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Design and Optimization of PC Thermal Energy Recovery Device Based on Thermoelectric Generator

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Abstract. Low grade thermal energy generated during the operation of personal computers is often directly emitted in the form of heat dissipation, resulting in significant energy waste. Thermoelectric Generator (TEG) is an ideal solution for PC waste heat recovery due to their simple structure, lack of mechanical parts, and suitability for low-temperature differential environments. Inspired by the waste heat recovery scheme of the data center, this paper designs a set of PC waste heat recovery device based on thermoelectric conversion. This study used the method of combining experimental test and theoretical analysis. By building the PC waste heat recovery experimental platform, the temperature data and TEG power generation performance parameters of the CPUs were collected, and verified and analyzed with statistical data. The PC waste heat recovery system designed in this study can generate 7.98 kWh per year per unit; If applied to 1% of Chinese PCs (about 2.225 million units), the annual emission reduction can be equivalent to the carbon sequestration effect of planting 450000 trees. The experimental results provide a feasible technical scheme for the recovery of low-grade thermal energy.

Keywords: Low-grade thermal energy, PC, waste heat recovery, Thermoelectric generator

1. Introduction

In recent years, low-grade thermal energy($<$ 150℃) has emerged as a green and environmentally friendly renewable energy source, which remains underutilized due to its dispersed nature and low recovery efficiency. In 2019, the U.S. wasted energy equivalent to 67.5% of its total energy consumption, with low-grade heat representing a major portion[1]. Similarly, China's industrial sector loses an estimated 15-40% of fuel input as recoverable waste heat[2]. PCs, as ubiquitous electronic devices, have long overlooked their waste heat potential. According to China Population: Number of Household: Total[3] China has approximately 222.5 million installed PCs, averaging 44.5 units per 100 households. During full-load operation, a typical PC dissipates 60-70% of its energy consumption as heat. With an average power consumption of 150W per unit, the global PC fleet of over 1 billion devices wastes hundreds of billions of kWh annually - equivalent to the output of multiple medium-sized thermal power plants[4]. Given carbon emission factor of 0.5 kg CO_2 per kWh, effective heat recovery could significantly reduce carbon emissions[5].

This research explores the development of a thermoelectric waste heat recovery system for personal computers, investigating its technical implementation and economic feasibility. It examines system integration with existing cooling solutions and evaluates energy conversion performance through experimental testing and computational modeling. Results demonstrate measurable improvements in energy recovery efficiency while maintaining effective thermal management. The proposed solution not only contributes to carbon emission reduction but also offers promising cost-benefit characteristics for large-scale adoption, providing a practical pathway for small-scale waste heat utilization.

2. Design scheme

2.1. Design of chip heat exchange structure

There are three main types of PC cooling methods: air cooling, liquid cooling, and passive cooling. Air coolers achieve efficient heat dissipation through a combination of metal fins and fans, and are typically designed in either tower-style or top-down configurations. Liquid cooling systems use circulating coolant to transfer heat to a radiator, where it is dissipated with the help of fans. These systems come in two forms: all-in-one and custom loop setups. Passive cooling, in contrast, relies entirely on large metal blocks to dissipate heat naturally, making it suitable for low-power scenarios.

Currently, air cooling is the most widely used method in PCs. This device has chosen to retain as much of the original air cooling structure as possible while making appropriate modifications to facilitate the installation of thermoelectric modules, aiming to recover thermal energy without compromising cooling efficiency.

As is shown in Figure 1, a standard PC air cooling system consists of a base plate, heat pipes, heatsink fins, fans, and thermal interface materials. It achieves efficient heat dissipation through metal conduction and forced airflow. The base plate is usually made of pure copper or a copper-aluminum composite and makes direct contact with the Integrated Heat Spreader (IHS) of the chip. It conducts heat rapidly and is often mirror-polished or designed with Heatpipe Direct Touch to ensure tight contact with the CPU. Heat pipes work based on the phase change principle for rapid heat transfer. They are vacuum-sealed and contain a small amount of volatile liquid, such as water or ammonia. When one end is heated, the liquid evaporates and flows to the cooler end, where it condenses and returns via a capillary structure, forming a continuous cycle. Mid-to-high-end coolers usually feature 4 to 8 heat pipes, each 6mm or 8mm in diameter, which are fixed to aluminum fins using fin-stacking or reflow soldering processes to maximize the heat dissipation area. Fans are typically PWM-controlled axial fans and use hydraulic or dual ball bearings to balance noise and lifespan. Additionally, thermal paste is applied to the contact surface. With a thermal conductivity of 5–15 W/m·K, pastes like TF9 offer superior performance by filling microscopic gaps between the chip and the base plate, reducing thermal resistance.

