Experimental research on thermoelectric application characteristics of thermobattery

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Abstract. In this work, experimental research was carried out to investigate the conversion output characteristics of thermobattery. The results showed that under the same temperature difference, the open-circuit voltage of the thermobattery showed a tendency of first increasing and then decreasing with the increase of hot end temperature. Under hot-end temperature of 95°C, the output open-circuit voltage reached the maximum. In addition, there was a maximum output point for the thermobattery. Regarding the thermobattery (TGM-287-1.4-1.5), its output power reached the maximum when the load resistance was 9Ω. This research provides a theoretical and experimental basis for the optimal design of thermoelectric power generation system.

1. Introduction
Thermoelectric power generation technology can be used to directly convert heat energy into electrical energy via the Seebeck effect (i.e., the thermoelectric effect of semiconductor materials). Since Seebeck discovered the Seebeck effect, thermoelectric power generation devices generally have no moving parts and require low maintenance. Compared with solar power generation, chemical batteries, fuel cells, it has higher power and is especially suitable for energy conversion in space or marine equipment. After the 1930s, with the development of thermoelectric materials and thermoelectric devices, thermoelectric power generation technology also gained a momentum [1]. By the 1960s, thermoelectric power generation technology has been widely studied and used in foreign countries (the United States, the former Soviet Union) in the fields of aerospace and navigation, however, the efficiency of thermoelectric power generation is low, which only 5%~7% [2-4]. In order to improve the thermoelectric conversion efficiency, thermoelectric power generation has been widely studied[5-8]. Researches on increasing conversion efficiency of thermobattery mainly focus on improving ZT values of new thermoelectric materials. For example, ZHAO et al. prepared Bi$_2$Te$_3$-Sb$_2$Te$_3$ and GeTe, AgSbTe$_2$ nanostructured materials with ZT values exceeding 1.5 through nanopowder doping [9]. The highest ZT value of the skutterudite structure thermoelectric material prepared by the Shanghai Institute of Ceramics, Chinese Academy of Sciences exceeded 1.7. Northwestern University of the United States introduced SrTe and Na doping to the PbTe material, and found that ZT value of the prepared thermoelectric material reached 2.2 [10]. The conversion efficiency of the CoSb3-based skutterudite material device developed by the Shanghai Institute of Ceramics reached 8.2%, and the conversion efficiency of medium temperature/low temperature (skutterudite/bismuth telluride) cascade device reached 10.4%[11]. In short, researches on thermobattery materials and structure have achieved ideal results, laying a good foundation for expanding the application range of thermoelectric power generation technology. However, there are few studies on the application characteristics of thermobatteries. In this
paper, the thermoelectric conversion characteristics of thermobattery are theoretically and experimentally studied under different hot-end temperatures and different temperature differences, including open-circuit voltage, output power, load characteristics, etc., thus providing theoretical and experimental basis for the application of thermobatteries.

2. Characteristic analysis of thermobattery
Thermoelectric power generation uses Seebeck effect to convert heat energy into electric energy, which structure diagram is shown in Figure 1[12].

![Figure 1. Structure diagram of thermoelectric power generation](image)

In Figure 1, when two different metal conductors (or semiconductors) A and B in a temperature difference environment are in contact with each other, if the two connectors 1 and 2 are maintained at different temperatures $T_1$ and $T_2$, that is, the temperature difference $\Delta T$ is generated. There will be a potential difference between the open-circuit positions $x$ and $y$ of conductor $A$, which can be expressed as follow:

$$V_{xy} = \alpha_{ab}(T_1 - T_2)$$

(1)

For Bi$_2$Te$_3$-based P and N type thermoelectric materials, the Seebeck coefficient fitting polynomials of the P and N type materials are shown in equations (2) and (3), respectively [13].

$$\alpha_p = (-488.41 + 4.41 \times T - 8.23 \times 10^{-3} \times T^2 + 4.03 \times 10^{-6} \times T^3) \times 10^{-6}$$

(2)

$$\alpha_n = (350.05 + 3.74 \times T + 7.61 \times 10^{-3} \times T^2 - 4.51 \times 10^{-6} \times T^3) \times 10^{-6}$$

(3)

Where, $T$ is the hot-end temperature (K). The Seebeck coefficient $\alpha_{ab}$ of Bi$_2$Te$_3$-based P and N type thermoelectric materials can be expressed as

$$\alpha_{ab} = \alpha_p - \alpha_n$$

(4)

It is related to the hot-end temperature.

According to equations (1)-(4) of thermoelectric power generation theory, the electromotive force at the output end of the thermobattery is subject to influence of the temperature difference between the hot-end and cold-end as well as the hot-end temperature, as shown in Figures 2 and 3.
Figure 2. Characteristics of electromotive force and temperature difference.

