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Experimental Study on a Novel Low-temperature Automobile Exhaust Thermoelectric Generator

[1,2]Rui Quan, [1,2]Guangyou Yang and [3]Liang Huang
[1]Agricultural Mechanical Engineering Research and Design Institute,
Hubei University of Technology,
[2]Hubei Agricultural Mechanical Engineering Research and Design Institute,
[3]School of Automation, Wuhan University of Technology, Wuhan, Hubei, 430070, China

Abstract: To further study on Automobile Exhaust Thermoelectric Generator (AETEG), an experiment setup based on low-temperature Thermoelectric Modules (TEMs) of Bi_2Te_3 materials, cold source of single-column cooling boxes and heat exchanger of herring-bone interior cavity was constructed. The hot source and cold source temperatures with different output powers and rotate speeds of engine were analyzed and the influences of the main operation conditions such as different contact pressures, the output currents, the output powers and rotate speeds of engine, on the maximum power and conversion efficiency were examined. The experimental results reveal that the maximum output power from the proposed AETEG setup is 179.7 W, the overall conversion efficiency at the maximum power generated from the exhaust waste heat is about 1.7%, the measures of thermal insulation and heat preservation are extraordinary important to improve the temperature differences and enhance the performance of AETEG. The meaningful results may serve as a good guide for further optimization of AETEG in next step.

Key words: Automobile exhaust thermoelectric generator, thermoelectric modules, maximum output power, conversion efficiency

INTRODUCTION

Owing to the advantages of Thermoelectric Generator (TEG) such as being highly reliable, having no moving parts and being environmentally friendly, there have been a variety of aerospace and military applications with TEGs (Niu *et al*., 2009). As to the internal combustion engine, only about 25% of its fuel energy is converted to mechanical energy, whereas approximately 40% of the fuel energy is wasted through exhaust gas, 30% is dissipated in the engine coolant, apart from friction and parasitic losses (Kim *et al*., 2011). Recovering and reusing some of the exhaust gas heat based on TEMs of low temperature and middle temperature has been a novel research focus so far (Karri *et al*., 2011; Phillip *et al*., 2013; Hsiao *et al*., 2010), for it can improve the overall efficiency of the internal combustion engine by applying the generated power in the vehicle's electric bus and decreasing fuel consumption and reducing environmentally harmful emissions (Domingues *et al*., 2013).

Up till now, the application of AETEG is on the initial stage, the output power and efficiency of AETEG developed is still low, some famous automobile manufacturers such as BWM, GM, Ford had done some researches in AETEGs, especially BWM, GM, BSST have exhibited different AETEGs from 200W to 400W. BWM reported about 200W AETEG in 2008 (Treffinger *et al*., 2008) while in 2012 it exhibited BWM X6 SUV with 300W AETEG of circle thermoelectric modules, GM applied the AETGE in the vehicle of Chevrolet Suburban, the maximum rate of fuel saving is about 10% from the 50000km road tests (Saqr *et al*., 2008). The BSST-led US department of energy-sponsored automotive thermoelectric waste heat recovery project, where the power outputs of AETEG up to 125 W were achieved on a 600°C hot-air test bench (Crane and Lagrandeur, 2010).

To investigate the viability and further performance of TEG for exhaust waste recovery in vehicles, we have fabricated a low-temperature AETEG based on Bi_2Te_3 TEMs that uses the exhaust of engine with a size of 2L, the experiments are carried out to examine the influence of the main operating conditions, the output powers and rotate speeds of engine, the hot and cold source temperatures, contact pressure and the load currents, on the power output and conversion efficiency of AETEG and several pieces of advices on the optimization and improvement of AETEG have been proposed.