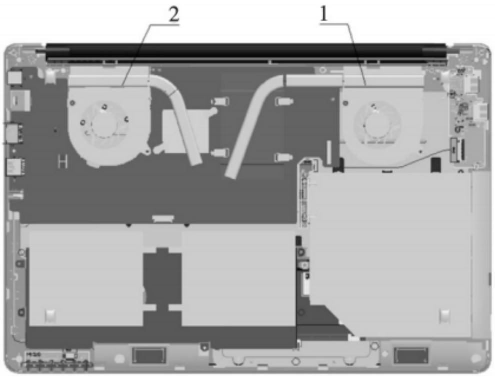

Figure 1: Laptop heat dissipation structure[6]

2.2. Thermoelectric conversion device design

In scenarios where the internal heat source temperature of a PC is relatively low, thermal energy storage systems face two major challenges: significantly increased energy storage costs and notably limited energy conversion efficiency. In contrast, electrical energy offers unique advantages for energy storage—it is supported by mature technology and enables highly efficient energy conversion. Based on this analysis, this design adopts a strategy of converting collected thermal energy into electrical energy. This not only addresses the low utilization efficiency of low-temperature heat sources but also facilitates efficient energy transformation and use.

There are two primary technological pathways for thermal power generation: direct thermoelectric conversion and indirect heat engine power generation. Given the low heat source temperature and extremely limited space within a PC, indirect power generation—which requires a two-step conversion from thermal energy to mechanical energy, and then to electrical energy—suffers faces system complexity, is limited by Carnot efficiency, and typically involves bulky components, making it impractical for PC integration.

In contrast, thermoelectric generators, which operate based on the Seebeck effect, can directly convert heat into electricity without mechanical moving parts. They offer advantages such as simple structure, silent operation, and low maintenance cost-making them particularly well-suited for environments with small temperature differences. Therefore, this solution adopts thermoelectric generation technology and seeks to optimize the temperature difference between the hot and cold sides to achieve efficient direct utilization of thermal energy. This approach avoids the limitations of traditional heat engines in low-temperature scenarios and enhances both the reliability and adaptability of the system.

The Seebeck effect arises from the directional diffusion of charge carriers induced by a temperature gradient. when a material has a temperature difference between its two ends, the Fermi distribution of high-energy electrons or holes at the hot end broadens, resulting in higher average kinetic energy and a longer mean free path, which causes the carriers to diffuse toward the cold end. Meanwhile, in semiconductors, carrier concentration changes significantly with temperature, creating a steep density-of-states gradient near the Fermi level. These combined effects generate net charge separation and a thermoelectric voltage. The magnitude of the voltage is proportional to the temperature difference (ΔT) and the Seebeck coefficient (S) of the material:

$$V = S \cdot \Delta T \tag{1}$$

In the design of the thermoelectric generation system, TEG modules are directly integrated into the CPU/GPU cooling assembly. The hot side of the TEG is in close contact with the copper heat pipes that dissipate heat from the chip, absorbing the waste heat produced during processor operation. The cold side is connected to the fan cooling module, which uses forced convection to maintain a temperature gradient. To enhance thermal exchange efficiency, TEGs are arranged in a uniformly distributed pattern, ensuring balanced heat flux density and avoiding local overheating that could affect power generation performance. This enables the direct conversion of waste heat into electricity via the Seebeck effect without compromising the original cooling performance, thereby achieving energy recycling. This solution retains the high efficiency of traditional air cooling while enhancing the system's energy recovery capability, making it especially suitable for PCs and other scenarios with stringent thermal and energy efficiency requirements.

