APPLICATION OF THERMOELECTRIC GENERATOR TO ENGINE EXHAUST SYSTEM FOR ENERGY RECOVERY

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In order to recycle the exhaust system energy of the internal combustion engine, one energy recovery system based on thermoelectric generation technology has been designed. firstly, the design process including the heat collector, the radiator system, and the connection is presented. It shows that the heat collector with inner hollow structure is easy to achieve collector surface temperature uniform and the radiator system with heat fins can realize enough temperature difference. Finally, the cost analysis demonstrates that the system is feasible, but it will cost too much time for its own cost recovery.

Keywords: Thermoelectric generation; Internal combustion engine; Energy recovery; Exhaust system; Numerical simulation

1. Introduction

Thermoelectric generation (TEG) technology is developed based on the see-beck effect of the semiconductor materials with no noise and vibration in the power generation process and therefore has important applications in energy recovery, especially in the IC engine [1-4].

Application of the TEG to the exhaust system of the internal combustion (IC)engine can be traced back to 1963 when the Bauer from the Clarkson University found that it is worthy of studying the TEG technology based on the

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vehicle engine [3]. Bass and others have realized the energy recovery on a diesel trucks using 72 TEG chips with the maximum output power 1.5kW when the hot end temperature is 230℃, while the cold end temperature is 30℃ and the thermal conversion efficiency can be 4.5% improved [4-6]. The results from Ikoma showed that the conversion efficiency is about 11% when the vehicle speed is 60km/h at climbing conditions for a 3.0L gasoline engine [7]. Thacher's experimental results show that the output power of TEG is increased with the speed incensement and has a limit by hot end hot sources when the TEG is made of 16 HZ-20TEG chips [8]. It is also concluded from Kobayashi that the maximum output power is 1.2W at 80km/h when the hot end is the exhaust pipe and cold end is the coolant of the TEG [9]. The results from Xiao show that heat exchanger of the TEG has a greater impact on its performance [10].

In order to realize energy recovery with TEG technology the temperature difference should be maintained for the TEG hot end and cold end respectively. Normally the cold end temperature is kept with natural cooling, forced air, or water cooling to improve the heat transfer. The existing research results show that both the forced air-cooling and water-cooling can achieve the temperature difference and ensure high efficiency [11]. However, the conversion efficiency of the TEG is between 2.5% ~ 3.2% using natural air cooling which can keep the cold end temperature at 80℃ and the hot end temperature at 225℃ [12]. Forced air cooling not only meets the cooling requirements, but also can reduce the resistance of TEG because the cold end temperature decreases [13].

Zhou's experimental results show that the heat transfer between the heat fins and the environment can be improved with forced air-cooling or water-cooling on the premise that heat source has enough energy [14].

However, due to the engine exhaust gas temperature is high (normally above 500 ℃), the current commercially available TEG chips is not suitable because its temperature limit is not higher than 210℃. In order to realize the application of commercially available TEG chips to the exhaust system for the energy recovery, one TEG is designed and the experiment tests also have been done in this paper.

2. The basic structure of the TEG

The TEG system is installed in the engine exhaust pipe and its structure is designed based on exhaust pipe too. It can be seen from figure 1 that the TEG system has a parallel relationship with the original exhaust pipe, which maintains its original structure. As mentioned before that the commercially available TEG chips' tolerant temperature is 210℃, so there is baffle used to maintain the heat collector temperature below 200℃.

The TEG mainly includes three parts, namely the heat collector, TEG modules, and radiator as shown in Fig. 2. The heat collector has a rectangular structure and connects with the exhaust pipe using the flange with size of 300 × 200 × 100mm (length × width × height) which is used to collect heat from the exhaust. The TEG modules are current commercially available TEG modules and its tolerant temperature is 210℃ with size of 40 × 40 × 20 mm (length × width × height). The radiator is composed of radiation fins and its size is 50 × 50 × 40 mm (length × width × height).

