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A research on thermoelectric generator's electrical performance under temperature mismatch conditions for automotive waste heat recovery system

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ABSTRACT

The thermoelectric generators recover useful energy by the function of thermoelectric modules which can convert waste heat energy into electricity from automotive exhaust. In the actual operation, the electrical connected thermoelectric modules are operated under temperature mismatch conditions and then the problem of decreased power output causes due to the inhomogeneous temperature gradient distribution on heat exchanger surface. In this case study, an individual module test system and a test bench have been carried out to test and analyze the impact of thermal imbalance on the output electrical power at module and system level. Variability of the temperature difference and clamping pressure are also tested in the individual module measurement. The system level experimental results clearly describe the phenomenon of thermoelectric generator's decreased power output under mismatched temperature condition and limited working temperature. This situation is improved with thermal insulation on the modules and proved to be effective.

1. Introduction

The thermoelectric generator (TEG) is a device for directly converting thermal energy into electrical energy based on the Seebeck effect and it has presented urgent potential in the case of waste heat recovery. The TEGs have many advantages such as no moving mechanical parts, long-lived, quiet, environmentally friendly and requiring little maintenance [1]. As a significant cause for the fuel crisis and environmental pollution, the internal combustion engine (ICE) drives vehicles with only 30% of the total heat generated by the gasoline used. During this process, the other 40% of the heat is lost through waste gas exhaust and 30% by the coolant [2]. The TEG using automobile waste exhaust as heat source is believed a new way to reduce ICE loads as well as the alternator and then decrease fuel consumption and environmental pollution.

Many automobile manufacturers, such as GM in the USA, BMW in the Germany, successfully developed TEGs to recover the exhaust waste heat [3,4]. Considering the challenges of complex automotive environment and being made commercially, the Be_2Ti_3-based bulk thermoelectric material was selected by most of the automobile manufacturers for application. However, limited by the thermoelectric materials, the efficiency of TEG system was limited and totally less than 5%. It was

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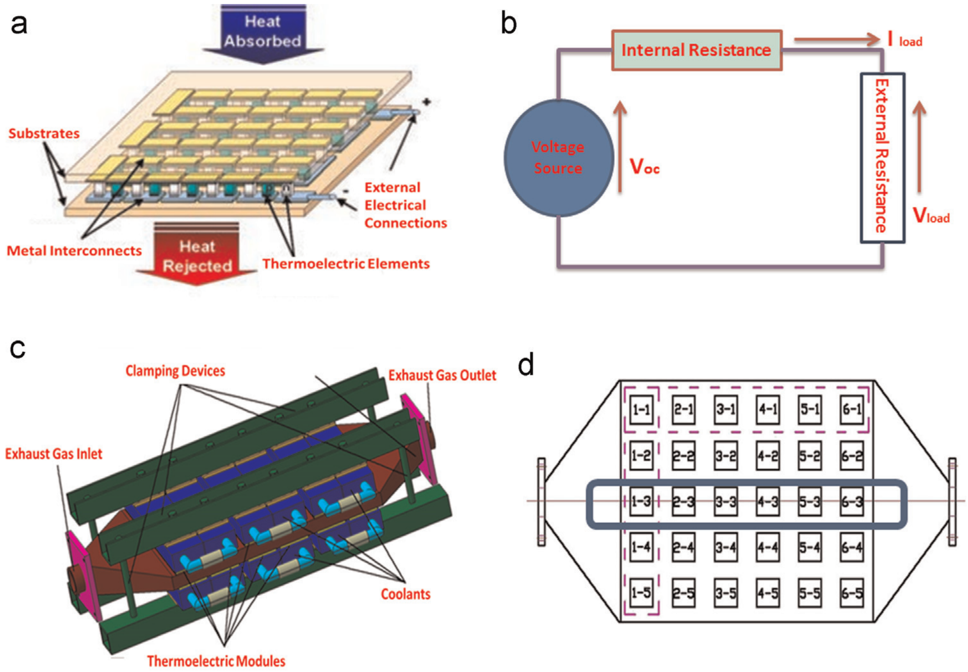

Fig. 1. Schematics of a TEM and TEG: (a) a TEM in generator mode, (b) electrical model of the TEM, (c) the structure of TEG, (d) the locations of TEMs in TEG system.

noticed that the temperature of exhaust gas is not constant and reducing along the flow direction in the TEG system in Lu's work [5]. The thermal variability and poorly controlled thermal conductivity accounts for the individual module's poor working performance under temperature mismatch conditions. Hsu et al. [6] suggested applying an appropriate pressure on the thermoelectric modules to improve performance. Andrea et al. [7] experimentally quantified the power loss due to temperature mismatch in TEG arrays and discussed advantages as well as drawbacks of TEG arrays in series and parallel. It is convinced that the thermoelectric modules in series connection perform better than in parallel connection.

