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PERFORMANCE STUDY OF A THERMOELECTRIC GENERATOR FOR WASTE HEAT RECOVERY FROM EXHAUST GAS OF DIESEL ENGINE

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ABSTRACT

Thermoelectric generation technology can be used for waste heat recovery of internal combustion engines to improve energy efficiency. In this study, the performance of a thermoelectric generator for exhaust heat recovery of a diesel engine under various operation conditions are analyzed. First, a three-dimensional model of the thermoelectric generator is built by CATIA software. The thermoelectric chip of TEP1-1264-3.4 is used in this study and its characteristic data such as Seeback coefficient, thermal conductivity, and internal resistance are modeled by different maps in MATLAB. Then, a mathematical model of the thermoelectric generator is setup and a finite volume method is employed to obtain a high accuracy. The results indicate that the power output of the thermoelectric generator is increased while the thermoelectric conversion efficiency reduces as the engine load increases. On the hand, the power output of the thermoelectric generator is decreased but the thermoelectric conversion efficiency is increased as the engine load rises.

Keywords: thermoelectric generator, waste heat recovery, diesel engine, finite volume method

NONMENCLATURE

Abbreviations	
TEG	Thermo-Electric Generator
TEM	Thermo-Electric Module
Symbols	
α	Seebeck coefficient
r	Resistance of TEM
k	Thermal conductivity of TEM
σ	Conductivity of TEM
P	Output power of TEG

1. INTRODUCTION

Thermoelectric generation is one of the effective approaches for energy conservation and environmentally-friendly and sustainable development of our society [1]. If thermoelectric generation is used to recover waste heat of an engine, the energy efficiency can be improved. Moreover, the thermoelectric generation technology takes advantages of zero noise, zero emissions, compact volume, long work life, high reliability, simple structure, easy maintenance. Currently, thermoelectric generation technology has been the focus of some institutions and automotive suppliers.

The study of thermoelectric materials can be carried out on both macro improvement and micro optimization. In 1993, Hirano et al. designed a multistage thermoelectric material using BiTe/PbTe/SiGe and the results from a mathematical model indicated that the thermoelectric conversion efficiency can be improved effectively [2]. In 2011, the American company BSST developed a new thermoelectric material with a mixture of hafnium and zirconium, and the theory proves that the new thermoelectric material could improve the efficiency of TEG by about 40% when working at high temperature [3]. Table 1 shows the progress of thermoelectric materials with time. The conversion efficiency is increased from 5% to 20% since 1990. The value of ZT is also improved significantly. In practice, the overall conversion efficiency may be lower than the theoretical value because there are many other factors that will influence the final energy efficiency.

The geometric structure design has an important influence on the heat transfer of TEG. The design of a thermoelectric generator mainly incorporates the structure design of the heat exchangers for the hot and cold ends, the arrangement of the thermoelectric chips, and the mechanical connection of these different parts. In addition, the layout and space requirements should also be taken into account. Aranguren et al. designed a simple thermoelectric generation model for waste heat of internal combustion engine [4]. TEG was installed close to the outlet of the exhaust manifold pipe. A net power output of 21.56 W was achieved by 48 TEM. The temperature and mass flow rate of the exhaust vary with time in different working conditions of an internal combustion engine, which also have a great impact on the performance of a thermoelectric generator.

Table 1 Progress of thermoelectric materials [5]

Time	Conversion efficiency	ZT
Before 1950	＜5%	＜1
1950-1990	no substantive breakthrough	-
After 1990	up to 20%	＞2.0

Note: ZT is a dimensionless merit value to measure the conversion performance of thermoelectric materials

Experimental research is a strong proof of workability of TEG, however, due to its lower conversion efficiency than theoretical results, we cannot get ideal electrical performance like Organic Rankine cycles and power turbines. Using GM250-127-28-10 as thermoelectric materials, Lan et al. found that the output efficiency of the optimized thermoelectric generator could be increased by 25% under transient conditions by experimental tests [6]. Xu et al. conducted experiments on tail-temperature difference power generation in order to improve the fuel efficiency of automobiles. The output power of a single thermoelectric device are obtain under different hot-end temperature (83~270°C) and loads (0~520Ω), and based on Dongfeng EQ140. -1, the economic performance of the thermoelectric generator was analyzed under the operating data of the truck [7].