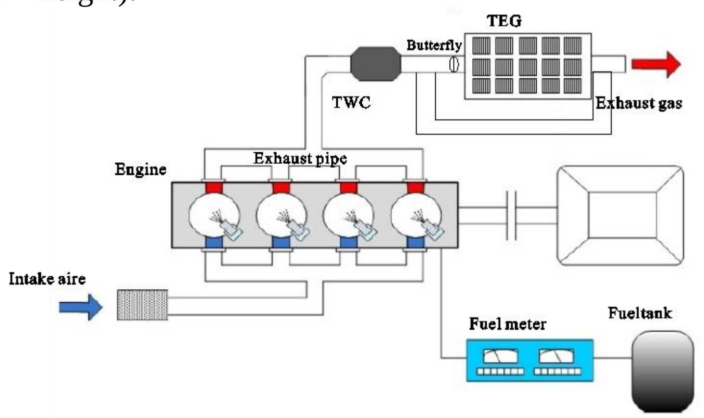


Fig.1 Diagram of the TEG installation in the exhaust system

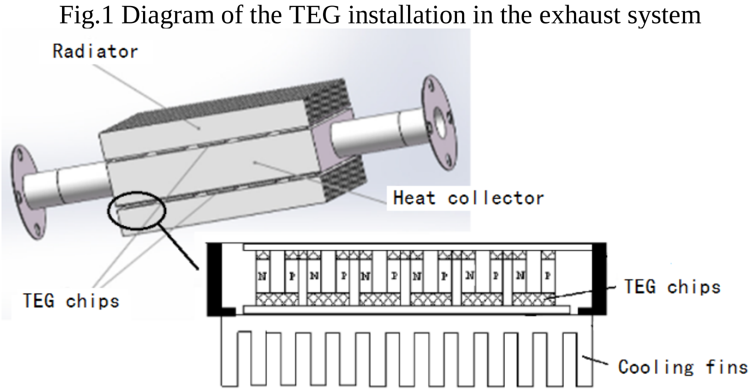


Fig.2 Schematic diagram of the TEG

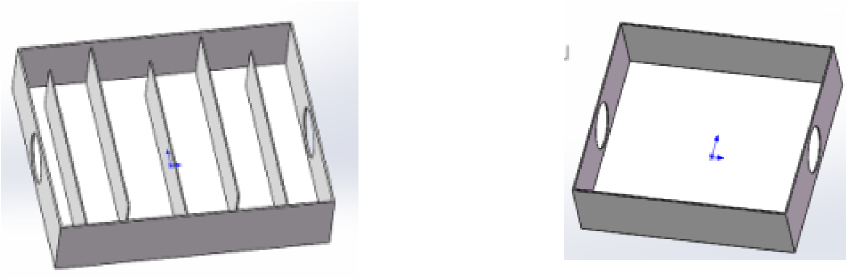
From the principle of the TEG technology, it can be found that the higher temperature difference the higher output power. So, in order to obtain high output power, the high temperature difference between both ends of TEG is necessary. For the exhaust pipe the heat source is good enough, while how to maintain cold end temperature at a low level is a problem. On the other hand, the temperature uniform is also very important to the TEG system, so the temperature of the heat collector is investigated as well. For that reason, these two problems are analyzed in the following parts.

3. TEG design

3.1 Heat collector design

In order to achieve temperature uniform two different collector inner structures are designed and simulated using CFD software respectively. And the hypothesis is referred to the exhaust gas which is that the fluid is considered as continuous, viscous and incompressible.

The structure can be seen in figure 3 where the 3.1 shows the heat collector separated with spacer and the 3.2 shows the heat collector with hollow structure. The dimension of the heat collector was based on the first section.



(1) Separated with spacer (2) Inner hollow structure

Fig.3 Diagram of heeat collector

The mesh models are established in CFD software platform for these two type collector respectively. Only the 3.1 mesh mode is given which is shown in figure 4 considering the same modeling process.

It should be noted that the model structure is different from figure 3 and two circular pipes are added for the collector in order to impose boundary conditions for the fluid analysis. The number of the element is 12203 where the minimum size was 0.0028m and the maximum size is 0.0561m.

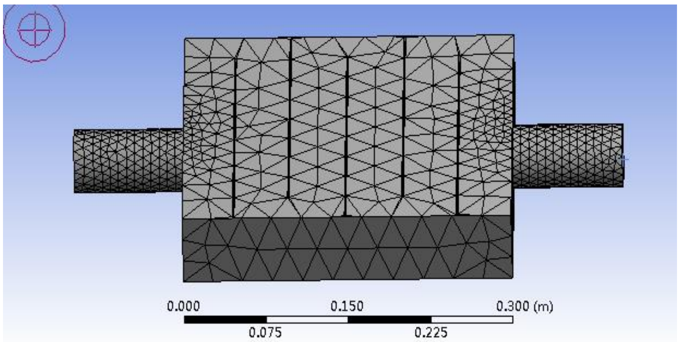


Fig.4 Mesh model of heat collector with spacer

The initial and boundary conditions parameters are specified according the exhaust system of the engine. The inlet is defined as mass flow rate and the value is 0.02kg/s. the outlet is defined as pressure boundary and the value is 1.1×10^5Pa. The fluid is exhaust gas whose density is 1.205kg/m^3 and dynamic viscosity coefficient is 1.820×10^{-5}N·s/m^2. Meanwhile the engine speed is 800 rpm and the exhaust temperature into the heat collector is 200℃.