In this study, an individual thermoelectric module (TEM) test system has been adopted for the measuring, testing and analyzing of the data acquired from the TEM used. The effect of clamp force pressed on the module is discussed and a database about the max power output is obtained under various temperature differences. Based on the experiment of individual module, the performance of TEG system (TEMs connected electrically in series) is tested and analyzed with a test bench. In addition, the power lost due to mismatched conditions is quantified and discussed. The performance of the TEG is improved by the adjustment of thermal insulation, as explained in the following sections.

2. Experimental setup

A TEM is composed of many thermoelements in series electrical link to increase operating voltage and in parallel thermal connection to increase the thermal conductivity. TEMs convert thermal energy to elecrical energy based on Seebeck effect when temperature difference occurs. As is shown in Fig. 1b, the electrical equivalent circuit of the TEM includes an ideal voltage V_{oc} and an internal resistance R_L, which is similar to a battery. The configuration of the TEG is presented in Fig. 1c. TEMs are placed on the top and the bottom surface and mounted uniformly over the available surface of the heat exchanger (60% of total surface area) as is shown. The inlet and outlet ports of the box are connected to the exhaust pipe of the automobile. The cold-side temperature of the modules is maintained by the engine coolant system.

Two bench tests are adopted for the measurement of TEM and TEG system. As is shown in Fig. 2, an individual TEM test system is used to measure the performance of a single TEM under different temperatures. An individual TEM (50*50 mm) provided by Institute of New Material in Wuhan University of Technology is sandwiched between a cold block on the upper side and a hot block on the bottom side. The former contains an oil tank cooled by a thermostatic oil bath (−10 °C to 120 °C), while the latter is a high-temperature heater (20 –700 °C) powered by a DC power supply. An adjustable load cell is used to apply the pressure over the TEM and the output power, as well as voltage, can be measured by an electronic load.

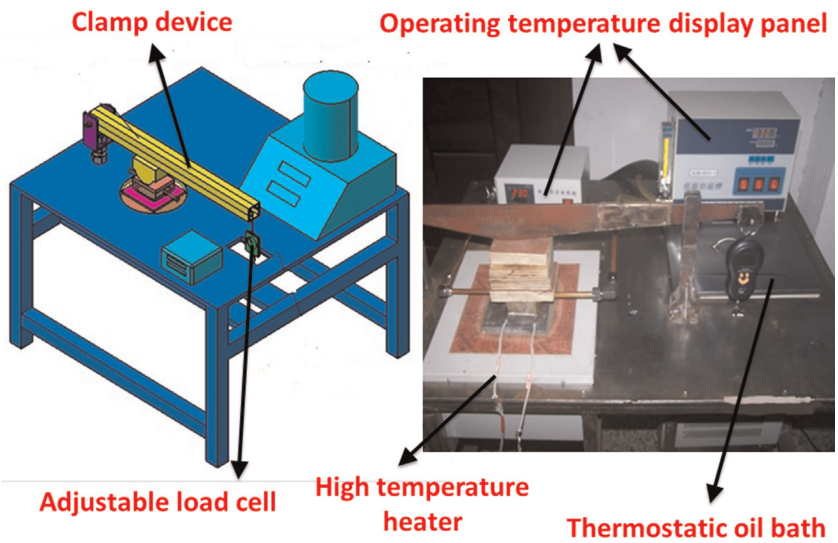

Fig. 2. The setup of the individual module test system.

3. Experimental results

3.1. TEM testing

Before the system performance testing, a performance analysis and evaluation should be achieved by means of testing an individual TEM. The experimental setup is described in Fig. 2. Considering the limited working temperature, less than 360 °C, the maximum working temperature is set to 350 °C. Different clamp loads are chosen and applied to the TEM for better electrical performance. The accurate electrical characteristics could be obtained by sweeping the electrical loads at different values and maintaining the temperature difference at the same time.

