An experimental investigation of a thermoelectric power generation system with different cold-side heat dissipation

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Abstract. Thermoelectric generation technology has attracted increasing attention because of its promising applications. In this work, the heat transfer characteristics and the performance of a thermoelectric generator (TEG) with different cold-side heat dissipation intensity has been studied. By fixing the hot-side temperature of TEG, the effects of various external conditions including the flow rate and the inlet temperature of the cooling water flowing through the cold-sided heat sink have been investigated detailedly. It was showed that the output power and the efficiency of TEG increased with temperature different enlarged, whereas the efficiency of TEG reduced with flow rate increased. It is proposed that more heat taken by the cooling water is attributed to the efficiency decrease when the flow rate of the cooling water is increased. This study would provide fundamental understanding for the design of more refined thermoelectric generation systems.

1. Introduction

Thermoelectric generators (TEGs) are solid state devices that use the Seebeck effect to convert heat (driven by a temperature difference) directly into electrical energy [1-3]. The basic structures of TEGs are formed by p- and n-type semiconductor thermoelements (TEs). TEs are connected electrically in a serial manner to increase the output voltage of the TEG and connected thermally in parallel to decrease the thermal resistance of the TEG [4]. Compared to the conventional generator, thermoelectric devices (TEDs) have numerous advantages such as low-grade thermal energy source required, environmental friendly, longer lifetime, high reliability, compactness and robustness [5-7]. Generally, a thermoelectric generation system mainly includes a heat source, a cooler, heat exchanger and thermoelectric device that are thermally and electrically combined together as a whole. The design of a good thermoelectric generation system involves integrate consideration of the structure, heat source, type of thermoelectric device, installation, etc. [8]

Over the past 30 years, there has been growing interest in applying TE technology to improve the efficiency of waste heat recovery, using various heat sources such as automotive exhaust systems [9, 10], cooling systems [11], solar thermal systems [12], domestic water heaters [13, 14]. Gou et al [15] investigated the viability and performance of the TEG for low-temperature waste heat recovery in industry area and showed a promising potential of using TEG in industrial fields. Lu et al. [16] studied two types of heat enhancement processes for exhaust heat exchanger on the performance of TEG. The result showed there was an optimal fin transverse spacing or fin thickness at the operating conditions
for rectangular offset-strip fin and metal foam with low porosity which made the TEG got maximum net power output. Hasani et al. [17] experimentally inspected that thermolectric cooler as a power generator applied in waste heat recovery from a Proton Exchange Membrane (PEM) fuel cell and proved a suitable solution for recovering waste heat from a PEM fuel cell.

However, low conversion efficiency and power density are crucial factors restricting the development of TEGs. Numerous studies have been conducted on improving the conversion efficiency of TEGs [9, 18-20]. Liu et al [21] studied the influences of the hot and cold side temperature, flow rates and the load resistance on the power output and voltage of TEG. Through adjusting the flow rates, the maximum power output was 183.24W with copper heat exchanger and engine revolution of 3200 r/min. Chen et al.[22] theoretically built a model of a two-stage TEG structure and conducted the performance of the model on the output power and thermal efficiency by different working electric-current. Casano and Piva [23] built an experimental rig to evaluate the characteristic of the thermoelectric modules . They presented the power output and the conversion efficiency of the thermoelectric modules under different load resistances. Researchers have proposed a number of TEG systems with different features, structures and properties to improve the output power and conversion efficiency. For a commercial TEG system, the physical properties such as Seebeck coefficient and thermal conductivity were always taken as constant to consider the external heat exchanger performance affecting the performance of a TEG. In this study, the output power and conversion efficiency of TEGs at various external parameters, such as cooling water flow rate and temperature of copper heat sink to change the cold-side temperature of TEG, were conducted by self-designed devices. The results of the experiments could provide a fundamental understanding for the optimization of more refined thermoelectric generation systems.