Since the TEG system's material is aluminum, so it is necessary to build an aluminum alloy material for this analysis. This work can be done by adding aluminum material in engineering data modifying interface where the density is 2700kg/m^3. Young's modulus is 7.2×10^8Pa and Poisson's ratio is 0.33 are defined respectively.

As can be seen from Fig. 5.1, which shows the temperature distribution of the heat collector separated with spacer, the temperature of inlet is close to 470K and the temperature is gradually decreasing along the flow path of the exhaust gas, while the temperature of outlet is only 200℃.

The behavior above can be explained by the residence time of exhaust gas in the collector. Since the material of the heat collector is aluminum alloy which has high heat transfer ratio and there is large temperature difference between the environment and the exhaust gas the rate of heat transfer between the exhaust gas and environment is very high and the temperature decreases along the exhaust gas flow. There is temperature difference between the collector surfaces at different locations for the inner separated structure.

However, it can be found from Fig. 5.2, which shows the temperature distribution of the heat collector with hollow structure, which the temperature around the axis is almost at 200℃ and declines when the location is away from the axis. Meanwhile the temperature can still be maintained at 200℃ or higher, which means the hollow structure can realize temperature uniform and it is better than the separator structure for the surface temperature uniform.

The reason also lines in the resident time of the exhaust gas in the collector. Since the heat exchange between the exhaust gas and the environment is small because of short transfer time, the temperature does not change significantly. So, the collector surface temperature is relatively uniform when the collector is with the hollow structure.

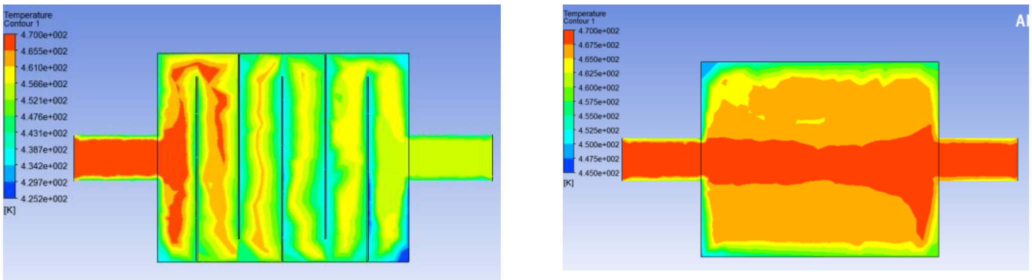
But it also should be noted that the lowest temperature of the two devices is at the corner of the collector and the temperature of the vertical connection location is low no matter what the structure is.

This behavior can be explained with the Fig. 6, which shows the velocity distribution of the heat collector for different structures. It can be seen from the figure that the velocity of the vertical connection location is very low or even equal to zero, which means the exhaust gas in this area is almost still and then the heat is transferred to the surrounding environment through the collector surface, which results in the presence of lower temperature region.

When the TEG is installed in the exhaust system, it will increase the exhaust pressure. The pressure loss is simulated for these two different inner structures of the collector. It is also completed in the CFD software and the results are shown in

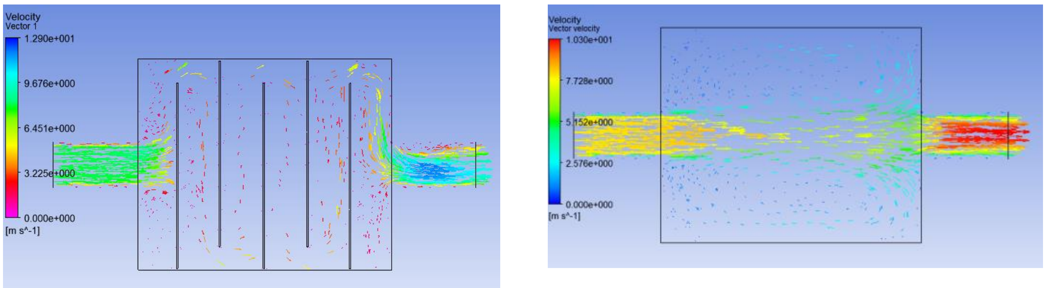
Fig. 7. It can be seen from the figure that the pressure difference for the collector with space between the inlet and outlet is only 0.3×10^4Pa, while the value is 0.9×10^3Pa for the collector with hollow structure. It can be concluded that the pressure loss of collector with hollow structure is smaller than the other structure.

