Study on electricity generation performance of thermoelectric device in extreme environmental conditions

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In this paper, studies were performed on the thermoelectric device to generate electricity in extreme outer-space environmental conditions. Mathematical models were established to relate the power generation and temperature difference across the cold and hot surfaces of thermoelectric device. Preliminary experiments were performed to test the practical output of a single stage TED. It was observed when the temperature difference was above one hundred centigrade, the voltaic output of the TED could reach about 5 V, which was capable of driving a small fan. However, a large temperature difference over the TED is hard to retain due to heat conduction, which would lower its electricity generation performance. As a remedy, transient thermal management may help to partially solve this problem.

INTRODUCTION

In a thermoelectric generator, heat is used to generate electricity based on the Seebeck effect. Since such devices are generally simple in structure and fabrication, they have been widely used in a series of practical situations [1]. The major applications of thermoelectric elements are to measure temperatures by thermocouples and thermopiles as heat sensors, or power generation and refrigeration. For the last two cases, efficiency of thermoelectric elements appears rather critical [2].

As is well known, TED plays a significant role in waste heat recovery, although it is still not prepared well for such practices due to insufficient studies [3]. In fact, it has long been a history for the thermoelectric generator to be used in space investigations. Due to the extreme environmental conditions in the outer space, the surface of the spacecraft exposed to the sun could have a temperature higher than 300 K, while the temperature on its other surface exposed to a vacuum space with extremely low temperature around 4 K may be rather low. Making full use of this totally free and huge temperature difference to generate electricity has been a great desire for space vehicle, satellite communication system, space station and other outer space activities. But up to now, little information was reported for such efforts. To better understand the electricity generation performance of the TED in space application, theoretical models were established to estimate the thermoelectric generator's efficiency and simulation experiments were conducted to test the output of a practical device.

THEORETICAL ANALYSIS

Theoretical model for single-layer thermoelectric generator

The thermoelectric generator consists of three major parts: a heat source, a heat sink and a thermopile. It is from the temperature gradient over the thermopile that electric current is generated and provided to the whole system. Here, the thermopile serves to convert the heat to electricity.

When the heat from the heat source is converted to electricity, it also generates Joule heating inside the thermoelectric materials. At the heat sink, some of the electricity changes back to heat. As shown in Figure 1, the energy circle consists of heat absorption, heat release, heat transfer and heat-to-electricity conversion [3]. Depending on the Peltier and Seebeck effect of thermoelectric element [4,5], one can obtain the transferred heat at the two surfaces of the generator, respectively as

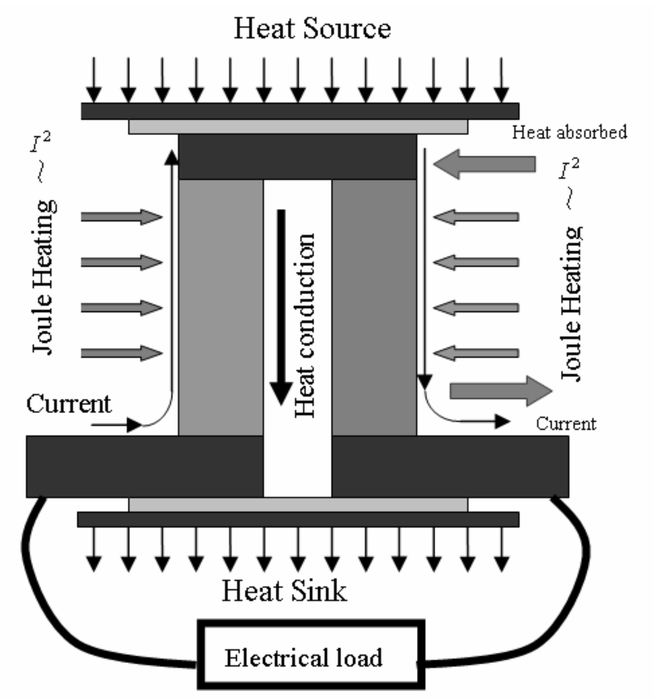

Figure 1 Energy circle in a thermoelectric generator [3]

$$Q_H = \alpha I T_H - \frac{1}{2} I^2 R + K \Delta T_{HC} \tag{1}$$

$$Q_C = \alpha I T_C + \frac{1}{2} I^2 R + K \Delta T_{HC} \tag{2}$$

where, subscript H stands for the upper surface exposed to the sun, C stands for the rear surface exposed to the space; I is electric current, α the Seebeck coefficient, R the resistance, K the thermal conductivity and T the temperature. Further, the temperature difference writes as $\Delta T_{HC} = T_H - T_C$. In the outer space vacuum, the convective heat can be neglected.

If defining $j = \frac{\alpha I}{K}, q_h = \frac{Q_H}{K T_H}, q_C = \frac{Q_C}{K T_C}, \theta_H = \frac{T_H}{T_C}$, Eqs. (1) and (2) are transformed as a dimensionless form [5], i.e.

$$q_H = j - \frac{1}{2ZT_H} j^2 + 1 - \frac{1}{\theta_H} \tag{3}$$

$$q_C = j + \frac{1}{2ZT_C} j^2 - 1 + \theta_H \tag{4}$$

where, Z=α^2 / RK is the Figure of Merit.