2. Experimentation
A schematic diagram of the experimental apparatus used in the present work was shown in figure1. The main components of the experimental apparatus include a peristaltic pump (Masterflex L/S, 77202-50), thermostatic bath (NingBo Scientz Biotechnology co., LTD, DCW-2008), copper heat sink (shown in figure 2(d)), thermolectric device (shown in figure 2(b and c)), heating plate (IKA, C-MAG-HP4) and liquid cabin.

In the thermostatic bath, the working medium, water, was guided through the copper tube with a radius of 2.4mm and total length of 3.50m. Three K-type thermocouples (Omega, KMTXL-040G-6) were used to test the initial temperature ($T_1$), terminal temperature ($T_2$) of the flowing water and water bath temperature ($T_w$), respectively. The liquid cabin with 1000ml accommodate of water was properly insulated for reducing heat transfer to the environment. Bi$_2$Te$_3$-based thermolectric device (TEDs) were supplied by Shanghai Institute of Ceramics, Chinese Academy of Sciences. The appearance and specifications of the TEDs are shown in figure 2(b), figure 2(c) and table 1, respectively. One side of the TED was attached to the heating plate and the other side was attached to copper heat sink in vertical orientation. The temperature of the heating plate was fixed at 100°C in the present work. The peristaltic pump with a maximum capacity of 1000 ml/min was employed to accurately control the flow of water through the copper heat sink. The pipe connecting the various components was platinum-cured silicone tubing (Masterflex, 96410) with internal diameter of 0.48cm.

The thermocouples (omega, K-type, KMTXL-040G-6) were fixed at appropriate points as shown in figure1. The thermocouples were connected to a data acquisition device (34970A, Agilent), which was connected to a computer to measure and record the detailed data (open circuit voltage, temperature) for further processing.

The resolutions of flow meter, voltage measurements, and thermocouple were 0.01L•min$^{-1}$, 1.25mV, and 0.1°C, respectively. The uncertainty of the experiments was smaller than 6% from references [7, 24] so that the experiments in the current study are reliable. Moreover, each case has been repeated twice at least and the data of experiments has been ensured.
Figure 1. Schematic of the experimental test setup

Figure 2. Photographs: (a) K-type thermocouples; (b) and (c) thermoelectric device; (d) copper heat sink

Table 1. Specifications of the thermoelectric device

| Specifications                      | Value         |
|-------------------------------------|---------------|
| Type of material                    | Bi$_2$Te$_3$  |
| Maximum current (A)                 | 7             |
| Maximum voltage (V)                 | 3.5           |
| Maximum power (W)                   | 7.6           |
| $T_{\text{max}}$ (°C)               | 270           |
| Dimensions(L×W×H) (mm$^3$)         | 50*50*3.5     |
| Number of couples                   | 49            |

3. Methodology

3.1. Thermostatic bath
The role of thermostatic bath was to adjust the fluid temperature of copper cube via heat dissipation. In the system, the thermostatic bath ensured the terminal temperature ($T_2$) (seen from figure 3) of the flowing water close to the set temperature of water bath ($T_w$) and made the fluid entering into the heat sink at the designed experimental temperature.

Figure 3. Schematic of fluid through thermostatic bath
Figure 4. Distributions of $T_1$, $T_2$, and $T_w$ with the thermostatic bath temperature set at 10 °C

3.2. Copper heat sink
Deionized water was used as coolant in this study. The inlet temperature ($T_{in}$) and outlet temperature ($T_{out}$) of the heat sink were measured by two thermocouples, the average temperature and the heat taken away by water was calculated by the following expressions.

$$T_C \approx T_{average} = \frac{T_{in} + T_{out}}{2} \quad (1)$$

$$Q_w = M \times C_p \times (T_{out} - T_{in}) \quad (2)$$

where $M$ is mass flow rate, $C_p$ is the fluid (water) heat capacity, $T_{in}$ and $T_{out}$ are the inlet temperature and the outlet temperature, respectively, as showed in Figure2 (d).

