Experimental investigation of the performance of a thermoelectric generator at various operating conditions

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Abstract. Thermoelectric generators (TEG) is the device that can directly convert heat into electricity by the Seebeck effect, which is fascinated for waste heat recovery. An experiment was setup to study the influence of heat flux through the thermoelectric module on the power output and efficiency of a commercial Bi₂Te₃-based thermoelectric modules. The experimental result indicated that the power output evidently increased with the increasing heat flux through the thermoelectric module (TEM), while the conversion efficiency increased significantly at first then the tendency became mild with the increasing heat flux for a given air flow velocity and flow temperature. The temperature differences across the thermoelectric module are almost identical with various air velocity, while the power output and efficiency increased with the increase of cooling flow velocity with a fixed heat flux through the TEM. The power output and efficiency almost linearly decreased with the increase of cooling flow temperature with a fixed heat flux through the TEM and a fixed cooling flow velocity. The maximum output power can be obtained by maximization heat flux without exceeding the upper temperature limit of thermoelectric module.

1. Introduction
There are still many problems for energy utilization such as low utilization efficiency, poor economic efficiency and environmental pollution. Waste heat utilization is an important way to promote energy efficiency, increase economic efficiency and improve environment. As an intelligent energy devices, thermoelectric generators (TEGs) is a potential method for waste heat recovery, which can directly convert waste heat into electricity[1-2]. Compared to traditional power generation device, there are many advantages for thermoelectric generators (TEGs) such as few moving parts, compactness, soundless operation, maintenance free, high reliability and environmental friendly. Therefore, thermoelectric generators have received much attention in the last past decades, and was applied for harvesting waste heat from various heat source such as power plants[3], steel plants[4], geothermal heat[5], stove[6,7], and automotive[8-10] and solar energy[11, 12] into electricity.

The power generation and conversion efficiency of thermoelectric generator is mainly dependent on the temperature difference between the two faces of thermoelectric module, naturally on the thermal resistances between the thermoelectric module and heat source or heat sink. Thacher et al. [13] examined the performance of automobile exhaust thermoelectric generator and found that the output power would be increased by insulating the exhaust, improving the exhaust heat exchanger and lowering the coolant
temperature. Astrain et al. [14] reported that the efficiency of TEG system is increased by 8% when the thermal resistances of heat sinks at the dual sides of TEGs is improved 10%. Gou et al. [15] measured a thermoelectric generator system of low-temperature waste heat and indicated that the performance could be elevated by expanding surface area of heat exchanger and enhancing heat capacity of cold-side in a thermoelectric generator system. Su et al. [16] showed that the coolant flow direction has a greater effect on the performance of thermoelectric generator system than that of coolant flow rate and the arrangement of cooling device. Aranguren et al. [17] reported the thermal resistances of heat pipes at the cold side of TEG is smaller that of finned dissipaters with similar electricity consumption of fans.

Much works have done to improve thermal resistances of the heat exchanger at hot side of the thermoelectric generator system. Hsiao et al. [18] showed that TEG on the exhaust pipe have a better performance than that on the radiator in the thermoelectric system of an automobile. Yu and Zhao [19] numerically studied the thermoelectric system and showed that the power output and efficiency increased with the increase of flow rate and hot fluid temperature. Then, their numerical model was further experimentally validated by Niu et al. [20]. Weng et al. [21] found that the average power per TE couple significantly decreased by implementing more TE couples. Chen et al. [22, 23] reported that the heat source or hot side temperature of the thermoelectric generator system plays an decisive role on the power generation and conversion efficiency. Laterly, Chen et al. [24] further indicated that the temperature oscillation has a great influence on the mean power generation and efficiency, while the mean absorbed heat by the TEG has a slight effect. Li et al. [25] presented shape-adapted thermoelectric module by integrating the heat pipe to improve the heat transfer at hot side of the thermoelectric generator system, which has an effective effect on power output and conversion efficiency. Ma et al. [26] proposed longitudinal vortex generators (LVGs) with a plate-fin heat exchanger and showed that the LVGs could improve the heat transfer and power output compared to a TEG without LVGs. Li et al. [27] indicated that the performance of the thermoelectric generator can be effectively improved by filling metal foam in the core flow region. Kim et al. [28] investigated waste heat recovery on a diesel engine using a direct contact thermoelectric generator (DCTEG) and indicated that the thermoelectric efficiency can be enhanced by higher temperature differences between two sides of thermoelectric module, larger engine loads and rotation speeds.

