A T-shaped, plate-type thermoelectric power generator for realizing the higher power density at a small temperature difference

H. Tohmyoh, T. Daimon, N. Ohgi
Department of Finemechanics, Tohoku University, Aoba 6-6-01, Aramaki, Aoba-ku, Sendai 980-8579, Japan
E-mail: tohmyoh@ism.mech.tohoku.ac.jp

Abstract. We report the performance of a T-shaped, plate-type thermoelectric power generator (TPG). The plate-type TPG has been proposed by the authors. A new design of the plate-type TPG realized the higher power density together with the higher power at a small temperature difference. For example, the maximum power of the T-shaped, plate-type TPG was 11.1 W m\(^{-3}\) at the temperature difference of 40 K, and this value was over 2 times greater than that of the previous TPG.

1. Introduction
Among the power generation technologies utilizing the renewable energy resources, such as wind, solar, vibration, etc., thermoelectric power generation has been attracted considerable attentions recently because our daily lives are full of waste heat. Seebeck effect is a phenomenon, which convert heat into electricity, can be explained simply by considering an electrical circuit comprising bi-metal wires. If there is a temperature gradient \(\Delta T\) between two bi-metal junctions, a thermoelectromotive force, \(\Delta V\), appears in the circuit and this is given by \(\Delta V = S \Delta T\), where \(S = (\alpha_1 - \alpha_2)\) is the Seebeck coefficient of the circuit, and \(\alpha_1\) and \(\alpha_2\) are the absolute thermoelectric powers of each wire metal.

Although the thermoelectric power generators (TPGs) composed of Bi, Te or its related alloys realize greater \(\Delta V\) [1, 2], such rare metals are the limited resources. Moreover, TPGs composed of Bi, Te or its related alloys have relatively higher internal resistance, which increases the power consumed in the circuit. To realize the efficient power generation from a small \(\Delta T\) without using such rare metals, a plate-type TPG, which is composed of an Fe plate and an Al layer, has been proposed by the authors [3].

In this paper, a T-shaped, plate-type TPG, which was also composed of Fe and Al, was designed for realizing the higher power density at a small temperature differences. The volume of the T-shaped TPG was 1/4 compared with the previous one, and the power densities of the T-shaped TPG measured at the temperature difference of 20 to 60 K were over 2 time greater than that of the previous one.

2. Plate-type thermoelectric power generator
Figure 1(a) shows the photograph and the cross section of the plate-type TPG [3]. The TPG is composed of the Fe plate of 0.1 mm thick, and the Al layer, and the interface between Fe and Al is electrically isolated with the SiO\(_2\) layer expect the part of the bi-metal interface. Because among the common metals, the absolute thermoelectric power of Fe (+16.2 \(\times\) 10\(^{-6}\) V K\(^{-1}\)) is greater than that of Al (\(-1.66 \times 10^{-6}\) V K\(^{-1}\)), we selected this materials combination [4]. The size of the TPG was 20 \(\times\) 30 mm\(^2\). In case that the
Figure 1. Plate-type thermoelectric power generator (TPG). (a) Schematic of the cross section and overviews. (b) An example of the temperature distribution on the TPG as obtained by an infrared camera. \( \Delta T = T_H - T_L \) in this case was 40 K. (c) The relationships between \( \Delta V \) and \( \Delta T \) for two types of TPGs with and without oxidation. Reprinted with permission from ref. (3). Copyright (2016) Elsevier.

The temperature of the bi-metal side, \( T_H \), becomes larger than that of another side, \( T_L \). \( \Delta V \) appears in the TPG due to the temperature gradient \( \Delta T = T_H - T_L \). An example of the temperature distribution on the TPG, which was measured by an infrared camera, is shown in Fig. 1(b). The heating area was 10 \( \times \) 5 mm\(^2\), and the value of \( \Delta T \) in this case was 40 K.

The relationships between \( \Delta V \) and \( \Delta T \) for two types of TPGs are shown in Fig. 1(c). The surface of the Fe plate of one TPG was oxidized before depositing the Al layer. The value of \( \Delta V \) of the TPG with oxidized bi-metal interface was greater than that of the TPG without oxidation, and oxidizing the bi-metal interface was found to be effective to enhance \( \Delta V \).

3. T-shaped, plate-type thermoelectric power generator

The design of the T-shaped, plate-type TPG proposed in this study is shown in Fig. 2(a) together with that of the previous TPG. Although the size of the bi-metal interface (20 \( \times \) 5 mm\(^2\)) was unchanged, the length of the TPG was decreased to 1/2. The cross-sectional structure of the T-shaped TPG was same as that of the previous TPG, see Fig. 1(a). In the results, the volume of the T-shaped TPG was decreased to 1/4 compared with the previous one.

Fabrication process of the T-shaped TPG is as follows. The thickness of the used Fe plate was 0.1 mm. Because oxidizing the bi-metal interface was found to be effective to enhance the thermoelectric power generation efficiency, the surface of the Fe plate was initially oxidized at 873 K for 3 h. After that, a part of the oxidized Fe plate was covered with a resist mask, and a tetraethyl orthosilicate (TEOS) layer was formed on the Fe plate for electrical insulation. After removing the resist mask, an Al layer was deposited, and the bi-metal interface was created between the oxidized Fe and Al. The thickness of the Al layer was about 5 \( \mu \)m.

