Application of Thermoelectric Generator (TEG) in IoT Sensors

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The Internet-of-Things (IoT) combines various sensors and the internet to form an expanded network, realizing the interconnection between human beings and machines anytime and anywhere. Nevertheless, the problem of energy supply limits the large-scale implementation of IoT. Fortunately, thermoelectric generators (TEGs), which can directly convert thermal gradient into electricity, have attracted extensive attention in the field of IoT due to their unique benefits, such as small size, long maintenance cycle, high stability, and no noise. Therefore, it is vital to integrate the significantly advanced research on TEGs into IoT. The authors first outlined the basic principle of the thermoelectricity effect and summarized the common preparation methods for thermoelectric functional parts in TEGs. Then, the application of TEG-powered sensors in the human body was wearable and implantable medical electronic devices. It is followed by a discussion on the application of scene sensors for IoTs, for example, building energy management and airliners. Finally, researchers provided a further outlook on the current challenges and opportunities.

Internet of Things | thermoelectric generators | fundamental principle | wearable devices | sensors

1. Introduction

Nowadays, about 75% of global energy consumption is based on non-renewable fossil fuels [1]. Many unexpected consequences have emerged after one hundred years of industrialization. The dilemma is that the abrupt reduction of fossil fuels will significantly downgrade the living standard of human society, and the continuous massive use of fossil fuels will further worsen environmental pollution and climate change. As a result, researchers are looking for available clean energy sources to ease the problem. Wind power [2], solar power [3], nuclear fission thermal energy [4], etc., are developed for this purpose. However, due to the inherent shortcomings of solar power and wind energy (requiring the existence of the sun and wind), thermal energy has become one of the relatively stable energy sources considered to be a vital part of solving the global energy crisis [5]. Therefore, the demand for thermal energy conversion technologies is becoming increasingly imperative.

Compared to regular heat engines, such as steam turbines, due to the small sizes and working mechanisms of TEGs, the output can only be in the order of milliwatts to microwatts, which cannot support the energy demand of daily life. However, this energy output is in line with the needs of specific small power equipment, such as the sensors for IoT. Moreover, TEG equipment does not require regular maintenance or replacement of batteries and, therefore, TEGs have long-term power supply capacities that dramatically improve the economic benefits. Wahbah et al. [6] showed that the maximum power output of 20 mW at 22 °C for commercially manufactured TEGs corresponds to a power density of merely 2.2 mW/cm^2. The study illustrates the worst-case power output of commercial TEGs and the potential of TEG equipment. Since TEGs are light in weight, without emissions and noise, they are more widely used in small electronic equipment [7], such as wearable devices, medical devices, wireless sensor devices, automobile waste heat treatments, and aerospace applications [8]. The following sections will introduce its application in IoT sensors, such as wearables and medical devices, wireless sensor networks, and architectures (**Table 1**).

Table 1. Power (the output power of TEG (1 mW or sub-1 1 mW) and output voltage of TEG (0.25 V–0.7 V)) required for partial thermoelectric applications.

Application	Power
Wearable watch [9]	100 μW
Human forehead to power a 2-channel EEG [10]	0.8 μW
Energy self-sufficient wireless weather sensor [11]	61.3 μW
Aviation field [12]	30 μW

2. Wearable Devices and Medical Equipment

Generally, there is a specific temperature difference between the human body and the ambient temperature, which provides a prerequisite for applying TEGs in wearable devices and medical devices. The human body, as with any object, can obtain and lose heat through conduction, convection, and radiation. Specifically, they include the conduction between the contact objects and/or substances; convection involving the transfer of heat from the warm body to the air above or inside the body, where blood, gas, and other fluids are the media; and radiation where heat transfers/exchanges between the surface of the human body and the surrounding environment. These three effects work together in most cases [13]. Wearable devices and medical equipment that can work using the power provided by the temperature difference could be important parts of IoT.

When using TEG as the power supply for wearable equipment, in addition to the requirement of conversion efficiency, one has to consider additional requirements, such as biocompatibility, wear resistance, toxicity, flexibility, and so on. So far, Bi2Te3 and its derivatives are the most commonly used low-temperature thermoelectric materials, showing high thermoelectric performance around room temperature. Even with the advantage of mass production, they suffered from poor mechanical properties and toxicity of telluride, which limits their application in some wearable or implanted devices. In general, the currently popular thermoelectric materials are not yet satisfactory for powering wearable sensor devices, considering their costs, limited large-scale availability, and high quality. For in-vitro application, Lu et al. [14] deposited the nanostructured telluride on silk fabric to produce a flexible

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thermoelectric materials, which can effectively convert body heat energy into electricity. The reduced direct contact with the human body by planting the pellets into the fabric can reduce harm to the human body.

