A Summary of wearable textiles power generation

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Abstract. With the advent of a series of wearable devices such as Google Glass, electronic bracelets, etc, people have become more and more interested in wearable devices, but because of the short power supply period, the function is greatly limited. So the use of fabric to generate electricity has slowly come into the eyes of researchers, to understand the history of fabric power generation, this paper mainly analyzes and summarizes the methods of power generation for different types of fabrics from domestic and foreign research, and proposes corresponding solutions based on practical problems. Secondly, the impact of the choice of materials on the actual power generation, including output performance, output stability is further outlined.

1. Introduction

Nowadays, dressing and matching are inseparable from people's lives, and clothing can also be vividly called the "second skin" of the human body. National wearable device shipments are increasing year by year as shown in Figure 1[1]. And clothing is practical and beautiful, and humans have been using it and innovating it since ancient times. First of all, textile products have good flexibility and deformation ability, both in terms of washing and abrasion, and have high retention; secondly, they have large pores and high air permeability, which also greatly improves the wearer's comfort, and cotton fabrics also have good warmth retention characteristics; third, because of its diverse design techniques and novel colors, it is widely consumed by people. As society slowly enters the age of intelligence, many researchers are now focusing on the "intelligence" of textile products to meet the information needs of society and all walks of life. But for the informatization of previous wearable products, most of them use hardware equipment. For example; bracelets, presses, etc., the power supply methods are mostly made of lithium batteries or non-recyclable objects. This method cannot realize the simplification of wearing, and it is easy to cause waste of resources.

The main theoretical basis of textile power generation is Maxwell's second law[2], which converts mechanical energy generated by motion into electrical energy. Wind energy, tidal energy, water energy, etc. in our lives can all be used to generate electricity, but from the perspective of collection efficiency, environmental energy collection is unstable and has great limitations.

Researchers found that the human body itself is a rich source of mechanical energy[3]. The direct combination of textiles and friction nanogenerators for energy harvesting to power wearable electronic products has become a new energy harvesting method. At the same time, electronic devices are also moving in wearable and even implantable direction. Growing. This assembled self-driving system can provide multiple functions including health monitoring, biomedical inspection, sensory information collection, etc., and can also realize real information exchange with the Internet of Things, and contribute to the fourth industrial revolution.
The triboelectric nanogenerator is mainly based on the frictional electrification and electrostatic coupling effect to generate electricity. Under the action of different external forces, the two media have different ability to gain and lose electrons, so that dielectric surface is charged with opposite polarities. The potential difference between the two will drive electrons flow on the top and bottom of the conductive material, thereby generating electric current. The friction sequence diagram of common materials is shown in Figure 1[9].

The greater the difference between the positive and negative conductivity of the material, the better the theoretical power generation effect. The physical model of the friction nanogenerator is equivalent to a capacitor in the circuit, the contact area, the distance between the friction objects and the material will affect the power generation efficiency. Nowadays, the working modes of friction nanogenerators are mainly divided into four types: contact-separation, horizontal sliding, single electrode, and independent layer. Among them, fabric-based power generation mainly adopts contact separation[1]and horizontal sliding[2].

2 Classification of textiles

Textiles on the market are mainly classified by raw material composition, structure, and manufacturing technology. People choose different materials according to different uses. In terms of textile structure, textiles are mainly divided into 0D, 1D, 2D, and more complex 3D structures. From the perspective of manufacturing technology, textiles can be manufactured through processes such as weaving and winding. Among them, the most commonly used weaving methods are warp and weft knitting, latitude weaving. This method can not only reduce the use area to the maximum extent, but also greatly increase the contact area of the fabric, thereby obtaining higher output efficiency. It is called 3D knitting in the industry. Thousands of fibers are twisted, wound, or blended to form one-dimensional yarns or threads through axial assembly/interlocking and other technologies. One-dimensional yarns can be further integrated into 2D or 3D fabrics, sewing, and felting. Or in 3D fabric. 2D fabrics can be made into three-dimensional fabrics by adding additional oriented yarns. In addition, the 3D fabric has the characteristics of good resilience, light structure, heat permeability, and moisture permeability, and is Widely used in insoles, mattresses, car seats, and other fields[3].