The internal resistance could be obtained by measuring open circuit voltage V_{oc} and the short circuit current I_{sc}. The match load point appears when the electrical load equals to the internal resistance R_L. Fig. 3 shows the measured curves of output power versus current and indicated in straight lines for different mechanical pressure when the temperature difference between surfaces of the TEM is $\nabla T=260$ °C (350 °C on hot side and 90 °C on cold side). The maximum electrical power is 4.19 W with 0.72 Mpa of mechanical pressure on the TEM, which corresponds to 180 kg on a surface of 50*50 mm^2. Compared with the conditions of 120 kg and 60 kg, the maximum output power reduces to 4.08 W and 3.85 W, 2.6% and 8.1% less than the original one. It is concluded that a proper mechanical pressure applied on the module improves the electrical performance of the TEM and the more proper pressure the better performance.

In Fig. 3, the electrical power has a change with mono-peak curve when the current varies and it reaches the maximum

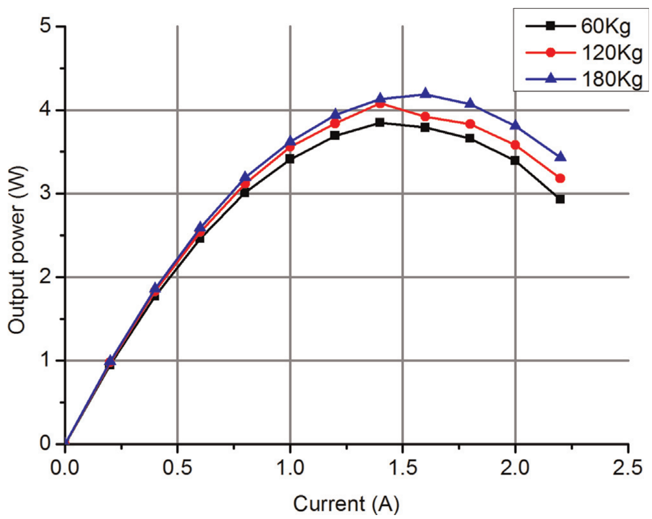

Fig. 3. Electrical performance of the TEM under different pressure loads.

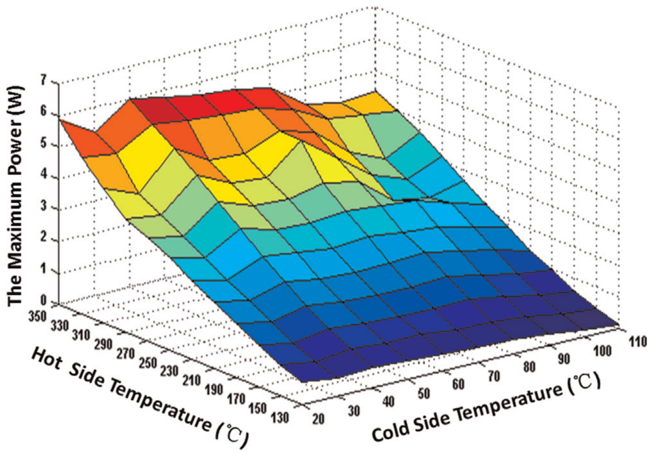

Fig. 4. The maximum output power of the TEM under different temperature differences.

4.19 W at 1.6 A. When the TEM is modulated on the condition that the current flow is less than 1.6 A, the output power reduces and the thermal conductivity decreases due to the parasitic Peltier effect. Thus the thermal energy passing through the TEM is less than the maximum output condition, which is advantageous for the heat exchanger design because it leads to increased thermal efficiency of the total system. Considering the condition when the current exceeds 1.6 A, the thermal conductivity increases and the thermal energy passing through the TEM is greater than the maximum power case, which leads to a reduced thermal efficiency. In actual automotive application, the temperature difference is not constant and varies in the actual running cycles. Based on this temperature mismatch conditions, the maximum power does not have a fixed value. As is shown in Fig. 4, a 3D map about the maximum output power of the TEM is obtained under various temperature differences, while the pressure load is 180 kg (0.72 Mpa).