Most previous works are focused on amplifying the temperature difference between hot and cold ends of thermoelectric module by reducing thermal resistance of heat exchangers. However, the heat flux through thermoelectric module plays a dominate role on the temperature difference across the module and the corresponding power generation and efficiency. The present work will study the influence of heat flux on the power output and efficiency of a commercial Bi$_2$Te$_3$-based modules. Other parameters such as inlet velocity and temperature of the coolant on the performance of the module will also be discussed.

2. Experimental Section

2.1. Experimental setup

The experimental system is displayed in Fig. 1, which is composed of a thermoelectric module (TEM), a heater, a heat sink, an electronic load, and a data acquisition system (Agilent 34970a). A commercial thermoelectric Bi$_2$Te$_3$-based module (Thermonamic: TEP1-12656-0.8, 56 mm×56 mm) was employed, while a heater (220V-500 W, 56 mm×56 mm×110 mm) was installed adjacent the hot side of module made of copper to adjust the heat flux across the thermoelectric module by a voltage regulator. The heater was insulated with 30 mm silica aerogel around the circumference to reduce the heat loss. A plate-fin heat sink (base size:60mm×60mm) are mounted at the top of the thermoelectric module and together with the wind tunnel, air flows through the fins to enhance the cooling of the cold side of the TEG. The temperature and flow rate was controlled by an electric heater and a frequency conversion fan, respectively. In order to reduce the contact thermal resistance, graphite based thermal grease was used between the interface of the module and heat sink or heater. The electronic load was used as an external load, and the corresponding voltage and power output were obtained. The hot and cold side temperatures
of the TEM were measured by two T-type thermocouples, which mounted at the top surface of the heater and the basement of the heat sink, respectively. The air flow temperature was also measured by a T-type thermocouple. Two multimeters (Fluke 179C) was used to measure the power of the heater, with an accuracy of 0.15% for the voltage and an accuracy of 1.0% for the current. All the temperature signals were acquired and recorded by Agilent 34970a data acquisition system.

![Figure 1. Schematic of the experimental setup.](image)

### 2.2. Parameter definitions

The heating rate of heater, the power output and the corresponding conversion efficiency of the TEG are calculated as follow:

\[
Q_H = U_H I_H \tag{1}
\]

\[
P_{\text{out}} = U_{\text{out}} I_{\text{out}} \tag{2}
\]

\[
\eta = \frac{P_{\text{out}}}{Q_H} \tag{3}
\]

Where \( Q_H \), \( U_H \), \( I_H \) is the heating power of heater, the voltage and the current of the heater, \( P_{\text{out}} \), \( U_{\text{out}} \), \( I_{\text{out}} \) is the output power, the output voltage and the electrical current, respectively. Then, the TEG conversion efficiency is given in Eq. (3).

The thermal conductivity coefficient \( k \) of TEG is defined in Eq. (4) including the heat conduction of two ceramic layers:

\[
\lambda = \frac{q\delta}{\Delta T} = \frac{Q_H \delta}{A(T_h - T_c)} \tag{4}
\]

Where \( \lambda \) and \( \delta \) is the thermal conductivity coefficient and the thickness of the thermoelectric module, \( A \) and \( q \) is the across surface of the heater and the heat flux across the TE modules which defined as \( q = \frac{Q_H}{A} \), where \( T_h \), \( T_c \) and \( \Delta T \) is the hot side temperature, cold side temperature, and the corresponding temperature difference, respectively.