![Figure 1: The Export trend of wearable devices.](image-url)
### Table 1. Textile structure comparing.

| Size | Classification | Main Representative | Structure-property |
|------|----------------|---------------------|--------------------|
| 0D   | Optical fiber  | Short fiber, filament| Basic unit, minimum visible part |
| 1D   | Sand line/line | Yarn/thread          | Thousands of fibres twisted/twisted |
| 2D   | Weaving        | Ordinary twilled satin | Warp and weft yarn are interwoven based on knitting pattern |
| 3D   | Weaving        | Fabric               | Two-axis, three-axis yarn laced, adjacent rows and columns intersected |
| Non-textiles | Net, sheets, mats, net | | Short fibres bonded together |
|       | Weaving        | Orthogonal, angular interlocking | Multilayer warp and weft yarns |
|       | Weaving        | Fabric               | Adhesion of four/five direction yarns in thickness direction |
| Non-textiles | Felt/film      |                     | Laminated splicing of multi-layer two-dimensional nonwovens |

### 3 Types and structure of wearable textile materials

Wearable materials are divided into friction materials and electrode materials. The commonly used electrode materials generally use metal foil or metal particles, and some use conductive metal films or new materials, graphene. The choice of friction materials is more extensive, for example; metals, oxides, polymers, and even human skin and hair can also be used as friction materials. As early as the 18th century, Wilcke published the first friction sequence of different materials[4].

In the table 2, various substances are classified according to their electronic gains and losses. Theoretically, the greater the gap between the gains and losses of electrons between two substances, the more accumulated charges, the better the power generation effect. The materials at both ends of the friction sequence in the laboratory are used more frequently, such as polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), polyvinylidenefluoride (PVDF) and positively charged terminals End polyamide (PA), polyethylene terephthalate (PET)[5].
Table 2. Triboelectric series for some common materials.

The power generation efficiency of triboelectric nanogenerators is not only related to the type of material but also the structure of the material. This is also the main direction of triboelectric nano generation research. Therefore, the relative friction area of the material and the surface charge density of the material can be improved by changing the structure and morphology of the material. With the development of micro-nano technology, different nanostructures have been introduced into the generator.

| Positive       | Polyformaldehyde | Left table          |
|----------------|------------------|---------------------|
| ethylcellulose | polyisobutylene  | polyester           |
| Polyamide (Nylon)-11 |                | Polyisobutylene     |
| Polyamide(Nylon)-66 |                | Polyurethane,flexible sponge |
| cyanuramide    | poly (ethylene terephthalate) (pet) | film |
| Wool prepared  | polyvinyl butyral |                    |
| Silk prepared  | neoprene         |                    |
| Aluminium      | Natural rubber   |                    |
| Paper sheet    | polyacrylonitrile|                    |
| cotton         | acrylonitrile-vinylidene chloride copolymer | |
| steel          | Polycarbonate bisphenol | |
| timber         | Poly-bis(chloromethyl)butane oxide | |
| ebonite        | Polyvinylidene chloride (Saran) | |
| Nickel, copper | polystyrene      |                    |
| sulfur         | polyethylene     |                    |
| Brass, silver  | polypropylene    |                    |
| Acetate fiber, artificial fiber | Polyimide (Kapton) | |
| Polymethyl methacrylate (Lucite) | polyvinyl chloride(PVC) | |
| polyvinyl alcohol | Polydimethylsiloxane(PDMS) | |
| Right table    | polytetrafluoroethylene (Teflon) | |
| negative       |                  |                    |
The most commonly used ones are Nanowires array rod as shown in Figure 2[6] Generating nanowires array rods on the surface of the material can greatly increase the relative surface area of the material contact, so this technology is widely used in material catalysis, sensing, energy storage, etc. Among them, the most commonly used oxide nanowires array rods are formed by the reaction of the material substrate. This structure of technology is relatively mature. Lin et al.[7] generated a titanium oxide nanoarray with a diameter of 67.2nm and a thickness of 4.2um on the surface of the titanium foil, as shown in Figure 2(a). The design of this structure greatly improves the output efficiency, the output voltage is increased by 359%, the short-circuit current is increased by 190%, and the sensing performance is also greatly improved. However, in Figure 2(b) due to the decrease in the friction characteristics of the oxide itself, the output efficiency of the entire device decreases as a whole. Its main purpose is to use the photocatalytic properties and high transmittance of some inorganic substances to make TENG devices. After that, in Figure 2(c) the researchers used inorganic substances as nano-templates and brushed polymer conductive materials on the surface to improve the power generation efficiency of the triboelectric nanogenerator. For example, Yang et al. covered it with a layer of copper mold, so that the PDMS on the upper and lower surfaces contacted the copper more fully so that the open-circuit voltage reached 101V and the short circuit current reached 55.7uA in Figure 2(f). On the basis of Yang, Seung et al. Adding a layer of PDMS film on the surface make the efficiency of the generator further improved, which can independently drive LED, LCD, and remote control car keys.