This device uses the TEG 1-127-2.0-6 model thermoelectric module, whose structure is shown in Figure 2, which is based on the Seebeck effect. It is composed of high-strength fragmented thermoelectric materials, high thermal conductivity and high-insulation Direct Bonded Copper ceramic substrates, and high-temperature solder. A single TEG module can achieve a power output of 4W when the temperature difference between the hot and cold sides reaches 170°C.

Regarding system architecture, this solution employs a "thermal parallel, electrical series" configuration for the TEG modules. Multiple thermoelectric semiconductor units are placed in parallel between the CPU/GPU thermal module's hot end (copper interface) and cold end (fan interface) to ensure efficient thermal conduction. These units are electrically connected in series to increase output voltage. The final experimental device is photographed as shown in Figure 3.

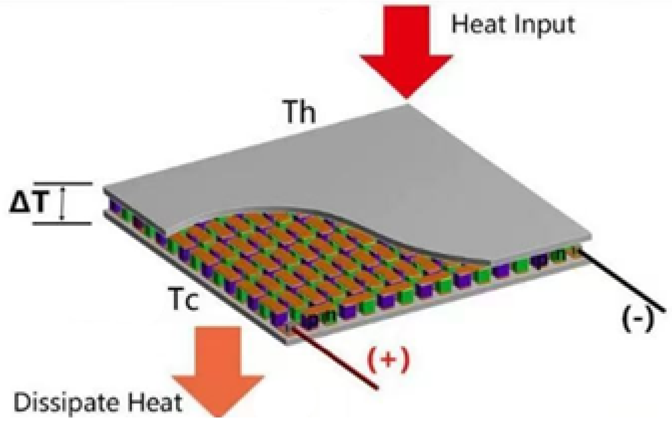

Figure 2: Operating principle of thermoelectric sheet

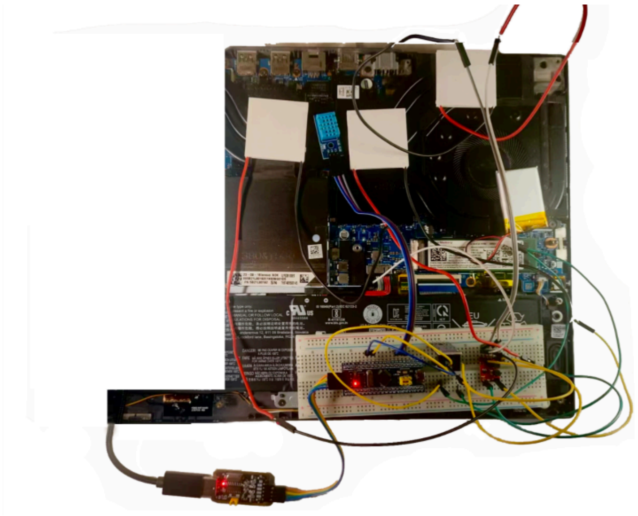

Figure 3: Experimental device

3. Theoretical design calculation

3.1. Theoretical design calculations for the power generation unit

The device utilizes the Seebeck effect to generate electricity. The essence of the Seebeck effect lies in the directional diffusion of charge carriers driven by a temperature gradient. When a material experiences a temperature difference between its two ends, the Fermi distribution of high-energy electrons at the hot end broadens, granting them higher average kinetic energy and longer mean free paths, which makes them more likely to diffuse toward the cold end. Additionally, in semiconductors, carrier concentration varies significantly with temperature, forming a steep density of states gradient near the Fermi level. Together, these factors produce a net charge separation and a thermoelectric voltage. The voltage magnitude is directly proportional to the temperature difference (ΔT) and the material's Seebeck coefficient (S):

$$\mathrm{V} = \mathrm{S} \cdot \Delta\mathrm{T} \tag{2}$$

The thermoelectric module used is model TEG1-127-2.0-6, with a surface area of 40×40 mm. Theoretically, under conditions where the hot side temperature is 200℃ and the cold side is 30℃, an open-circuit voltage of 7V can be achieved. With a matched load, the system can deliver 4V at 1A, resulting in an output power of 4W:

$$\mathrm{V}_{\Delta 170℃} = \mathrm{S} * \mathrm{T}_{\Delta 170℃} = 7\mathrm{V} \tag{3}$$

$$\mathrm{V}_{\Delta 60℃} = \mathrm{S} * \mathrm{T}_{\Delta 60℃} = 2.5\mathrm{V} \tag{4}$$