Corresponding Author: Rui Quan, Agricultural Mechanical Engineering Research and Design Institute, Hubei University of Technology, Wuhan, Hubei, 430068, China

AETEG EXPERIMENT SETUP

The schematic diagram of an experiment setup of AETEG is shown in Fig. 1. It includes engine, dynamomemter, heat exchanger, cooling system, catalytic converter and so on. The engine is controlled by dynamomemter, i.e., different absorbed power, different heat exhausted from the outlet gas. The inlet of heat exchanger is connected with the outlet of engine, when the surface temperature of heat exchanger caused by inlet exhaust approaches the maximum operating temperature of single thermoelectric modules, the exhaust gas is directly bypassed to the catalytic converter to protect them. In the thermoelectric converter there are two groups of thermoelectric modules sandwiched between heat exchanger and cooling system which includes pump, fan, fluid bath and cooling unit 1# and 2#. The overall output of thermoelectric modules is connected with relay (S1) and diode (D1) in sequence. All the important process parameters such temperatures, voltages and currents are detected with monitoring system developed by our group.

Distribution of thermoelectric modules: The heat exchanger of herring-bone structure (Quan *et al*., 2012a) is made of brass with the thickness of 3 mm, the number and distribution of 32 single thermoelectric modules in both group 1 and group 2 are shown in Fig. 2, respectively.

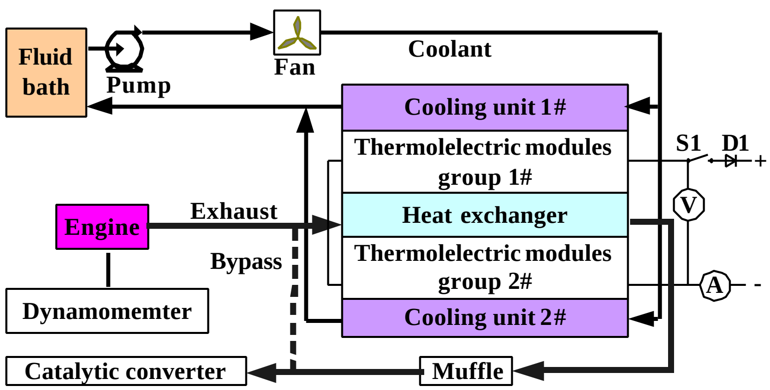

Fig. 1: Schematic of an experiment setup of AETEG

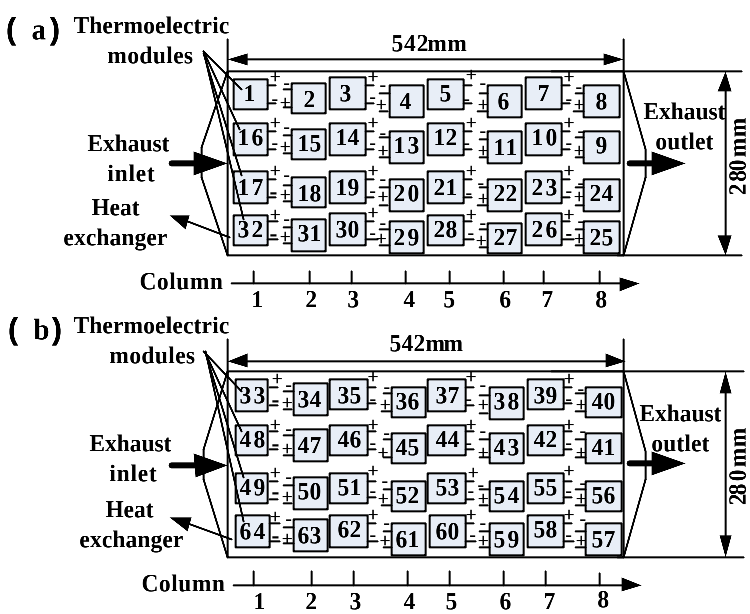

Fig. 2(a-b): Number and distribution of thermoelectric modules, (a) Group 1 and (b) Group 2