Figure 2. SEM images of the Ti foil covered with TNW array(a); schematic diagram of the PDMS-based triboelectric na-nogenerator with vertically-ligned ZnO NRAs on ITO/ PET as a top electrode(b); electron microscopy SEM image of Cu film coated ZnO nanowire arrays(c); FE-SEM images of the bottom textile with nanopattern PDMS, inset is a high-resolution image clearly showing the ZnO NR-templated PDMS nanopatterns(d); SEM image of nanorod structure on the FEP surface(e); SEM image of surface-etched PTFE nanowires(f).

Although this method greatly improves the efficiency of the friction nanogenerator, it also has great limitations. For example, the ductility and flexibility of the surface-modified structure are not very good. Since the device is moving in a vertical or horizontal direction for a long time, resulting in poor wear resistance of the device, it is necessary to improve the wear resistance of the device.

4 Wearable friction nano generator and its development direction

4.1 Fiber-based friction nano generator

The team of Z.L.Wang[1] of the Chinese Academy of Sciences first proposed textile fiber power generation. The generator is made of two processed cotton threads. One is cotton thread coated with
carbon nanotubes (CCT), and the other is cotton thread coated with polytetrafluoroethylene and carbon nanotubes (PCCT). The cotton thread is knitted with warp and weft technology to form a fabric for friction power generation. Its working principle is that the two substances have a big difference in the ability to gain and lose electrons, so the rectifier device is used to output the energy after the charge is generated by the extrusion. This way of generating electricity can charge a 2.2 μF capacitor, which also opened the prelude to fabric power generation. Although its flexibility has been solved, the output effect is not very satisfactory, and the service life is relatively short, and there is still a lot of room for improvement.

After that, H. Li [7] of Donghua University proposed the use of PA6 and PET and silver-plated filaments to weave the friction nano power generation fabric, the output power can reach 1.6 mW/m² in the case of a load of 7 million ohms. The mentioned power generation fabric is undoubtedly a breakthrough leap in terms of technological improvement, and this research has received extensive attention from scientific researchers.

Z. M. Tian's team at North University of China [9] proposed to use room temperature vulcanized rubber and polyester fiber-coated conductive cloth to produce a fully flexible friction nano-generator using a flat weaving process. Its outstanding characteristics are lightweight and low cost. This technology is easy to produce, so it will have great potential in the wearable field in the future. However, there is still a phenomenon of fiber membrane delamination.

With the emergence of graphene materials, more and more researchers have conducted research on it. The Beijing University of Chemical Technology research team K. Pan [11] and others have greatly improved the scalability of friction nano-power generation by using the three-dimensional surface characteristics of wrinkled graphene. At the same time, it also solves the phenomenon that nanofiber membranes are prone to delamination. This single-electrode triboelectric nanogenerator can directly attach to human skin and effectively obtain the mechanical energy lost by the human body.

Many people now use a variety of textile threads and materials to make friction nanogenerators. The domestic polymer materials laboratory of Donghua University [12] proposed to use high-performance multilayer optical fiber friction to collect biomedical energy. From the beginning of the nanowire and nanoparticle assembly to synthesize friction materials to the manufacture of silicon plates, to the use of anodized aluminum membranes, to the current ion beam etching method, each step of this technology is improving the output of friction nano power generation. Effectiveness. This experiment is to maximize the efficiency of charge transfer and at the same time lead to the concept of the charge storage layer.

4.2 Friction nanogenerator combining power generation and storage

The previous fiber power generation has a big drawback, which is the problem of charge storage. As mentioned earlier, the maximum storage period of Fiber power generation can only reach 20 days, which will bring a lot of inconvenience to people's daily life.

As power generation technology matures, power storage has become an urgent problem to be solved. Many people have proposed related solutions. For example, L. Liu's team [12] from Donghua University proposed a flexible friction nanogenerator with spacers. The power generation device is composed of energy-generating devices and energy storage devices. Similarly, PDMS and CNT films are used to prepare carbon nanotubes to generate electricity through the electron evaporation beam process, but the focus of this experiment is to use supercapacitors (SC) to store electric charges, and make supercapacitors through the combination of CNT and fabric, and combine the two to assemble into an integrated energy device.

Zhen also used electrospinning to prepare polyvinylidene fluoride (PVDF) and polyamide (PA) fiber membranes at both ends of the friction sequence. The friction of the two fiber membranes produced up to 1163 V and 11.5 mA·cm⁻² open-circuit voltage and short circuit current, the peak power density is 26.6 W·m⁻². However, the electrospun film is very sensitive to environmental humidity during use. When the humidity is high, its output performance will drop sharply, which is very unfavorable for its use in the wearable field and This is bad for its use in wearables.