Based on the given parameters, the internal resistance of the TEG can be estimated at approximately 3Ω. In this system, it is assumed that under high-power operation, the average CPU/GPU temperature is 80℃, and the ambient room temperature is 20℃. Therefore, the open-circuit voltage from a single TEG module based on the Seebeck effect would be around 2.5V, and the maximum output power—based on optimal load matching—can reach 0.52W.

Using the ROG Strix SCAR 18 Plus as an example, which has an approximate heat dissipation area of 28,000 mm^2, the potential of waste heat power generation can be calculated. Assuming full utilization of this area for TEG placement, 18 TEG modules can be installed. Adopting a "thermal parallel, electrical series" architecture, the theoretical maximum power generation from waste heat can reach:

$$\mathrm{P}_{\text{total max}} = \mathrm{n} \cdot \mathrm{P} = 18 \times 0.52 = 9.36\mathrm{W} \tag{5}$$

3.2. Theoretical calculation of economic and environmental benefits

According to data from the U.S. Department of Energy, the average annual electricity consumption of a typical PC is about 600 kWh. Assuming an average operating power of 150W, which includes standby and sleep modes, this design conservatively estimates the actual working power at 100W. Thus, the annual effective operating time is:

$$\mathrm{t} = \frac{\mathrm{E}}{\mathrm{P}} = \frac{600}{0.1} = 6000h \tag{6}$$

Assuming the PC operates 6000 hours/year, and each device equipped with our generator produces 7.98 kWh/year, then at an electricity price of 0.5 CNY per kWh, the annual cost recovery per device is:

$$7.98 * 0.5 = 3.99 \tag{7}$$

From an economic perspective, due to current limitations in material performance, the power generation output remains relatively low, and short-term financial returns are modest. However, as TEG materials improve, their conversion efficiency is expected to rise, and costs will likely decrease. This suggests significant future market potential and supports global carbon reduction goals. Moreover, compared to other waste heat recovery scenarios, PC waste heat recovery is particularly suitable for daily personal use. As long as a PC is running and dissipating heat, this device can contribute to both energy conservation and economic benefits.

From a social perspective, this device can significantly reduce carbon emissions. Based on China’s current energy mix, the CO_2 emission coefficient is approximately 0.5 kg/kWh. With a previously calculated annual power generation of 7.98 kWh per PC, this corresponds to an annual reduction of approximately 3.99 kg of CO_2 emissions per unit. For just 1% of China’s 222.5 million PCs, the total annual CO_2 reduction would be 8,882 tons, which is equivalent to the carbon absorption capacity of planting over 450,000 trees, yielding considerable environmental benefits[7].

4. Conclusion

This paper, from the perspectives of energy conservation and carbon emission reduction, proposes a PC waste heat recovery system based on thermoelectric conversion. The system is designed to integrate thermoelectric modules (TEG1-127-2.0-6) between the heat source and the cooling end, this layout allows for both efficient thermal conduction and effective voltage output stacking, all while preserving the original cooling performance of the PC. Under theoretical operating conditions with a temperature differential of approximately 60 °C, each TEG module achieves a matched output power of approximately 0.52 W and an annual reduction of 3.99 kg of CO_2 emissions.

The internal environment of a PC is complex, and the output power of thermoelectric generators is influenced by multiple factors, including temperature fluctuations, the intermittent operation of heat sources, and varying cooling efficiency. As a result, the electrical output of TEGs typically exhibits low voltage, low current, and significant instability. To address these challenges, future optimization efforts can focus on the development of a dedicated voltage regulation circuit tailored to the characteristics of thermoelectric output. Additionally, the integration of a battery management system would allow for more effective energy buffering, storage, and utilization, which would stabilize the output, protect the storage components, and improve the reliability of power delivery, paving the way for broader adoption of PC-based waste heat recovery solutions.

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