3.3. Thermoelectric generator
The temperature difference between the hot and cold sides is got as the following.

$$\Delta T = T_H - T_C \quad (3)$$

where $T_H$ and $T_C$ are the hot-side temperature and the cold-side temperature of TEG, respectively. The output power (W) can be calculated as

$$P_{out} = \frac{U^2}{4R} \quad (4)$$

where $U$ is the output voltage (V) which is measured from the electronic load, $R$ is the internal resistance of the TEG and is measured to be 0.254Ω.

The efficiency of the thermoelectric generation power is calculated by

$$\phi = \frac{P_{out}}{P_{out} + Q_w} \times 100\% \quad (5)$$

4. Results and discussion
4.1. Thermostatic bath
Figures 4-6 show the distributions of $T_1$, $T_2$, and $T_w$ at different flow rate with the thermostatic bath temperature set at 10, 20, and 30 °C, respectively. It can be seen that there is an obvious change from initial to terminal temperature of the fluid at low flow rates and the difference between $T_1$ and $T_2$ becomes smaller with the flow rate increased. The terminal temperature ($T_2$) was close to the designed water bath temperature ($T_w$) which made the fluid entering into the heat sink at the designed experimental temperature.
4.2. Copper heat sink

To test the influence of cold-side heat dissipation on the performance of TEG, cooling water with different initial temperature (from the thermostatic bath) was flow through the copper heat sink at different flow rate. Figure 7 presents the temperature difference of outlet and inlet of the heat sink at different flow rate and thermostatic bath temperature. It can be seen from figure 7 that temperature difference of outlet and inlet of heat sink reduced rapidly at the lower flow rate (≤100ml/min). This means that water can effectively transfer heat from the cold side of TEG. When the flow rate was over 100ml/min, the temperature difference only changed slightly with the flow rate increase. It indicates that further increasing flow rate would not have obvious effect on reducing the average temperature of the cold side of TEG when the flow rate was over 100ml/min. That is to say, the output power will not improve obviously by increasing flow rate when the flow rate was over 100ml/min. Further discussion will be presented in the following part. When the flow rate of cooling water is increased, more pump power would be consumed. Also, the cooling water may take away more heat from the cold side of the TEDs. Therefore, increasing the flow rate of the cooling water is not always helpful to the TEG system, especially at high flow rates.

Figure 7. Temperature difference of the outlet and inlet of the heat sink at different flow rate and thermostatic bath temperature

Figure 8. Variation of the heat flow of the cold side of the TED with the flow rate

Figure 8 shows the variation of the heat flow taken away by the cooling water at different flow rate and different temperature conditions of thermostatic bath. From Eq.(2), it can be seen that the heat flow is related to the flow rate, water specific heat capacity and the temperature difference of outlet
and inlet of the heat sink. Although the temperature difference from Figure 7 was reduced, the heat flow was enhanced with flow rate increased (seen in Figure 8). This means that the effect of the flow rate and fluid special heat capacity surpasses that of the temperature difference under high flow rate. More heat is taken from the cold side of the TEDs. That is, when the hot-side temperature of TEG is fixed, the heat taken away by heat sink mainly depends on flow rate and fluid self-characteristic.

Figure 9 presents the temperature difference between the hot- and cold-side of the TED. It is seen that the temperature difference rises rapidly when the designed thermostatic bath temperature is lower than the room temperature (25 °C), but reduces slightly when the designed thermostatic bath temperature is over room temperature at relatively low flow rate (≤100 ml/min). When the flow rate is higher than 100 ml/min, the temperature difference has only slight change when the flow rate is further increased.

**Figure 9.** Temperature difference between the hot and cold sides of the TED at different flow rates

**Figure 10.** Distribution of the output power of the TEG system at different flow rate

4.3. Thermoelectric generator

The influence of temperature difference and flow rate on the performance of TEG is shown in figure 10. The cold-side temperature was varied while the hot-side temperature of TEG was fixed at 100 °C in this study. The temperature difference between the hot-side and cold-side of the TED is shown in figure 9. It can be seen that the temperature difference has a great effect on the output power. When the flow rate was 0 (namely natural convection cooling), the output power was 0.08152W, 0.07102W and 0.07069W when the thermostatic bath was set at 10 °C, 20 °C and 30 °C, respectively. When the cooling water flow rate was 20 ml/min, the output power was 0.27669V, 0.26267V and 0.24078V when the thermostatic bath was set at 10 °C, 20 °C and 30 °C, which was increased by about 239%, 270% and 241% compared to natural convection cooling, respectively. Cold side heat dissipation has significant effect on the output power of the TEG system.