### 2.3. Uncertainty analysis

An uncertainty was implemented with the combination of the elemental errors for air velocity, temperature measurement, heating power, power output, heat flux and thermal conductivity of the thermoelectric module using root-sum-squares (RSS) method[29]. The uncertainty of temperature is the combination of terminal block and thermocouple. The uncertainties of the maximum power is estimated with the combination of the measured voltage and current. The uncertainty for the size of TE module and flow channel is 0.05 mm and 1.0 mm, respectively. Hence, the uncertainty for the air flow rate is 0.5 m³/min and the uncertainty for air velocity is determined as 1.5%. Similarly, the uncertainty for heat flux and thermal conductivity were obtained based on the heating power of the heater and size of TE module. The uncertainties of measurement are tabulated in Table 1.
Table 1. Uncertainty for measured variable.

| variable | uncertainty | variable | uncertainty |
|----------|-------------|----------|-------------|
| \(T_h\)  | 2.5%        | \(\delta\) | 2.0%        |
| \(T_c\)  | 3.7%        | \(V_f\)  | 1.5%        |
| \(T_{ave}\)| 2.1%        | \(T_f\)  | 2.7%        |
| \(U_{out}\) | 0.9%        | \(U_H\)  | 1.0%        |
| \(I_{out}\) | 1.3%        | \(I_H\)  | 1.6%        |
| \(P_{out}\) | 3.3%        | \(Q_H\)  | 1.3%        |
| \(\lambda\) | 2.3%        | \(q\)    | 3.4%        |
| \(\eta\)  | 1.9%        |          |             |

3. Results and discussions
The hot and cold side temperatures of thermoelectric module (TEM), and the corresponding temperature difference between them are obtained for different flow velocities and temperatures of the cooling air, and heat fluxes through the TEM. The thermal conductivity coefficient of TEM can be obtained according to Fourier law, which are determined by the heat flux through the TEM, the thickness and the temperature difference between dual sides of the TEM. The relationship between the thermal conductivity of TEM and the mean temperature is shown in Fig. 2. Similar to pervious work [30], the thermal conductivity coefficient typically increased after a certain temperature, and there is a minimum value with the change of mean temperature. The thermal conductivity of TEM decreased with the increase of mean temperature of TEM when it is below 100°C, and the thermal conductivity of TEM increased with the increase mean temperature when it is above 100°C. The reason of electronic contribution to thermal conductivity of thermoelectric module can be found in reference [31].

3.1. Effect of cooling flow velocity at the cold side
The hot and cold side temperatures, and the corresponding temperature difference between them at various air flow velocities are obtained with a fixed heat flux of 8W/cm² as displayed in Fig. 3. It is because that the temperature drop at the hot side is smaller than that at the cold side of the TEM with the increasing cooling flow velocity, resulting in a tiny increment in temperature difference. For instance, the hot and cold side temperatures of the TEM were declined from 319.0°C to 292.3°C and 130.4°C to 85.6°C respectively as the cooling flow velocity increased from 2.0 to 10.0 m/s, while the corresponding temperature differences increased from 188.6°C to 206.7°C. In other words, the temperature drops at the hot and cold side of the TEM were 26.7°C and 44.8°C respectively, while the increment of their temperature difference is 18.1°C as the cooling flow velocity increased from 2.0 to 10.0 m/s. This implies that the temperature difference is almost identical with various air velocity for a given heat flux through the TEM.

The performance of the thermoelectric module with various cooling flow velocity for a given heat
flux of 8W/cm² is displayed in Fig. 4. It is reported that the current dwindled and the voltage ascended with the increase of external load R_L, and therefore the power output firstly increased and then declined. The maximum power are achieved when the external load R_L and internal load R_I of thermoelectric generator are identical, as shown in Fig. 4 (c). This is because the output power is the product of voltage and current through an external load. The voltage, the current and power output were all increased with the increase of flow velocity, this tendency is remarkable at lower flow velocities and became tiny at the higher flow velocities. The reason is that the convective heat transfer ascended with the increase of flow velocity, but is not proportional.