Conductive wires were attached on both surfaces of the Fe plate and the Al layer using conductive tape, and the wires were connected to a voltmeter. A part of the surface of the T-shaped TPG was heated with a ceramic heater, and \( \Delta V \) was measured for this open circuit. The heating area was 10 \( \times \) 5 mm\(^2\), and this was same as that of the previous experiment shown in Fig. 1(c).
Figure 2. T-shaped, plate-type thermoelectric power generator (a) Schematic. (b) The relationship between $\Delta V$ and $\Delta T$.

Figure 3. Experiment to confirm the power generation performed for the closed circuit. (a) The $I - V$ characteristics measured at $\Delta T = 0$ to 60 K. (b) $P$ against $V$ at $\Delta T = 20$ to 60 K. Here the values of $P$ were determined from the $I - V$ characteristics in (a).

The relationship between $\Delta V$ and $\Delta T$ is shown in Fig. 2(b). The value of $\Delta V$ was measured for 10 seconds for each condition after the temperature of the hater reached the set value, and the average values of $\Delta V$ are plotted in Fig 2(b). $\Delta V$ increased linearly against $\Delta T$, and Seebeck effect was clearly observed for the T-shaped TPG fabricated. From the slope of the $\Delta V - \Delta T$ relation, the value of the Seebeck coefficient, $S$, was found to be $8.2 \times 10^{-6}$ V K$^{-1}$, and this was very close to that of the previous one ($8.1 \times 10^{-6}$ V K$^{-1}$). The results suggest that $\Delta T$ induced in the TPG was maintained although the length of TPG was reduced to $1/2$.

4. Power generation characteristics

To evaluate the power generation characteristics, the current-voltage ($I - V$) characteristics for $\Delta T = 0$ to 60 K were measured. Conductive wires attached on the surfaces of the T-shaped TPG were connected to a source measure unit, and $I$ flowing in the closed circuit was measured under applying $V$. $\Delta T$ in the TPG was induced by a ceramic heater similarly to the experiment for open circuit.

The current ($I$) – voltage ($V$) characteristics measured in the closed circuit at $\Delta T = 0$ to 60 K are shown in Fig. 3(a). The slopes of the $I - V$ characteristics for all values of $\Delta T$ are almost constant, and this indicates that the internal resistance of the T-shaped TPG was unchanged in the examined temperature range. The internal resistance of the T-shaped TPG was determined to be 0.158 $\Omega$. Although the internal resistance was 28 % larger than that of the previous one (0.123 $\Omega$), this value was relatively lower compared with the reported TPGs [1, 2]. Figure 3(b) shows the power curves determined from the $I - V$ characteristics, and the power $P$ was determined by $VI$. For all $\Delta T$, $P$ takes its maximum values, $P_{\text{max}}$. The values of $P_{\text{max}}$ are summarized in Table 1 together with those of the previous TPG. The values
Table 1. Performance of the T-shaped, plate-type thermoelectric power generator.

| TPG       | volume (m³) | $S$ (µV K$^{-1}$) | $R$ (Ω) | $P_{\text{max}}$ (µW) | $\Delta T$ (K) |
|-----------|-------------|-------------------|--------|------------------------|----------------|
| Previous  | $6.0 \times 10^{-8}$ | 8.1               | 0.123  | 0.071                  | 20             |
| T-shaped  | $1.5 \times 10^{-8}$ | 8.2               | 0.158  | 0.037                  | 40             |
|           |             |                   |        | 0.167                  | 60             |

Figure 4. Power density ($= P_{\text{max}} / \text{volume}$) against $\Delta T$.

of $P_{\text{max}}$ of the T-shaped TPG were decreased to $1/2$ compared with those of the previous one. The main cause of this decreases might be the increase in the internal resistance of the TPG.

Figure 4 shows the values of power density, which is determined by $P_{\text{max}} / \text{volume}$, against $\Delta T$. Although the values of $P_{\text{max}}$ became about $1/2$ of the previous TPG for all the values of $\Delta T$, the values of power density became over 2 times greater than that of the previous one. For example, at $\Delta T = 40$ K, the power density per unit temperature difference is determined to be $0.27$ W m$^{-3}$ K$^{-1}$, and this value is much greater than those of the previously reported TPGs without composed of Bi, Te or its related alloys [5, 6].

5. Conclusions
In this paper, a T-shaped, plate-type thermoelectric power generator (TPG), which is composed of the Fe plate and the Al layer, was reported for power generation form a small temperature difference. Although the volume of the T-shaped TPG became $1/4$ compared with the previous TPG, the thermoelectromotive forces generated due to the temperature gradient in both generators were same. Moreover, the power density of the T-shaped TPG, which was determined from the current-voltage characteristics measured at the temperature difference of 0 to 60 K, became over 2 times greater than that of the previous TPG.

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