At the condition of the same inlet temperature of the cold side heat sink and fixed temperature of the hot-side heat sink, more heat would be taken away by the cooling water when the flow rate is increased. The average temperature of the cold-side will be decreased. The open circuit voltage and the output power will be increased. Practically, when the flow rate was lower than 100 ml/min, the temperature difference could not reach the ideal temperature difference (the temperature difference between the hot side and the set thermostatic temperature), as showed in figure 9. The output power could be increased obviously when the flow rate of the cooling water was increased. However, from figure 10, it can be observed that the output power was not change accordingly to the temperature difference shown in figure 9. When flow rate was greater than 100 ml/min, the effect of flow rate increase was not so significant. Similar behavior has been reported in the theoretical and practical results of Esarte et al. [7, 25] and Chen et al. [7, 25].
Figure 11. Conversion efficiency of the TEG system at different flow rate

Based on the heat flow taken away by the cooling water (figure 8) and the output power (figure 10), the conversion efficiency of the TEG system can be obtained by using Eq. (5). Figure 11 shows the variation of the conversion efficiency at different flow rate and different temperature conditions of the thermostatic bath. The conversion efficiency of the TEG system was enhanced with temperature difference increased and reduced with flow rate increased for the same thermostatic bath temperature when the hot-side temperature fixed. As expressed in Eq. (5), the efficiency of the TEG system was inversely proportional to $Q_w/P_{out}$. With increasing the flow rate, the output power increased slightly. At the same time, more heat was taken away from the cold side. Therefore, the conversion efficiency would not be raised with increasing flow rate accordingly. However, in spite of the efficiency of the TEG is not increased with the flow rate of the cooling water, it is desirable to enhance the capacity of the cold side cooling. Because many types of the heat sources for the TEG systems, e.g. the waste heat such as automobile exhaust heat and solar heat are continuous. If the heat is not used or recovered, it will be lost totally. Therefore, more power generation is utmost consideration and the optimal efficiency is not always required.

5. Conclusions

The paper presented the experimental results of the performance of a model thermoelectric generator for heat recovery and power generation at various external parameters. Water as flowing fluid could absorb and release heat to adjust the whole system temperature. The primary conclusions from this study are summarized as follows.

1) The thermostatic bath was employed to adjust the cold-side temperature of the TEG by controlling the set temperature. It was found that the terminal temperature ($T_2$) of the copper cube was close to the set water bath temperature ($T_w$), making the cooling water to enter into the cold-side heat sink with the designed temperature.

2) For the cold-side heat sink, although more heat ($Q$) was taken away by the cooling water with flow rate increased, the temperature difference ($\Delta T$) between hot-side and cold-side of TEG was not always increased. When the flow rate was over 100ml/min, $\Delta T$ only changed slightly because the heat transfer capacity could overpass the heat transfer capacity from the hot side to cold side.

3) For the TEG, the temperature difference was the most important factor for the output voltage and the power. Although the efficiency of the TEG was enhanced with the temperature difference between the hot and cold sides increased when the hot-side temperature was fixed, it was interesting that the efficiency of the TEG was reduced with the cooling water flow rate increased under the condition of the same inlet temperature. It is proposed that more heat taken by the cooling water is attributed to the efficiency decrease.
Acknowledgment
This work was supported by the Major Program of the National Natural Science Foundation of China (51590902), the National Natural Science Foundation of China (51476095), and the Program for Professor of Special Appointment (Young Eastern Scholar, QD2015052) at Shanghai Institutions of Higher learning.

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