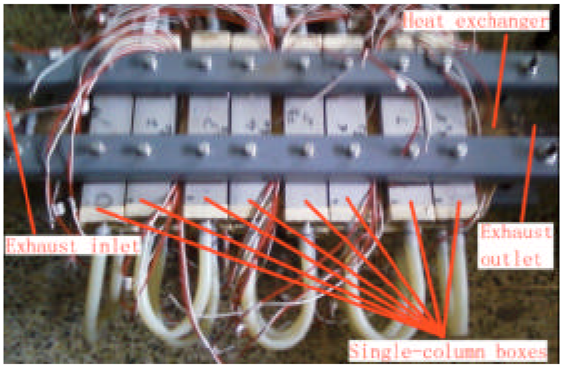

Fig. 3: Single-column boxes cooling unit

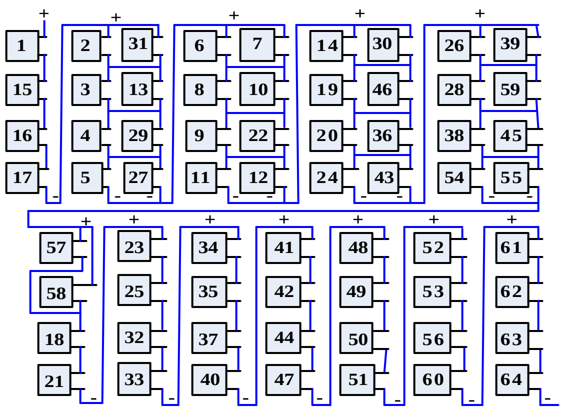

Fig. 4: Optimized electric topology of the AETEG

Cooling unit: Engine coolant is a good source to cool the AETEG instead of air cooling because the larger heat transfer coefficient available with liquid cooling (Saqr *et al*., 2008). However, lots of heat removed from the exhaust is mainly delivered to the coolant system and then it will affect the original performance of engine to some degree, in the AETEG experiment setup the cooling system based on independent water coolant is adopted, it includes two cooling units, pump, fan, fluid bath. Considering the conveniences and costs of manufacturing, each cooling unit consists of eight single-column aluminum boxes with thickness of 2 mm, the dimensions of each box is 280×60×26 mm, as shown in Fig. 3, the inlet and outlet of each single-column aluminum boxes are connected in parallel, the cold sides of four TEMs of each column in a layer are contacted with a common rectangular box, the contact pressure among TEMs, heat exchanger and cooling units can be screwed from 0 to 1200 N arbitrarily.

Electric topology of AETEG: If all the 64 modules of AETEG in Fig. 2 are connected in series, the internal resistance will be too large and the reliability of the system will be greatly reduced. If the modules with different open-voltage values are connected in parallel, the current will be too large to be dealt with (Zhu *et al*., 2011), furthermore, due to the different voltage and current characteristics of each thermoelectric module, if they are all connected in series, there will be a ring current among them and the internal power loss of AETEG will be largely increased (Quan *et al*., 2011). Figure 4 gives the final electric topology of AETEG optimized with Genetic Algorithm (GA), i.e., all the single thermoelectric modules of the same or similar open circuit voltage are connected in parallel as a basic voltage element, all the different basic voltage elements are connected in series as the overall output of AETEG (Quan *et al*., 2012b). When the electric output of AETEG is applied in the vehicle's electric bus, a DC/DC converter will be connected to interface them together.

In addition, the monitoring system includes a real-time voltage monitoring unit (Quan *et al*., 2012c) and a temperature monitoring unit (Hu *et al*., 2011), the voltage monitoring unit detects the real-time voltage of 64 single thermoelectric modules and the temperature monitoring unit detects the hot source temperatures of 64 single thermoelectric modules and the temperatures below the surface of the 8 single-column boxes as their corresponding cold source temperatures, when the AETEG is applied in a vehicle electric system these are not essential and can be omitted to simplify the system.