In summary, for the vehicle temperature difference power generation technology, domestic and foreign scientific research workers mainly engage in materials, theoretical analysis and experimental research by materials mechanics, thermodynamics, and other multidisciplinary knowledge. This paper lies in the following aspects: first, based on the accumulation of previous references, the three-dimensional structure diagram of vehicle exhaust TEG is established, and based on the partial data of TEM provided by the manufacturer, the performance parameters of TEM are obtained more accurately under all working conditions. Second, based on the known structural parameters, the zero-dimensional numerical model of TEG is established, and the piecewise structure and iterative algorithm are used to accurately calculate the power generation characteristics. Thirdly, the influence of exhaust temperature, exhaust velocity and engine speed on the output power of TEG is analyzed based on the steady-state operating condition data of a vehicle engine.

2. MODEL DESCRIPTION

2.1 Schematic structure

On the basis of relevant reference [8], CATIA software is used to set up the following 3d model. The whole geometric size of TEG is 185mm*95mm*375.2mm, with 14 sub-units and 16*14 TEMs. Exhaust from the engine will flow through a tube-fin heat exchanger along the Y direction, and the cooling water channel is a pipe heat exchanger along the X direction. Fig. 1 shows the layout of flow direction. Along the z direction, it is orderly the cold-end heat exchanger -8 TEMs – hot-end heat exchanger -8 TEMs - cold end heat exchanger. Considering the influence of factors of layout space and the coolant's temperature gradient on the results, the flow direction of the coolant and the exhaust is shown in the figure below. After entering from one end, the coolant which is perpendicular to the exhaust flow direction flows through cooling pass 1, reaches the other end, then flows through cooling pass2, and finally returns to the initial end.

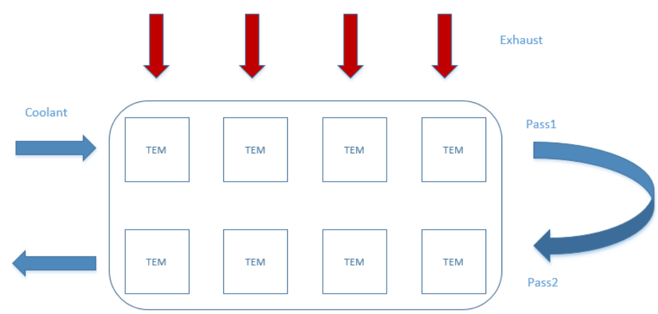


Fig 1 Flow diagram of exhaust and coolant

TEM materials used here are TEP1-1264-3.4, and the base material is Bi-Te, of which optimal operating temperature is at about indoor temperature, and the highest operating temperature can reach at 400 ℃ sometimes. The surface diagrams of α , r and k varying with temperature are obtained by polynomial fitting and interpolation algoritms.

2.2 Mathematical modelling

Thermoelectric conversion modeling can be divided into thermal process, thermoelectric process and electrical process. The specific steps are as Fig 2:

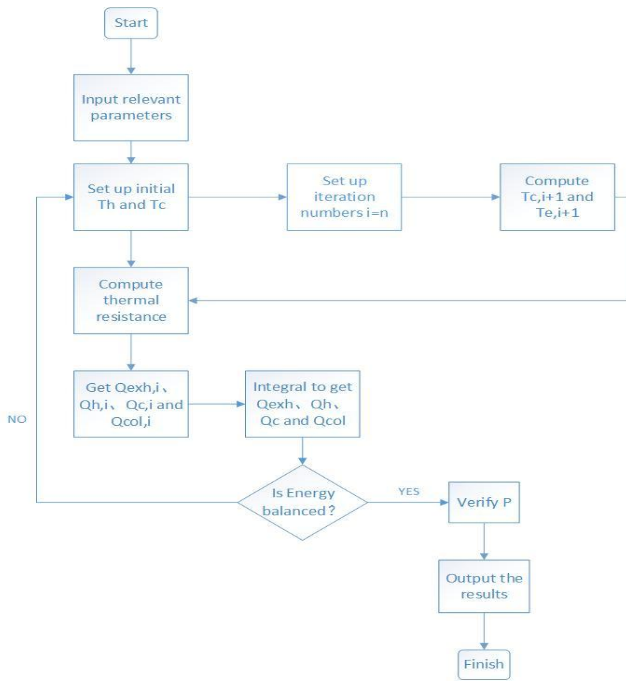


Fig 2 Calculation flow chart of thermoelectric conversion

Taking the energy balance of TEG as the target, the output power of each part is calculated by piecewise iteration, and the output value at the ith stage is the input value at the ith +1 stage. The number of iterative convergence is determined by the change value of output power, which is 0.1. The overall thermal resistance include: R_h -thermal resistance from heat source to hot end of TEM; R_c - thermal resistance from cold end of TEM to cold source; R - thermal resistance from hot source to cold source. And the heat from exhaust to hot end of TEM is:

$$Q_{exh} = \frac{T_{exh} - T_h}{R_h} \tag{1}$$

The heat from cold end of TEM to coolant is:

$$Q_{col} = \frac{T_c - T_{co}}{R_c} \tag{2}$$

Where, T_{exh} is the temperature of exhaust; T_h is the temperature of hot end of TEM; T_c is the temperature of TEM; T_{col} is the temperature of coolant. In the process of thermoelectric conversion, the transfer heat, Joule heat and Peltier heat will flow towards hot end and cold end of TEMs, and the heat flowing to the hot end is:

$$Q_h = \alpha T_h I - \frac{1}{2} I^2 r + k\left(T_h - T_c\right) \tag{3}$$

The heat flowing to the cold end is:

$$Q_c = \alpha T_h I + \frac{1}{2} I^2 r + k\left(T_h - T_c\right) \tag{4}$$

Where, I is the loop current. Output power is:

$$P = Q_h - Q_c = I^2 R_L \tag{5}$$

Where, R_L is the load resistance. When $R_L = r$, we have the maximum output power. Generally speaking, as Thermal equilibrium is achieved, there is:

$$Q_{exh} = Q_h \qquad Q_{col} = Q_c \tag{6}$$

As for the thermal resistance network: Exhaust is the heat source, along the flow direction, followed by the exhaust heat exchanger's fin (heat convection), the base (heat conduction). This process includes contact thermal resistance (also known as lubrication thermal resistance), ceramic resistance of TEM (heat conduction), thermocouple resistance (heat conduction), ceramic resistance (heat conduction), and contact thermal resistance (heat conduction). Finally, it flows through the base of the coolant's heat exchanger (heat conduction) and the pipeline (heat convection), which means the whole heat transfer ends. When the heat reaches the hot end of TEMs, in order to use as much heat as possible for thermoelectric conversion, the insulation material is used to dissipate the heat from the wall to the environment (heat conduction). Thermoelectric conversion process occurs in thermocouple, and external load is linked to form a circuit, then output electrical energy.

2.3 Simulation conditions

In order to verify the correctness of the model, the test condition data of a certain engine is selected for comparative analysis, as shown in the following Table 2 and Table 3.

Table 2 Engine data of constant-fuel-consumption engine operating points

Fuel Consumption (kg/h)	Exhaust Mass Flow (kg/h)	Engine Speed (kg/h)	Exhaust Pipe Temperature (℃)
19.96	452.96	800.00	526.00
19.20	526.20	1000.00	435.00
19.06	635.06	1200.00	379.00
19.5	752.076	1400.00	352.7847
19.66	854.66	1600.00	333.00
19.5	924.7559	1800.00	308.5859
19.5	965.214	2000.00	285.5094

As we can see from the table below, when the engine speed is constant, the greater the actual effective torque is, the greater the fuel consumption and the actual air consumption will be, and the larger the exhaust temperature and mass flow will be. When fuel consumption is constant, with the increase of engine speed, the actual air consumption will increase, the exhaust mass flow will increase, but the exhaust temperature will decline