3.2. System performance testing

The experimental test bench for system performance measurement, the main parts of which consists of an Engine(2.0 L), a dynamometer, a monitor console, an electrical load and some measuring apparatus, as is shown in Fig. 5. The TEG system described in Fig. 1 is connected to the middle part of the exhaust pipe of the engine. As the temperature distribution decreases along the exhaust direction and its symmetrical characteristic perpendicular to the flow direction, six TEMs (numbered 1-3, 2-3, 3-3, 4-3, 5-3 and 6-3), showed in Fig. 1d, are selected and mounted along the central axis in series electrical connection. The mechanical pressure loads applied on the modules are set as 180 kg. Two thermocouples are arranged on the inlet and outlet part and a bypass gas circuit is designed to protect the TEM from damage by shunting excess waste heat to the rear part of the exhaust pipe.

At the cold side, the TEG coolant unit is integrated with the engine cooling system, which can avoid problems such as lack of space and cost saving for automotive application, thus the cold side temperature keeps around 90 °C. When the engine runs, a temperature difference occurs and a direct voltage across the TEG is achieved. Fig. 6 indicates the status of

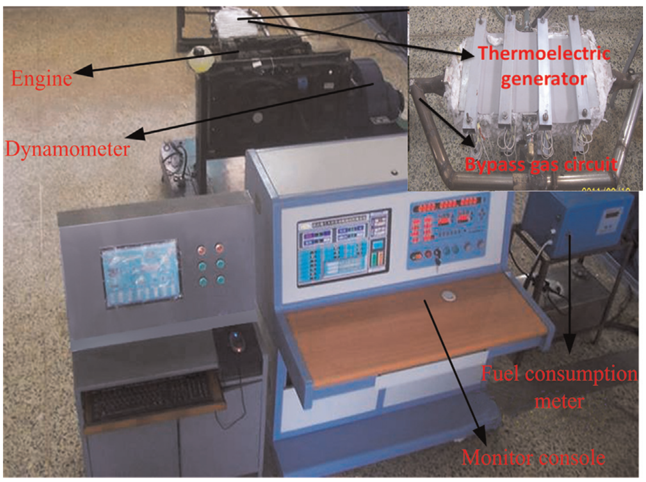

Fig. 5. The setup of the test bench.

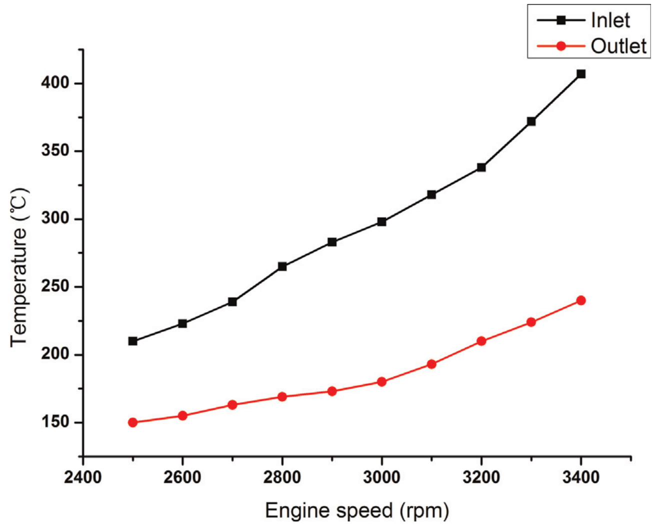

Fig. 6. The inlet and outlet temperature under different engine speed.

inlet and outlet temperature when the engine operates from 2500 rpm to 3400 rpm, the common operating speed on highway driving cycle. With the growth of engine speed, the temperature difference between the surfaces of TEM is increased rapidly, thus the output power gained from the TEG system also increases. The bypass gas circuit is turned on to protect the TEM when the hot side temperature approaches 350 °C (3200 rpm). Beyond this point, the maximum output power is limited even when the engine runs at higher speeds.