EXPERIMENTAL RESULTS AND DISCUSSION

Hot source and cold source temperatures distribution: Experiments in this study are conducted for a range of operating constraint conditions as follows: the hot source temperature of each single module is between 323 K and 623 K, the cold source temperature is between 303K and 373 K, the rotate speed of fan is kept constant, the fluid flow rate of water coolant is about 13.1 L min^{-1}, the output of AETEG is connect directly with the controllable electronic load (ZY8713). Figure 5 shows an infrared image of the surface of heat exchanger (The thermal infrared imager adopted is ThermoproTMTP8) when the output power of engine is 12.7 kW and its rotate speed is 3200 r min^{-1}, it illustrates that surface temperature distribution of all the heat exchanger is not uniform, i.e., the hot source temperatures of each thermoelectric modules are different from one another, the ones close to the inlet and center of heat exchanger are much higher than others. At this moment, the corresponding cold source temperatures (denoted T_L) from column 1 to column 8 based on the bottom surface of single-column boxes and the maximum hot source temperature (denoted $T_{H,max}$) are given in Fig. 6, respectively.

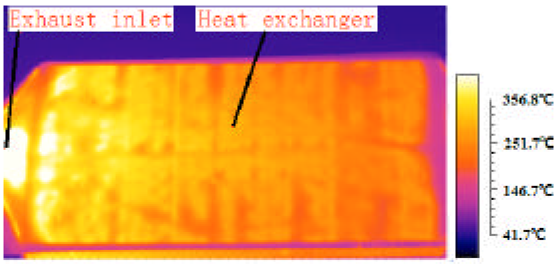

Fig. 5: Infrared image of the surface of heat exchanger

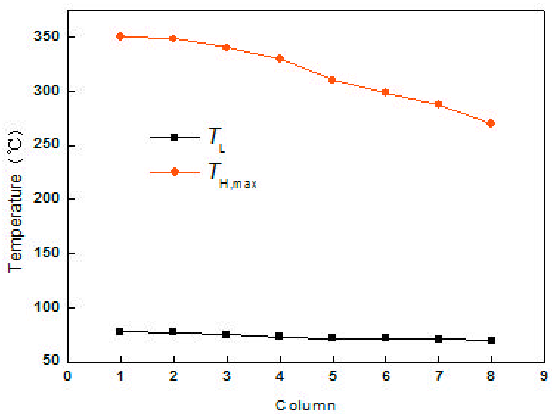

Fig. 6: Maximum hot source temperatures and cold source temperatures from column 1 to column 8

The cold source temperatures keep relatively steady (decrease from 351 to 342 K, respectively) for the parallel inlet and outlet coolant structure of cooling system while the hot source temperatures drop evidently from the exhaust inlet to exhaust outlet, i.e., the temperature differences of TEMs from column 1 to column 8 decrease accordingly. Different output power and rotate speeds of engine, different hot source and cold source temperatures, in fact, the surface temperature distribution of heat exchanger of all the other different output powers and rotate speeds of engine has the same variation trend as Fig. 6.

As shown in Fig. 5, the surface temperature distribution of heat exchanger is difficult to be kept completely uniform despite the optimization of its different flow structures, the maximum hot source temperatures of AETEG with different output powers and rotate speeds of engine are given in Fig. 7.

As the output power and rotate speeds of engine increase, more of the exhaust waste heat is discharged in the pipe, the maximum hot source temperatures of AETEG increase accordingly, when the output power is 12.7 kW and the rotate speed is 3200 r min^{-1}, the maximum hot

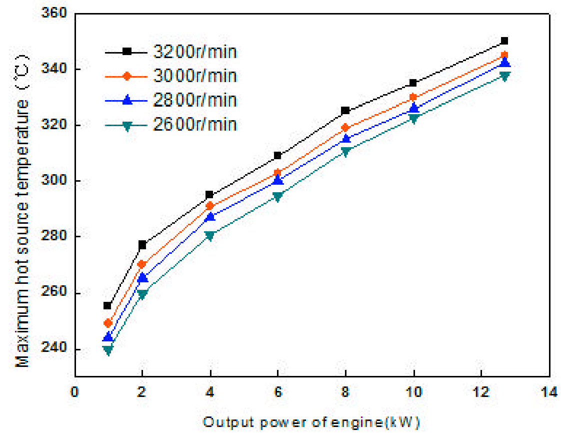

Fig. 7: Maximum hot source temperatures of AETEG with different operations of engine