Table 3 Engine data of constant-speed engine operating points

Engine Speed（rpm）	Actual Effective Torque（Nm）	Exhaust Mass Flow（kg/h）
1500	1696.00	1511.70
1500	1524.00	1459.74
1500	1350.00	1395.29
1500	1189.00	1316.71
1500	1012.00	1171.20
1500	838.00	1045.29
1500	667.00	890.31
1500	501.00	769.79
1500	335.00	663.63

Exhaust Pipe Temperature（℃）	Exhaust Counter Pressure（kPa）
491.00	15.10
483.00	14.00
473.00	12.80
459.00	11.20
432.00	8.70
406.00	6.80
373.00	4.80
331.00	3.60
270.00	2.50

3. *RESULT AND DISCUSSION* MODEL DESCRIPTION

3.1 Result of TEM parameters simulation

Through interpolation and fitting method of MATLAB software, the surface diagrams of α , r and k can be showed as Fig 3.

According to the characteristics of Bi-Te material, when the operating temperature is higher than indoor temperature, that is, the optimal operating temperature, α will gradually decrease with the increase of temperature, and k will gradually increase with the increase of temperature. σ is generally at a higher optimal temperature, and it decreases and then increases before the optimal temperature. In this paper we randomly select five points and compare them with the data provided by the manufacturer, as shown in table 4, 5 and 6.

Table 4 Conversion efficiency (%) contrast value when Tc=100℃

T_h (℃)	150.3960	183.6634	216.9307	250.1980	283.4653
Exact Value	2.4681	3.2695	3.7441	3.9899	4.0649
Fitted Value	2.4868	3.2660	3.7513	4.0009	4.0683
Relative Error	0.007577	-0.00107	0.001923	0.002757	0.000836

Table 5 Contrast value of V (V) contrast value when Tc=100℃

T_h (℃)	100.9479	125.1184	149.2891	172.0379	194.7867
Exact Value	0.1702	1.3521	2.4470	3.4072	4.2763
Fitted Value	0.1643	1.3490	2.4480	3.4011	4.2825
Relativ-e Error	-0.03467	-0.00229	0.000409	-0.00179	0.00145

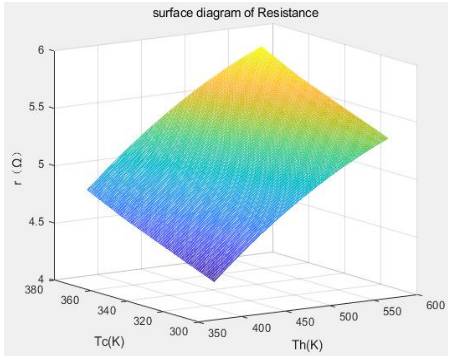
Table 6 Contrast value of r (Ω) contrast value when Tc=100℃

T_h (℃)	100.5414	133.2297	165.9229	231.3228	198.6206
Exact Value	4.7889	5.0170	5.2229	5.5725	5.4078
Fitted Value	4.7873	5.0154	5.2222	5.5720	5.4078
Relative Error	-3.3E-04	-3.2E-04	-1.3E-04	-9E-05	0

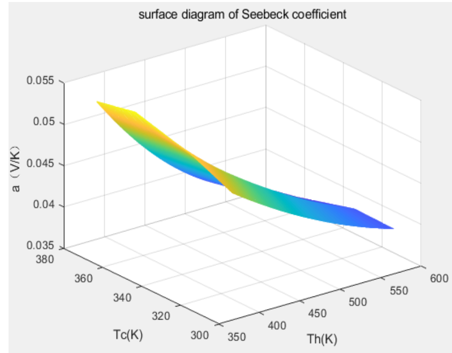
As we can see from table 4, 5, and 6, the relative error value is no more than 0.1, and the performance parameters of TEM obtained by fitting method are in good agreement with the data provided by the manufacturer, which is of practical value.