It can be seen from Figures 2 and 3 that the electromotive force at the thermobattery output end has a relation to the temperature difference between the hot and cold-end as well as the hot-end temperature. Where, the temperature difference between the hot-end and cold-end exerts a great impact on the output of thermobattery. Under the same hot-end temperature, as the temperature difference between the hot-end and cold-end increases, the output open-circuit voltage increases linearly. Under the same temperature difference between the hot-end and cold-end, the open-circuit voltage of the thermobattery shows a tendency of first increasing and then decreasing with the increase of the hot-end temperature.

The equivalent circuit of the thermoelectric generator shown in Figure 1 is equivalent to a closed circuit with series connection of voltage source and load resistance [14,15], and its equivalent circuit diagram is shown in Figure 4.

Figure 4. Equivalent circuit of thermobattery.

From Figure 4, the power $P_L$, output from the thermoelectric to the load resistance $R_L$, can be expressed as:

$$ P_L = I^2 R_L = \left( \frac{V_{xy}}{R_m + R_L} \right)^2 R_L $$

(5)

By solving the first derivative of $P_L$ against $R_L$, there is

$$ \frac{dP_L}{dR_L} = \frac{R_m - R_L}{(R_m + R_L)^3} V_{xy}^2 $$

(6)

Let $\frac{dP_L}{dR_L} = 0$, then

When $R_m = R_L$, the load $R_L$ has the maximum output power $P_{Lm}$. According to (1), (5), $P_{Lm}$ is expressed as

$$ P_{Lm} = \frac{\alpha^2 (T_1 - T_2)^2}{4R_m} $$

(7)

3. Experimental test on thermobattery output characteristics

The thermobattery is TGM-287-1.4-1.5, which has 287 pairs of PN thermoelectric arms. HER-250
heating stage is taken as the thermobattery heat source and its maximum temperature can reach 250°C. The thermobattery cold-end dissipates heat via a radiator. A multi-channel data acquisition system was used to build a test system for measurement of parameters including the cold-end and hot-end temperature, output voltage and current of the thermobattery, etc. The test system is shown in Figure 5.

Figure 5. Photo of thermobattery characteristic test system.

For the open-circuit voltage test, the thermobattery hot-end was placed on the heating stage, the thermobattery cold-end was equipped with an aluminum radiator. The hot-end and the cold-end temperatures were collected using a PT100 platinum resistance, and then converted into voltage via a temperature transmitter. After that, the temperature information was transferred to the computer for recording through the data acquisition system. When the thermobattery output terminal is open, the voltage is collected by the data acquisition system and transmitted to the computer for recording. The open-circuit voltage of the thermobattery under different temperature difference and hot-end temperature conditions is shown in Figures 6 and 7, respectively.

![Figure 6](image1.png) ![Figure 7](image2.png)

Figure 6. Characteristics of open-circuit voltage and hot-end temperature.

It can be seen from Figure 6 that under the same temperature difference, the open-circuit voltage of the thermobattery shows a tendency of first increasing and then decreasing with the increase of the hot-end temperature. When the hot-end temperature is 95°C, the output open-circuit voltage reaches the maximum. It can be seen from Figure 7 that, under the same hot-end temperature, the greater the thermobattery temperature difference is, the higher the output open-circuit voltage is. The experimental test results are consistent with the theoretical analysis results (Figures 2 and 3).

In the test of thermobattery load characteristics, the thermobattery output power changes with the load resistance hot-end temperature is 90°C, as shown in Figure 8.
Figure 8. Load power characteristics of thermobattery.

It can be seen from Figure 8 that under the same temperature difference, there is a maximum output point. For the thermobattery (TGM-287-1.4-1.5), when the load resistance is 9Ω, the output power reaches the maximum. According to the matching principle of maximum power output load, as shown in equation (7), the thermobattery internal resistance is 9Ω. In addition, as the temperature difference of the thermobattery increases, its output power will increase. The influence of temperature difference on Bessel effect is further proved.

4. Conclusions

Through the above theoretical and experimental research, it can be seen that there is a maximum output point for thermobattery. For Bi₂Te₃-based thermobattery, the open-circuit voltage increases with the increase of temperature difference, and reaches the maximum when the hot-end temperature is 95℃. The experimental results are consistent with the theoretical analysis results. Based on the thermobattery load characteristics, the internal output resistance of the thermobattery is about 9Ω. The experimental results provide a reference basis for the optimization of loading and working conditions of the thermoelectric power generation system. However, the effects of series and parallel connection on the open-circuit voltage and load characteristics of thermoelectric cells need to be further studied.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (No: 51566001), Science and Technology Department basic research joint project Yunnan province (No: 2019FH001-071) and Education department Foundation Research Project Yunnan province (No.2021J0677).

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