The influence of cooling flow velocity on the maximum power and efficiency for a given heat flux of 8W/cm² is shown in Fig. 5. The maximum power output is obtained when the external load R_L and internal load R_I are identical. The maximum power output firstly increased and then evolved slowly after a certain value with the increase of flow velocity due to the characteristic of the Bi₂Te₃ modules. The maximum power is not linear but square to the temperature difference, and is amplified the two physical scales for the temperature difference. The TEG conversion efficiency throughout the test was calculated by Eq. (3). The similar tendency was found for the conversion efficiency. This is because the efficiency is increased with the increasing temperature difference across the thermoelectric module or decreasing mean temperature of the thermoelectric module. The temperature difference across the thermoelectric module is enlarged with the increase of flow velocity, whereas the average temperature of thermoelectric module is declined.

3.2. Effect of cooling flow temperature at the cold side
The hot and cold side temperatures of the thermoelectric module (TEM), and the corresponding temperature difference between them for various cooling flow temperature are shown in Fig. 6 with a fixed heat flux of 8W/cm². The temperature at both ends of the TEM increased with the increase of air flow temperature, whereas the temperature rise was smaller at the hot side than that at the cold side with the increasing air flow temperature, leading to a tiny decrement in temperature difference. Moreover,
the temperature difference across the TEM slightly declined with increase of air flow temperature for a given heat flux. This is because the cold side temperature of TEM increased with the increase of air flow temperature, while the temperature increment at the hot side of the TEM is smaller than that at the cold side due to the increasing average temperature and thermal conductivity of the TEM. For instance, the hot and cold side temperatures are increased from 292.3℃ to 319.5℃ and 85.6℃ to 122.7℃ respectively, while the corresponding temperature differences decreased from 206.7℃ to 196.8℃ when the cooling flow temperature increased from 30℃ to 70℃. The hot and cold temperature rise is 27.2℃ and 37.1℃ respectively, while the decrement of their temperature difference is 9.9℃ as the air flow temperature increased from 30℃ to 70℃.

The performance of the thermoelectric module for different cooling flow temperature at a fixed heat flux of 8W/cm² is plotted in Fig. 7. The current dwindled and the voltage ascended with the increase of external load $R_L$, and therefore the power output firstly increased and then declined. The maximum power output are achieved when the external load $R_L$ is equal to the internal load $R_I$ due to the power output is the multiplication of voltage and current, as shown in Fig. 7 (c). Furthermore, the current, voltage and power outputs are decreased with the increasing temperature of air flow, and this tendency is proportional augmented or declined with the increase of air flow temperature.

The influence of cooling flow temperature on the maximum output power and efficiency for a given heat flux of 8W/cm² is shown in Fig. 8. The maximum output power almost linearly decreased with the increase of air flow temperature. This is because the cold side resistance of the thermoelectric generator is almost constant with different air flow temperature, while the thermal conductivity increased with the increase of mean temperature of thermoelectric module for a given heat flux. The power conversion efficiency decreased with the increase of air flow temperature. This is because the output power is decreased with the increasing temperature of air flow, while the power input keep constant for a given heat flux.