The six TEMs are linked electrically in series into an array and TEM_{1-3} works under its limited hot temperature when the engine operates at 3200 rpm. The independent electrical characteristics of the six TEMs are measured and listed in Fig. 7, from which the total maximum electrical output power can be obtained as 4.19 W+ 3.53 W+ 2.7 W +2.39 W +1.95 W+1.1 W=15.86 W. However, this value becomes 14.12 W with the current 1.25A when the six modules are connected in series and measured as a whole, which is 11% less than the sum of power that could be achieved by the TEMs if individually measured. The current of TEM_{1-3} and TEM_{2-3} are less than their best operating points(1.6 A and 1.4 A) which means they are working on a more efficient thermal operation with less parasitic Peltier effect. TEM_{3-3} and TEM_{4-3} operate very close to their maximum power output point, while TEM_{5-3} and TEM_{6-3} work on the condition that the operating current is larger than their best working points(1.1 A and 1 A). This results in a less efficient working point and more thermal conductivity with higher parasitic Peltier effect, which leads to a reduction of temperature difference between the modules and deteriorates the temperature mismatched condition in turn. Furthermore, the wiring and connectors used for the series link would also contribute to the power loss. When the inlet temperature exceeds 350 °C, the bypass gas circuit is turned on to split extra waste heat for module protection, thus the maximum output power keeps at 14.12 W.

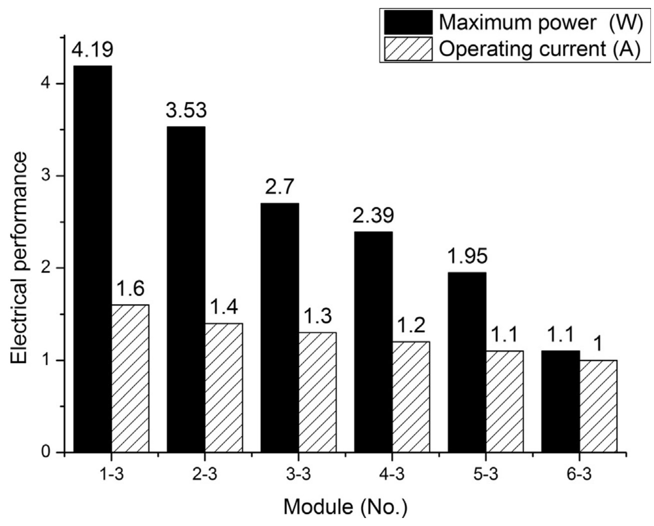

Fig. 7. Electrical performance of the TEMs.

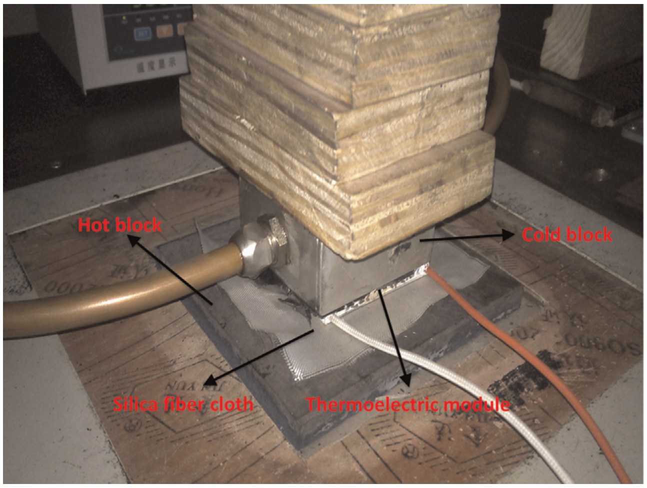

Fig. 8. The schematic of thermal insulation test.

4. Thermal insulation

In the TEG system, the temperatures attached to the hot side of the TEMs decrease along the exhaust flow direction, which leads to different individual electrical performance of the six modules. When linked in series, the six modules operate at the same current and some power lost due to this temperature mismatch conditions, as is discussed in Section 3.2. Limitation of the selected TEM that restricts the allowable operating temperature is another factor resulting in temperature mismatch condition. The electrical characteristics change and shift when the temperature difference varies by regulating the thermal conductivity.