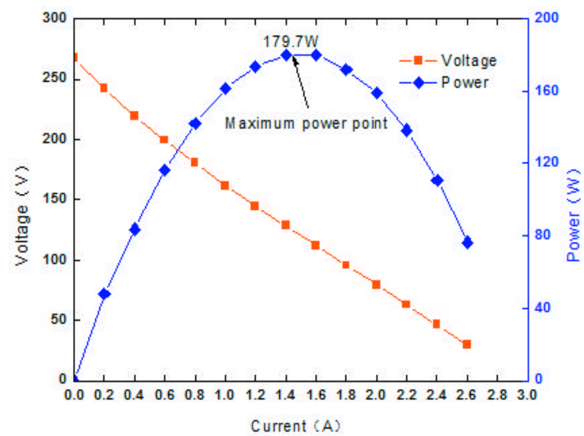

Fig. 8: V-I-P characteristics for maximum hot-source temperature of 350°C

source temperature of AETEG is about 623 K which is equal to the maximum operating temperature of single thermoelectric module.

Influence on the maximum power: Based on the electric load of controllable voltage and current, Fig. 8 depicts the Voltage-current-power (V-I-P) characteristics of AETEG when the maximum hot source temperature of thermoelectric modules is 623 K.

As the output current increases, the voltage decreases on the contrary while the power first increases to a peak value (179.7 W) when the output current is 1.4 A (i.e., the load resistance is equal to the interior resistance of AETEG) and the output voltage is about 128 V while the open circuit voltage is 267 V in such situation, then it reduces accordingly. For the soft output characteristic and small current of AETEG, when it is connected to vehicle's electric bus with DC/DC converter, we can figure out the maximum power point of AETEG by controlling the output current of DC/DC directly until the output voltage of AETEG is approximately half of its open circuit voltage value.

The performances of AETEG are usually evaluated by calculating the power output and the conversion efficiency. The output power of AETEG is given by Niu *et al.* (2009):

$$P = \frac{V_1^2}{R_1} \tag{1}$$

where V_1 is the output voltage, R_1 is the load resistance, based on the method of Maximum Power Point Tracking (MPPT) above, the maximum power of AETEG with different output power of engine from 1 to 12.7 kW is provided in Fig. 9. At this moment, the contact pressure between TEMs and cooling boxes of each column is set 1200 N (for the dimensions of single-column box is 60×280×26 mm, the average intensity of pressure exerted on each single module is about 0.72 Bar), it increases as the output powers of engine increase, when the output power of engine is constant, the higher rotate speed is, the larger maximum power of AETEG is. According to Seebeck effect (Kushch *et al.*, 2001), the performance of AETEG is proportional to the temperature difference between the hot sides and cold sides of semiconductor couples of TEMs. For the pump rotate speed of cooling system is invariable, the hot source temperatures of AETEG are enlarged greatly compared with the cold source temperature as the rotate speeds of engine increase with the same output power.

In addition, when the rotate speed of engine is kept at 3200 r min^{-1}, the maximum power of AETEG based on the method of MPPT above with different contact pressures (1200, 1000, 800, 600 N, respectively) between each thermoelectric module and cooling box of each column is given in Fig. 10. The larger contact pressure is, the higher maximum power of AETEG is at the same rotate speed of engine, it can be easily drawn that the thermal contact resistance decreases as the contact pressures between TEMs and cooling boxes increase for the contact between them is much closer, i.e., more of the heat can be easily took away from the cold sides of TEMs with the current cooling system and more of the exhaust waste heat can be absorbed by the hot sides of TEMs with the heat exchanger of current herring-bone structure, therefore, the temperature differences of AETEG are raised evidently to enhance the maximum power.