### 3.3. Effect of heat flux through the thermoelectric module

The hot and cold end temperature of the thermoelectric module (TEM), and the corresponding
temperature difference across the two end at different heat flux are shown in Fig. 9 for a given flow velocity of 10m/s and air flow temperature of 30℃. The cold side temperature of the TEM is slightly increased with the increasing heat flux through the TEM, while the temperature at hot side of the TEM and the corresponding temperature difference across the TEM is almost linearly proportional to the heat flux. For instance, the temperatures at the hot and cold sides are increased from 98.5℃ to 343.9℃ and 43.1℃ to 98.0℃ respectively, when the corresponding temperature differences increased from 55.4℃ to 245.9℃ when the heat flux increased from 2.0 to 10.0 W/cm². The hot and cold temperature rise of the TEM are 245.4℃ and 54.9℃ respectively, while the increment of their temperature difference is 190.5℃ when the heat flux increase from 2.0 W/cm² to 10.0 W/cm². This implies that the temperature difference is significantly influenced by heat flux for an available heat sink, which can be explained by the Fourier law as expressed in following equation.

$$q = \lambda \frac{\Delta T}{\Delta x}$$

where \(q\), \(\lambda\), \(\Delta x\) and \(\Delta T\) is the heat flux through the TEM, the thermal conductivity, the thickness, the temperature difference across the TEM, respectively. The temperature difference is significantly increased, while the corresponding cold side temperature of the TEM is marginally increased with the increasing heat flux through the TEM. The thermal conductivity is marginally increased with the increasing heat flux through the TEM due to the increasing mean temperature of the TEM, while heat transfer coefficient at the cold side of the TEM is almost identical with a fixed cooling flow velocity.

The performance of TEM for various heat fluxes with a fixed cooling flow velocity of 10.0m/s is plotted in Fig. 10. The current and voltage were increased with the increase of heat flux due to the increasing temperature difference across the TEM, resulted in an enlargement of power output. This tendency is proportional augmented or declined as the heat flux changed. Similar to the above description, the power output firstly increased then decreased with the increase of external load \(R_L\), and the maximum power outputs were acquired as the external load \(R_L\) and internal load \(R_I\) were equal, as shown in Fig. 10(c).

The influence of heat flux on the maximum power output and efficiency for a given cooling flow velocity of 10m/s is shown in Fig.11. The maximum power output enlarged with the increasing heat flux through the TEM due to the higher temperature difference between the dual sides of the TEM as displayed in Fig. 9. The maximum power output is increased from 0.53W to 5.4W when the heat flux increased from 2.0 W/cm² to 10.0 W/cm². This is consistent with the enlargement of temperature difference across the TEM due to the increasing power input. Higher power output can be easily obtained by increasing the heat flux through the module when the temperature below maximum allowable temperature of the TEM, which is suggested below 350℃ for the hot side in present work. However, the conversion efficiency of output power increased with the heat flux and evolved slowly after a certain value due to the characteristic of the Bi₂Te₃ modules. This is because temperature difference across the TEM and average temperature of the TEM both amplified with the increase of heat flux through the TEM, the former had a positive influence on the power efficiency while the later had a negative influence.
on the power efficiency. The maximum efficiency was 3.5% with the highest temperature difference at the heat flux of 10.0 W/cm².

![Figure 11. Power and efficiency for different heat fluxes.](image)

4. Conclusion
An experiment was setup to study the influence of heat flux, velocity and temperature of cooling flow on the power and efficiency of a commercial TEG Bi₂Te₃-based modules. The thermal conductivity of commercial TEG Bi₂Te₃-based modules typically increases after a certain temperature. The output power is firstly increased and then decreased with the increase of external load, and the maximum power output are achieved when the external load and internal load of the TEM are identical. The temperature differences across the thermoelectric module are almost identical with various air velocity for a given heat flux through the TEM, while the power and efficiency increased with the increase of cooling flow velocity. The power output and conversion efficiency almost linearly decreased with the increase of cooling flow temperature with a fixed heat flux through the TEM and a fixed flow velocity. Furthermore, the power output and efficiency increased significantly at first then the tendency became mild with the increasing heat flux through the TEM. Higher power output can be easily obtained by increasing heat flux through the module when the temperature below the allowed maximum temperature of the TEM. The augment of heat flux is an important way for higher temperature differences between dual sides of the TEM and higher power output.

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