Flexible thermoelectric materials show broad prospects in wearable thermoelectric materials. To avoid the low performance of organic thermoelectric films, Cao et al. [15] prepared flexible thermoelectric films by sputtering Sb (p-type) and Ni (n-type) films on the polyimide substrates. Since transparency is essential for wearable devices. Wang et al. [16] prepared TEG with p–n junctions formed by p-type PEDOT: PSS and n-type indium tin oxide (ITO), respectively, to obtain transparent flexible thermoelectric films with high conductivity and the Seebeck coefficient.

Perovskite materials have attracted much attention in thermoelectric applications due to their low thermal conductivity, high carrier mobility, and the Seebeck coefficient [17]. Ye et al. [18] developed organic–inorganic lead halide perovskite single crystal ($MAPbI_3$)-based TE devices and found that improving electrical conductivity is the key factor to realizing the high thermoelectric performance of perovskite.

In this regard, highly efficient TEGs that can produce tens or hundreds of microwatts in the presence of such temperature differences are highly desired. In addition, to making the wearer comfortable and suitable for mass production, some basic rules must be followed [19]:

(1) TEGs cannot be designed independently of their environment, and they must meet the thermal matching conditions between the heat source (person) and radiator (ambient air);

(2) The thermal resistance and heat source of the thermal reactor and the environment should be as exact as possible to achieve the maximum output power;

(3) Generate enough voltage to supply power to the electronic device;

(4) Wear comfortably;

(5) The size should be as small as possible.

3. Wireless Sensor Networks

Nowadays, wireless sensors can be found in every aspect of life, including industrial and agricultural monitoring systems, wearables, medical devices, etc. Furthermore, a single wireless sensor has been replaced by wireless sensor networks, which are similar to a neuron network in a specific area playing the role of real-time monitoring.

Due to the rapid development of the Internet, the rapid transmission and charge of information provided an opportunity for developing the next-generation power supply for the wireless connection. For example, Georg et al. [11] combined TEGs with the Bluetooth systems of mobile phones, allowing mobile phone users to receive the weather conditions in real time, which significantly changed the lag of the current mobile phone weather forecast information transmission and improved user experience.

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Recently, wireless sensor networks have been considered for various aviation applications in sensing, data processing, and wireless transmission of information. Dilhac [12] thoroughly introduced the installation position of TEG in aviation applications. In addition to the traditional application of the generator and exhaust system, etc., they can be included in the hot positions in the cabin, the outer surface (external air exchange, cruise altitude changes will produce the instantaneous thermal gradient, mainly in the take-off/climb and descent/landing stages), and on the rear hanger fairing. Furthermore, sensors on the fuselage can monitor the mechanical load during the operation to achieve early detection of the fatigue of materials. TEG-powered sensors not only solve the cumbersome wiring problems of traditional sensors but also alleviate the battery instability in extreme environments and the high cost of regular battery replacement.

4. Architecture Field

There has been a long history of TEGs being used in the field of architecture, and they have been commercialized. The buildings are full of populations who live or work inside and, therefore, they can produce large amounts of heat losses, which are opportunities for TEGs. The thermal qualities of general buildings are excellent, so their temperatures change very slowly. Therefore, when there are temperature fluctuations in the weather, these fluctuations may lead to local temperature gradients that allow the TEG-powered sensors to operate. Wang et al. [20] believed that many high-voltage AC units, water heaters, boilers, hot water pipes, and other heating units existing in modern buildings are all potential heat sources. For example, Lezzi et al. [21] designed and implemented a radial TEG integrating thermal pipe insulation, which can power the sensor circuits with wireless transmission capacity and make good use of the waste heat generated by the hot water pipeline. The waste heat in buildings is tremendous; if they could be effectively exploited, this may somehow alleviate the energy supply problem.

In conclusion, wearable devices powered by mini-TEGs for monitoring the medical or physical conditions of patients need to form wireless sensor networks to realize real-time detection and diagnosis of the status of the object. Furthermore, by using the TEG as the energy supply for the signal transmission and reception unit, the advantage will be the ability to reuse the widely available low-grade thermoenergy from the human body or building, which can alleviate the extra cost from the external energy supply. A summary of TEG applications for IoT is listed in **Table 2**.

Table 2. A Summary of TEG applications.

Field	Application
Medical equipment	• Wireless dual-channel electroencephalography (EEG) systems. • A wireless pulse oximeter. • A biomedical hearing aid.

Field	Application
Wireless sensor networks	• Combine TEGs with the Bluetooth systems of mobile phones. • In aviation applications.
Architecture field	• Heating units in buildings are all potential heat sources. • The buildings are full of populations that produce large amounts of heat.