When the thermoelectric element works at its normal temperature, ZT_c is generally close to 1. Therefore, one can derive the electricity generation efficiency as

$$\eta_{Max} = j \cdot \frac{(\theta_H - 1) - 2ZT_C \frac{\theta_H - 1}{\theta_H + 1} \cdot (-1 + \sqrt{\frac{\theta_H + 1}{2ZT_C}} - 1) \cdot j}{2\theta_H \frac{\theta_H - 1}{\theta_H + 1} \cdot (-1 + \sqrt{\frac{\theta_H + 1}{2ZT_C}} - 1) \cdot j - 2ZT_C (\frac{\theta_H - 1}{\theta_H + 1})^2 \cdot (-1 + \sqrt{\frac{\theta_H + 1}{2ZT_C}} - 1)^2 \cdot j^2 + (\theta_H - 1)} \tag{5}$$

If using Bi_2Te_3 as the arms of the thermoelectric element, the typical parameters are applied as $\alpha = 170 \mu V \cdot K^{-1}$, $K = 2W \cdot m^{-1} K^{-1}$, and $I = 2 \times 10^2 A \cdot m^{-1}$. For the two cases of $\theta_H = 4$ and $\theta_H = 2$, η_{Max} is predicted as 1.16% and 0.85%, respectively. Both results indicate that the electric generation efficiency for the thermoelectric generator is around 1%.

It should be pointed out that the above calculation is still a rough estimation, because the parameter ZT_c may not be exactly 1, and the arms of thermoelectric material could have many other choices. However, it looks from the calculation that the efficiency of a thermoelectric generator is low. The advantage for the application of thermoelectric generator in outer space is that the solar energy there is totally free and durable, and the temperature difference induced can be high sometimes. To improve the efficiency, a multiple-layer thermoelectric generator can possibly be adopted.

Theoretical model for double-layer thermoelectric generator

When the temperature difference is very large, the single-layer thermoelectric generator only has a low efficiency and will hardly meet the need in power generation. So the double-layer or even multiple-layer thermoelectric generators are often proposed to improve the efficiency [6].

Here a double-layer thermoelectric generator is particularly analyzed for illustration purpose. This device has an upper layer and a bottom layer. Both of them have n pairs of thermoelectric elements. Similar to the analysis of the single-layer device, one gets:

$$q_H = nj - \frac{n}{2ZT_H} j^2 + n - \frac{1}{2}\left(\frac{1}{ZT_H} j^2 + 1 + \frac{1}{\theta_H}\right) \quad (6)$$

$$q_C = nj + \frac{n}{2ZT_C} j^2 - n + \frac{1}{2}\left(\frac{1}{ZT_C} j^2 + 1 + \theta_H\right) \quad (7)$$

$$\eta = 1 - \frac{Q_C}{Q_H} = 1 - \frac{q_C}{\theta_H q_H} = 1 - \frac{nj + \frac{n}{2ZT_C} j^2 - n + \frac{1}{2}\left(\frac{1}{ZT_C} j^2 + 1 + \theta_H\right)}{\theta_H \left(nj - \frac{n}{2ZT_C} j^2 + n - \frac{1}{2}\left(\frac{1}{ZT_C} j^2 + 1 + \theta_H\right)\right)} \quad (8)$$

In the spacecraft or shuttle, the temperature inside is generally 300K, while the outside surface temperature is below 100K. The actual temperature difference depends on whether the surface is exposed to the sun or not. It also relies on the distance between the spacecraft and the earth. With the theoretical model, it is possible to estimate the efficiency under various environmental conditions.

EXPERIMENTS AND DISCUSSIONS

To simulate the extreme environmental conditions and to test the out-put of a practical generator, a copper block pre-cooled by liquid nitrogen or ice-water mixture was adopted as the cooling medium. Meanwhile, heating was applied by an electric heater with power of 80W. The experimental setup is schematically shown in Figure 2. Agilent 34970A (USA) was used as the data acquisition system. Three essential parameters were recorded: the temperatures at both the cold and the hot sides and the voltaic output of the thermoelectric element. The applied exterior load was about 20 ohm. Further, a switch on-off resistor with 1 ohm was introduced to measure the resistance of thermoelectric element. When switching on or off this resistor, a change on the voltaic output is observed. From its variation the inner resistance of the thermoelectric element could be calculated. In this study, two cases were considered: (1) The cold side of the generator was cooled by a pre-cooled copper plate, while the hot side was placed at the room temperature. The test result is shown in Figure 3; (2) The cold side was cooled by the ice-water mixture, while the hot side was heated by an electric heater. The test result is given in Figure 4.