In response to the environmental problem of wearable adaptation, researchers have also proposed solutions. When we are outdoors, sweat and rain will inevitably cause interference to the generator. On
this issue, foreign countries\[15\][16] proposed a flexible triboelectric nanogenerator that can be washed and charged. It is also used for biological movement to collect energy storage using super capacitors. It adopts carbon nanofiber(CNF)and (PEDOT:PSS) using the latitude weaving process and uses three strands of stainless steel to cover the surface of silicone gel support, which has a good waterproof effect. The output effect of this friction nano power generation device is also very impressive. It can light up 124 LED lights at the same time, and it has also made amazing progress in energy storage. This is undoubtedly a breakthrough in the field of power generation and energy storage research.

4.3 Textile-based friction nano power generation

Due to its instability and low output efficiency, the fiber base is gradually replaced by the textile base. Pu\[17\]designed a wearable energy device composed of all-textile-based friction nanogenerator clothes and flexible lithium-ion batteries(LIB). In this experiment, the insulating polyester fabric was transformed into a conductive material by a non-plated uniform nickel film to generate electricity. The experiment finally charged the lithium battery for three cycles and drove the heartbeat measurement that can communicate with a smartphone wirelessly, instrument.

since conductive electrodes are the core of triboelectric nano power generation, it is important to choose a wearable conductor as the electrode. Domestic scholars early proposed the use of polyester fabric as the substrate. Due to its difficult production process, it was quickly replaced by a flexible ribbon-shaped nickel and propylene fabric as the substrate.

4.4 Fiber-based composite friction nano power generation

Researchers are paying more and more attention to the application of friction power generation in practice\[18\]. Such as medical and health testing, human behavior monitoring, etc. LI designed a composite friction nanogenerator on the basis of predecessors. The generator combines frictional power generation and piezoelectric power generation, using zinc oxide and carbon nanotubes to make it and nylon Fiber friction generates electricity, and it is assembled and fixed by a three-dimensional coaxial assembly device to realize a wearable power generation device. The output efficiency of the device is very high, and it can be used as a commercial LED to deliver electrical energy to a self-driving alarm system, and it can also be used as a self-driving strain sensor for medical testing.

Using the triboelectric effect to integrate the energy generated when the material is "deformed", triboelectric and piezoelectric devices can effectively improve the energy conversion efficiency. Based on this concept, Li prepared a fibrous triboelectric-piezoelectric device. Hybrid nano power generation device. The three-dimensional structure of this device can collect mechanical energy in all directions and convert it into electrical energy more effectively.

The hybrid device of triboelectric nano power not only has its effect on triboelectricity but also can produce effects on heat, magnetic energy, and solar energy in this kind of hybrid device.\[19\]The feature of this device is that it can maintain a high output efficiency under complex environmental conditions., This is also a way to improve output efficiency.

5 Summary and Prospects of Wearable Textiles

This article mainly introduces the fiber base, textile fabric base, composite fiber base, and collects some domestic and foreign research results. From the level of social information and environmental development needs, it mainly introduces the development history of fiber-based fabrics in detail. From the generation of electric energy to storage, to the combination with the real environment.

After recent years of development, researchers have started from the selection of materials, the morphology and structure design of materials, and the use of hybrid devices, which have greatly improved the output power and output stability of TENG. These researches have also attracted the attention of more and more researchers. However, as an emerging research field, TENG still has some key problems to be solved, and there is still a long way to go before it can be put into practical use.

The author’s research team believes that future research needs to be carried out from the following aspects: 1:In-depth research on TENG generator theory and formulation of measurement standards; 2:Based on the characteristics of TENG high voltage and low current, further increase TENG output current; 3:Integration of energy transfer, rectification and The energy storage device constitutes the
TENG micro-system, which overcomes the shortcomings of the TENG AC pulse current that it is difficult to continuously supply power. Therefore, it is believed that the future development of TENG is bright, and it is expected to be applied to the continuous energy supply of wearable devices, which will greatly facilitate our daily life.

Although the friction nano power generation fabric is not widely used in people's daily life, the wearable friction nano power generation technology in the micro-electromechanical field will be combined with the 5G network information era to form a self-powered "smart" platform. Wearable intelligence will become a major direction of the times. Looking to the future, information transmission will develop rapidly, and self-powered technology will play a pivotal role in information transmission. For wearable textile products, it will slowly enter people's lives, bringing more convenience to people's lives, medical treatment, health, and many other aspects!

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