed in this study can harvest three main types of natural environmental energy: wind energy, solar energy, and thermal energy. The calculation of the input power for each energy source[16] is as follows.

The wind energy power formula can be expressed by equation (6):

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{6}$$

Where ρ represents the conventional value at 25℃ under standard atmospheric pressure, A represents the area swept by the fan blades, and v represents the rotational speed of the blade tips.

The solar power formula can be expressed by equation (7):

$$P_{solar} = GA\eta_{solar} \tag{7}$$

Where G represents the standard solar radiation intensity, A represents the area of the photovoltaic panel, and η_{solar} represents the photoelectric conversion efficiency of the photovoltaic module.

The formula for the power of temperature difference energy can be expressed by equation (8):

$$P_{thermo} = \Delta T \alpha A \tag{8}$$

Where α represents the Seebeck coefficient of the thermoelectric power generation material, ΔT represents the temperature difference, and A represents the area of the power generation chip.

The total input power P_{in} is the sum of the power from wind energy, solar energy, and temperature difference energy, that is $P_{in} = P_{wind} + P_{solar} + P_{thermo}$.Based on the actual composite nanogenerator prepared, when the rotation speed is 120 rpm, the input power P_{in} is 750 mW. The total output power $P_{out} = UI$. After connecting the composite nanogenerator to a load, the measured P_{out} is 90 mW, which is higher than the average efficiency of similar multi-source hybrid devices (about 5%-7%).

The energy generated by the hybrid nanogenerator is calculated according to the energy formula $E = PT$, with 1 hour as the time unit. By comparing the input energy and output electrical energy, the distribution of energy conversion losses is clarified: the total input energy E_{in} is 2700J, and the total output energy E_{out} is 324J. Due to various energy losses during transmission, such as mechanical friction loss of the fan blade rotating components, photoelectric conversion loss of the photovoltaic panel, heat conduction loss of the thermoelectric generator, and circuit matching loss between each energy harvesting module, etc., the output energy is much smaller than the input energy. However, it still meets the electrical energy conversion efficiency. In the future, the power generation efficiency of the hybrid nanogenerator can be improved by modifying the size and material of the rotating components or optimizing the matching circuit to reduce transmission loss.

3.5 Application Test of Composite Nanogenerator

In order to show more intuitively the effect of the nano-generator on the energy collection of the self-powered sensor, this paper uses a commercial temperature and humidity sensor to connect into the circuit to test the output of the composite nano-generator under normal conditions, as shown in Figure 15. The electricity generated by the composite nano-generator can make the temperature and humidity sensor work continuously. This shows that the composite nano-generator in this paper has a good prospect in the development of self-powered systems and small electrical equipment.

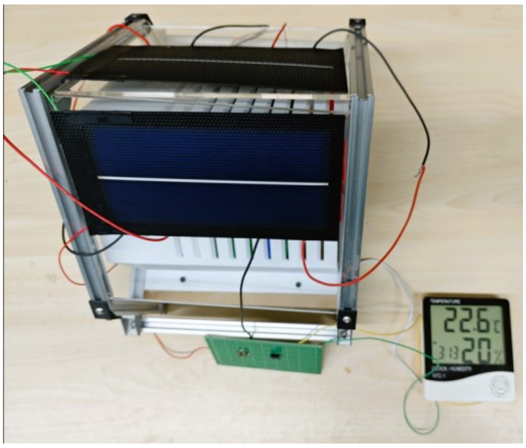


Figure 15: The composite nano-generator supplies power to the temperature and humidity sensor.

4. Conclusions

In this paper, a composite nano-generator is designed based on micro-energy collection technology, which can combine electromagnetic power generation, friction power generation, piezoelectric power generation, photovoltaic power generation and temperature difference power generation. By analyzing the working principle of each power generation mode, a prototype of composite nano-generator is finally built. After testing the prototype, it is found that the rectified composite nano-generator can supply normal power to commercial temperature and humidity sensors by collecting energy in the natural environment, showing good output performance and broad application prospects.

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