Three different thickness of silica fiber cloth, ranging from 0.1 mm to 0.3 mm, are selected to adjust the heat transferred to the hot side and investigate the effect to the electrical performance. The experiment is carried out with the individual module test system and the silica fiber cloth is mounted between the hot block and the hot side of the TEM as is showed in Fig. 8. The clamp load pressed on the module is set as 180 kg. As shown in Fig. 9, the electrical characteristic of the same module varies greatly with different thermal insulations, which works at the temperature of hot side 250 °C and cold side 90 °C. The maximum electrical power reduces from 2.2 W to 1.33 W with 0.1 mm silica fiber cloth thermal insulation, while the current of the operating point changes from 1.2 A to 1 A. In the cases of 0.2 mm and 0.3 mm, the optimum operating current shifts from 0.8 A to 0.6 A, while the maximum power changes from 0.92 W to 0.6 W. Table 1 lists the electrical characteristics of the module with 0.1 mm, 0.2 mm and 0.3 mm thermal insulation cases when the working temperature exceeds 350 °C. The thermal insulated module works safely with the temperature above 350 °C, which is not allowable for the no-insulation one. The optimum operating point is also changed and the maximum electrical power decreases.

Based on the experimental data mentioned above and the decreasing temperature distribution along the waste gas flow direction, the modules numbered 1-3 and 2-3 are thermal insulation processed with 0.2 mm and 0.1 mm silica fiber cloth to

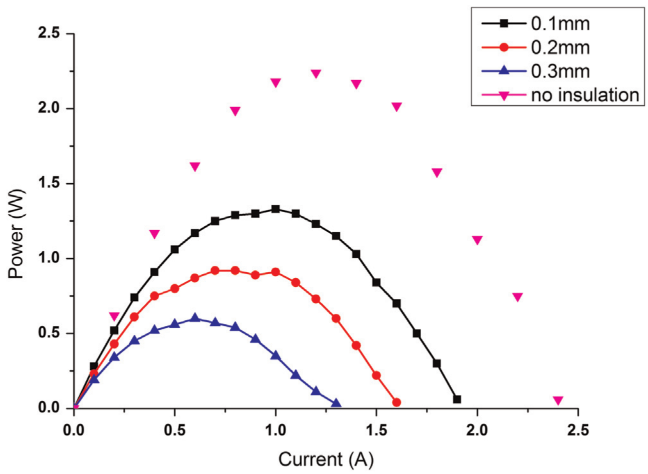

Fig. 9. Results of individual TEM thermal insulation test.

Table 1
Properties of the module under three different thermal insulation cases.

Hot side temperature	350 °C		360 °C		370 °C		380 °C		390 °C		400 °C	
Properties	I_{load}	P_{max}	I_{load}	P_{max}	I_{load}	P_{max}	I_{load}	P_{max}	I_{load}	P_{max}	I_{load}	P_{max}
Case 0.1 mm	**1.4A**	**3.24 W**	**1.5A**	**3.46 W**	**1.5A**	**3.6 W**	**1.5A**	**3.82 W**	**1.6A**	**3.95 W**	**1.6A**	**4.1 W**
Case 0.2 mm	**1.3A**	**2.83 W**	**1.4A**	**2.91 W**	**1.4A**	**3 W**	**1.4A**	**3.13 W**	**1.4A**	**3.32 W**	**1.4A**	**3.52 W**
Case 0.3 mm	**1.1A**	**1.85 W**	**1.2A**	**2.17 W**	**1.2A**	**2.35 W**	**1.3A**	**2.49 W**	**1.3A**	**2.63 W**	**1.3A**	**2.87 W**

improve the temperature mismatch conditions of the total system. Fig. 10 illustrates the independent electrical characteristics of the six TEMs when the inlet temperature reaches 350 °C and 400 °C. In the 350 °C case, the theoretically maximum power is 14.02 W, which is calculated by the sum of individual ones. This value turns to 13.69 W with the current 1.25 A in series connection level measurement, 2.4% less than the theoretical maximum power. In this situation, only TEM5-3 and TEM6-3 operate beyond their maximum power output point and the power lost because that the temperature mismatched condition is improved (2.4% vs 11%). In the 400 °C case, the maximum output power rises to 17.3 W in series linked circuit under 1.35 A, 22.5% more than the power generated by the TEG without thermal insulation, as shown in Table 2.

Such operations are also measured and compared under lower engine speed 2900 r/min, as shown in Fig. 11 and Table 2. The power loss dues to the temperature mismatch conditions reduced from 10.4% (original case) to 4.5% (thermal insulation case). But the maximum electrical output of the thermal insulated system decreased by 7.6% compared with the original case. It is convinced that the thermal insulated TEG system performs better under the temperature mismatch conditions at higher engine speeds, including the limited working temperature condition and the unwanted temperature gradient distributions on the hot side of the modules. Under lower engine speeds, when the modules operate below their limited working temperature, the thermal insulation case is inferior to the original one, although the power loss dues to the temperature mismatch conditions is reduced.