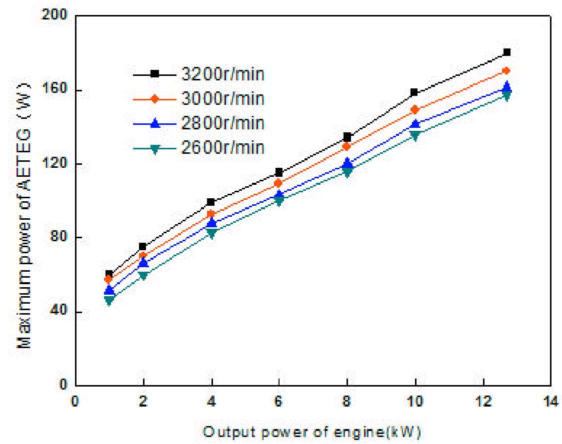

Fig. 9: Maximum power of AETEG with different output power and rotate speeds of engine

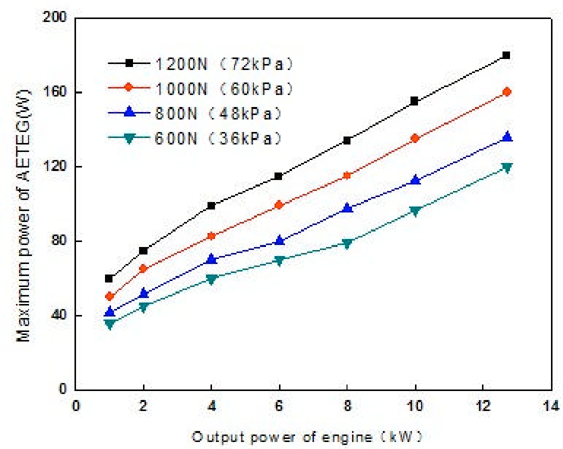

Fig. 10: Maximum power of AETEG with different contact pressures between TEMs and cooling box of each column when the rotate speed of engine is 3200r/min

Influence on the conversion efficiency: The heat balance of AETEG presented in Fig. 1 and 3 can be expressed as (Saqr *et al.*, 2008):

$$Q_{in}\text{-}Q_{out} = Q_0 + Q_{losses} \tag{2}$$

where, Q_{in} and Q_{out} are the exhaust gas energy at the inlet and outlet of heat exchanger, respectively and Q_0 is the effective heat transferred through TEMs, Q_{losses} means the heat losses which include the heat lost from the non-used zones of heat exchanger by radiation and convection (denoted Q_1), the heat lost from the leg-sides of the TEMs by convection and radiation (denoted Q_2), the heat lost by conduction through the assembly structure (denoted Q_3), the heat lost through gaps between the TEMs (denoted Q_4) and the heat lost by conduction in the TEMs due to thermal contact resistance (denoted Q_5) (Saqr *et al.*, 2008).

$$Q_{in} = m_{in} \times c_{in} \times (T_{in} - T_0) \quad (3)$$

$$Q_{out} = m_{out} \times c_{out} \times (T_{out} - T_{out}) \quad (4)$$

where, m_{in} and m_{out} are the average mass flow rates (kg sec^{-1}) of inlet exhaust and outlet exhaust, c_{in} and c_{out} are the average specific heat capacities (kJ/(kg K)) of inlet exhaust and outlet exhaust, T_{in} and T_{out} are the average temperatures of inlet exhaust and outlet exhaust, respectively, T_0 is the environmental temperature. The overall efficiency of AETEG can be expressed as:

$$\eta_{all} = \eta_m \times \eta_{HX} \times \rho \quad (5)$$

where, the conversion efficiency of TEMs is shown as:

$$\eta_m = \frac{P}{Q_0} \quad (6)$$

The efficiency of the heat exchanger can be expressed as:

$$\eta_{HX} = \frac{\text{Actual heat transffered}}{\text{Maximum possible heat transfer}} = \frac{Q_0 + Q_4}{Q_{in} - Q_{out}} \quad (7)$$