3.2 Result of TEG power generation performance simulation

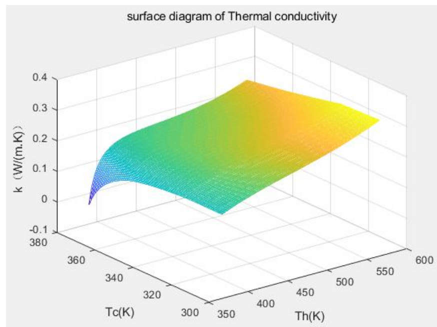
In order to verify the accuracy of subsection calculation, the operating points was randomly selected in order to compare experimental and calculation results as follows, on the premise of referring to relevant reference:



(a)



(b)



(c)

Fig 3 Surface diagrams of α (a), r (b) and k (c)

In order to compare experimental and calculation results as follows, on the premise of referring to relevant reference. Considering the influence of exhaust temperature gradient on the output power of TEG, the relative error can be reduced by half, and the results obtained by numerical simulation are closer to the experimental results. Therefore, the subsection calculation is an effective optimization method, showed at Table 7.

Table 7 Comparision between the output power calculated by subsection and the calculated without subsection

Exhaust Temperature（℃）	Exhaust Mass Flow（kg/h）	Iteration numbers（W）
386	1017	3000
352	949	3000
313	803	3000
346	1079	3000
Experimental Oouput Power（W）	Simulation Output andwith Segmentation（W）	Simulation Output without Segmentation（W）
600	623（3.69%）	651（8.5%）
515	537（4.27%）	593（15.1%）
400	466（16.5%）	523（30.8%）
525	555（5.71%）	585（11.4%）

As Table 8 shows, when the engine speed is constant, the reduction of exhaust temperature and mass flow will lead to the decrease of electrical output power of TEG, however, the conversion efficiency will increase. The reason is that the fuel consumption and actual air consumption reduce, the produce heat of engine fuel combustion will reduce, too. The heat of exhaust system can be passed to the TEG will reduce accordingly, output power is less. However, due to the beat working temperature of TEM is low, so the conversion efficiency increases. When the engine fuel consumption are constant, the actual air consumption increases, the exhaust mass flow rate increases, the temperature of exhaust gas temperature will decline. Because engine air-fuel ratio does not achieve optimal value, but gradually rises, the heat generated by the fuel decreases, exhaust temperature decreases, the output power decreases, and as the same principle, the thermoelectric conversion efficiency is rising.

Table 8 The thermoelectric results of TEG' constant speed and constant fuel consumption

Output Power （W）	Conversion Efficiency （%）	Output Power （W）	Conversion Efficiency （%）
798.61	3.37	740.6385	3.56
781.60	3.41	639.5908	3.96
761.58	3.47	577.1845	4.24
735.67	3.55	547.8128	4.36
688.74	3.75	517.8000	4.46
644.92	3.95	485.5077	4.55
587.71	4.21	447.0913	4.62
514.42	4.47		
403.27	4.67		

Note: the two columns on the left are the output power and conversion efficiency of TEG at constant speed, and the two columns on the right are the output power and conversion efficiency of TEG at constant fuel consumption. The number of iterations converges is 3000.

4. CONCLUSION

Through setting up the schematic model and mathematical model of automobile exhaust segmentation TEG and apply fitting method to the Seebeck coefficient, resistance and thermal conductivity of TEM, the thermal and electric performance of TEG is researched, detailed conclusion are as follows:

(1)The changing of key parameters of TEM with temperature is as follows: α first increases and then decreases (change at the optimal temperature); decreases first and then increases (change at the optimal temperature). σ is first decreased and then increased (change at the optimum temperature). Moreover, Bi_Te material is a thermoelectric material of low temperature.

(2)The simulation results of segmental TEG are more consistent with the experimental results than those of a non-segmental one, which is mainly due to the uneven temperature distribution caused by the temperature gradient of heat source.

(3)When the engine speed is constant, the output power of TEG increases with the increase of exhaust mass flow, but the conversion efficiency decreases. When the engine fuel consumption is certain, the actual air consumption increases, the speed increases, and the exhaust mass flow increases, the air-fuel ratio increases, the exhaust temperature decreases, the output power of TEG decreases, but the conversion efficiency increases.

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