5. Conclusion

This work describes the electrical performance of the TEM and TEG system under mismatch conditions, such as the limited working temperature and the inconsistent temperature distributions among the modules in series connection. An individual module test system and a test bench have been designed and adopted to test and analyze the impact of thermal imbalance on the output electrical power at module and system level.

The experimental data are presented to illuminate the effect on the electrical performance when the modules are operated under mismatch conditions, such as mechanical load and temperature. It is concluded that a proper mechanical pressure applied on the module improves the electrical performance. The experimental results show that the power loss of the modules in series connection is significant, 11% less than the theoretical maximum power, due to the temperature mismatch condition. This situation is improved with thermal insulation on the modules and the power loss due to the inconsistent temperature distributions reduces to 2.3% at the same working condition. The maximum output power rises to 17.3 W, 22.5% more than the power generated by the TEG without thermal insulation, when the engine operates at 3400 rpm. It is suggested that thermal insulation method trades a new effective way to regulate the inconsistent electrical

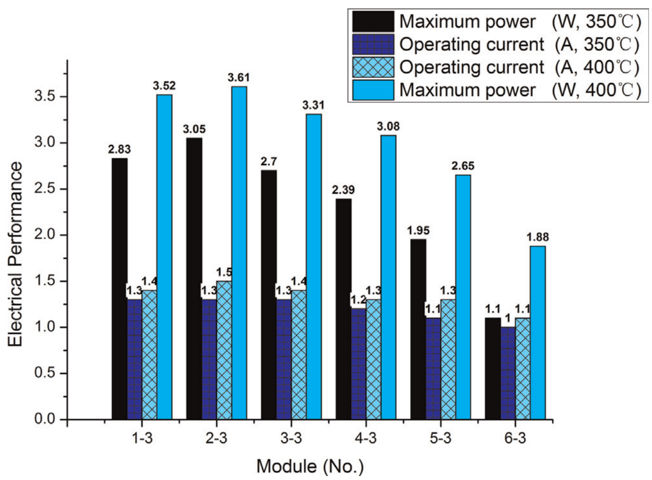

Fig. 10. Electrical performance of the TEMs with thermal insulation in TEG system.

Table 2
The comparison between the original case and the thermal insulation case.

Category					
Condition	**No thermal insulation case**		**Thermal insulation case**		**Improving the maximum output power(%)**
	Maximum power	**Operating current**	**Maximum power**	**Operating current**	
2900 r/min (inlet 280 °C)	10.32 W	1.1 A	9.53 W	1.1 A	−7.6
Power loss	10.4%		4.5%		
3200 r/min (inlet 350 °C)	14.12 W	1.25 A	13.69 W	1.25 A	−3
Power loss	11%		2.4%		
3400 r/min (inlet 400 °C)	14.12 W	1.25 A	17.3 W	1.35 A	22.5
Power loss	11%		4.2%		

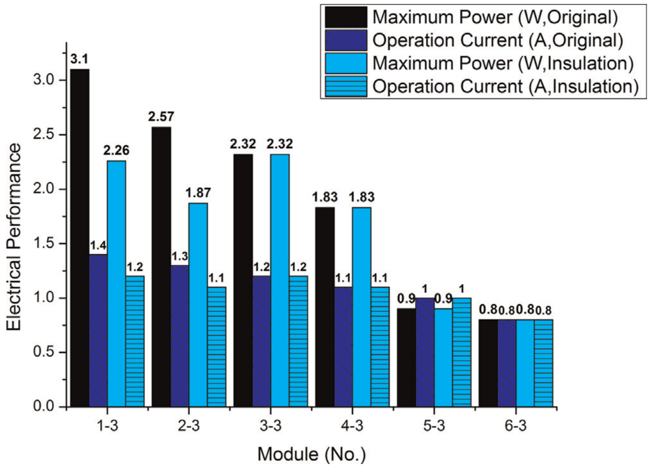

Fig. 11. Comparison between the original case and the thermal insulation case under 2900r/min.

characteristics of the modules under mismatch conditions and improve the performance of the TEG system under higher engine speeds.

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