$$\rho = \frac{Q_0}{Q_0 + Q_4} \quad (8)$$

The heat loss and the useful amount of heat passing through TEMs to the available heat entering AETEG are mainly based on the design and structure of AETEG. However, a recent case study revealed that Q_{out} account for 45% of the total exhaust heat while another 45% is represented in Q_2, Q_5 and Q_0 together (Rowe, 2005). Based on the equations above and the maximum power of AETEG with different output power of engine presented in Fig. 9 and 10, without considering the power consumed by pump and fan, the maximum efficiency of AETEG is depicted in Fig. 11 when the contact pressure is 1200 N which is close to the maximum pressure resistance of TEMs.

It decreases from about 3.8-1.7% as the output power of engine increases while it increases as the rotate speed of engine increases with the same output power. It can be concluded that Q_1, Q_2, Q_3, Q_4 and Q_5 increase more than the maximum power of AETEG recovered from exhaust heat as the output power of engine increases. For the

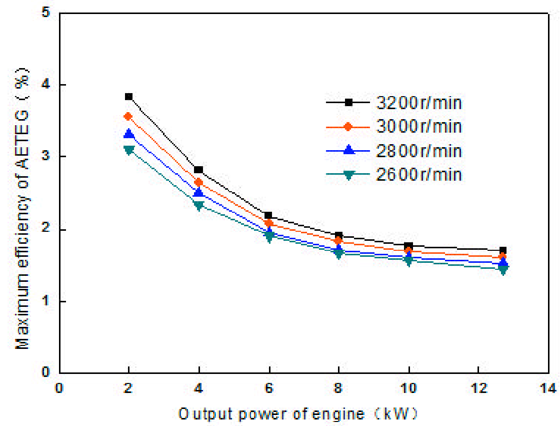

Fig. 11: Maximum efficiency of AETEG with different output power and rotate speeds of engine

contact pressure among TEMs, heat exchanger and cooling boxes of each column is set constantly at 1200 N, Q_5 can be considered constant with different operations of engine. In addition, there is no direct contact between the assembly devices and heat exchanger, the distance is about the height of cooling boxes, Q_3 is relatively small. Thus, it can be concluded that much more exhaust heat is lost with form of Q_1, Q_2 and Q_4 as the output power of engine increase. For Q_1, Q_2, Q_3, Q_4 and Q_5 can't be detected directly, it will be analyzed quantitatively by modeling the heat balance of AETEG designed and with the fluent software in our further work.

CONCLUSION

For the Bi_2Te_3 is the most common material that is commercially available so far, it has been a promising research focus on the automotive exhaust heat recovery based on low-temperature TEMs all over the world. Nevertheless, it is still a big challenge to enhance the overall power and efficiency of AETEG based on the TEMs for the highest ZT value of Bi_2Te_3 at present is about 1.1 and they have very restrictive operational temperatures (usually 20-300°C) and relative large thermal resistances.

In this study, an AETEG experimental setup based on single-column cooling system is designed, even though the surface temperature distribution of heat exchanger of herring-bone structure is not uniform, the back pressure of engine caused is only 0.3 Mpa at most when the output power of engine is 12.7 kW (3200 r min^{-1}), thus, the effect on the original performance of engine can be neglected. Whereas, how to enhance the uniformity of the surface temperature distribution of heat exchanger as much as possible without increasing the back pressure of engine evidently is our further work on the optimization of heat exchanger.

As shown in Fig. 8 above, the V-I-P characteristic of AETEG is extremely soft, a DC/DC converter is essential to be connected with AETEG when interfacing the AETEG output to the vehicle electric system. When the output of AETEG is used to charge the batteries or supply power to the vehicle electric system, the approach of MPPT by controlling the output currents of DC/DC converter directly is available, for the input currents of DC/DC converter (the output currents of AETEG) will be adjusted indirectly until the output voltage of AETEG is almost half of its open circuit voltage, the efficiency and performance of AETEG can be enhanced largely on this occasion.

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