From the data in Figure 3, it was noticed that cooling of the thermoelectric generator was initiated at the time of 100s and a voltaic output was induced. Clearly, the voltaic output was proportional to the temperature difference between the hot and cold sides of the generator. The temperature at the cold side dropped quickly due to contact cooling and the voltaic output then increased gradually due to growth of the temperature difference. At 160s, the temperature difference approached its maximum value of 75°C and the voltaic output becomes 2.8 V. However, such huge temperature difference will not be retained due to heat conduction inside the generator. After 160s, it was noticed that the temperature difference slowly decreased, while the voltaic output also dropped at the same time. At time of 300s, the thermoelectric generator was turned off and a quickly disappearing voltaic output was observed.

From the data in Figure 4, it was seen that there were several voltaic output jumps because of the switch-on or off of the 1 ohm resistor. From the voltaic output variation, the inner resistance of the thermoelectric element was calculated as 2.94 ohm.

CONCLUSIONS

The aim of the present experiment is to simulate the extreme environmental conditions of outer space where the thermoelectric generator is especially useful. The efficiency measured in the present experiment is corresponding to the theoretical prediction. Further, the theoretical model established in this paper can be used to predict the working efficiency of TED in extreme environment. Clearly, liquid helium with much lower temperature can be used to produce a much huge temperature difference and thus test the electricity generation behaviors. The present study warrants further investigations along this direction.

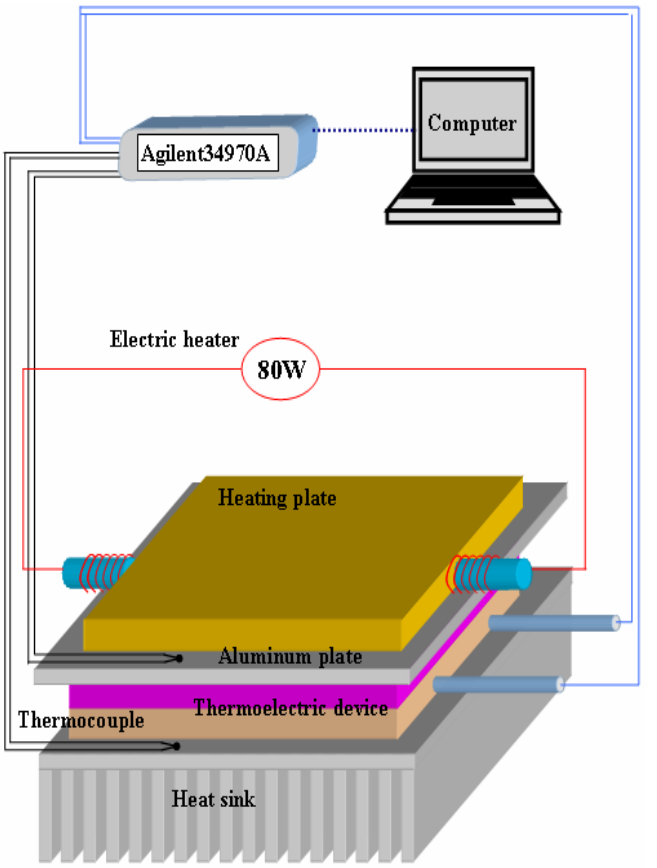

Figure 2 Schematics of the experimental setup

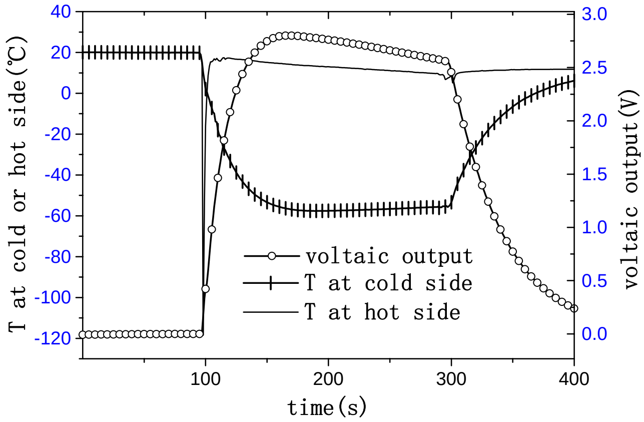

Figure 3 Temperature and voltaic output for case (1)

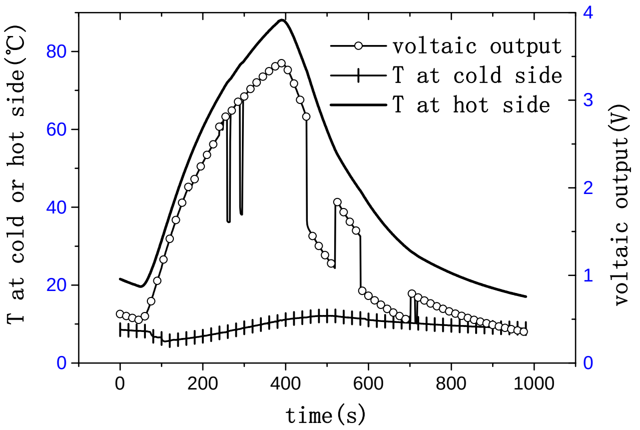

Figure 4 Temperature and voltaic output for case (2)

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