Therefore, from the temperature uniform and pressure loss the collector with hollow structure is selected for the TEG.



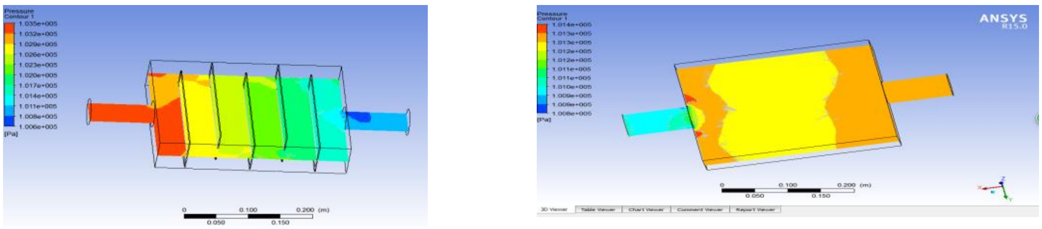
(1) Separated with spacer (2) Inner hollow structure

Fig.5 Temperature distribution of the heat collector



(1) Separated with spacer (2) Inner hollow structure

Fig.6 Velocity distribution of the heat collector



(1) Separated with spacer (2) Inner hollow structure

Fig.7 Pressure field of the heat collector

3.2 Radiation capacity analysis

It is known that the height of the TEG is only 20mm and then the heat radiation from the hot end to the cold end is inevitable. As we all know that for TEG system the temperature difference has an important effect on out power and energy recovery efficiency. So, it is very important to reduce the cold end temperature when the hot end temperature is almost fixed.

For the radiation capacity analysis, the main assumption is that the engine exhaust temperature is kept constant (as mentioned in temperature uniform analysis of the heat collector) and then the radiation capacity is examined by the cold end temperature changes. It should be noted that due to the TEG energy recovery symmetrical structure, 1/2 model is suitable for simulation then only half the structure is analyzed in this paper. After the establishment of the solid models, they should be imported into workbench platform for processing. The first step is meshing with parameters setting as follows. The minimum boundary dimensioned is 1e-3m, refined level is medium, and other parameters are the default settings for meshing. Then the final mesh model can be obtained. The dimension of the cooling system is based on the first section.

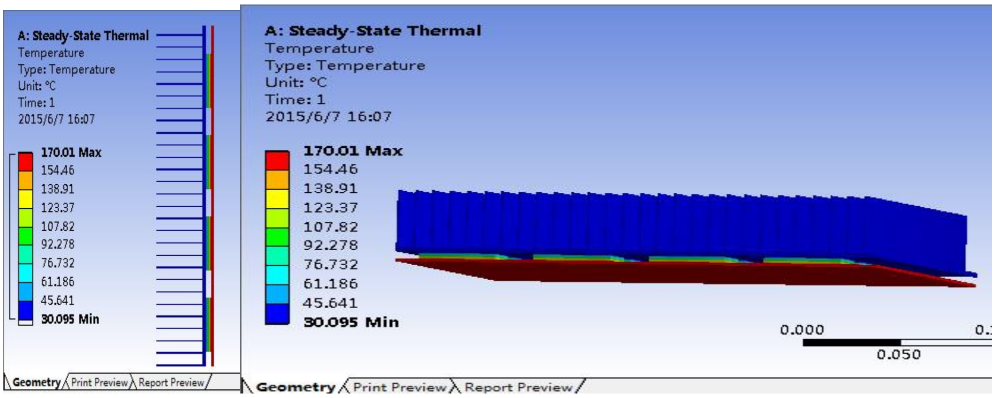
According to product materials, TEG energy recovery system is made of aluminum alloy material so the material definition of the thermal conductivity should be defined based on its properties. Then the thermal conductivity of aluminum alloy is set as 237W/m·°C and the value is only 0.6W/m·°C for semiconductor material properties [15]. And the number of the element is 233998 where the minimum edge length is 0.001m. The flux convergence is 0.0001 and maximum iteration is 1000.

Then for the thermal analysis the temperature and convection should be considered. Based on the operation condition the exhaust temperature is 170°C and the surrounding temperature is 30°C considering the engine cabin.

Fig. 8 shows the calculation results of the temperature distribution of the TEG energy recovery system where the 8.a is the side view and 8.b is front view.

It can be seen from the Fig. 8 that the heat collector’s temperature is 170°C, which means the hot end of the TEG energy recovery system is 170°C, while the cold end temperature is 46°C, which is connected to the TEG chips, and the temperature difference between both ends is 124°C. Therefore, it indicates that the designed TEG radiation system can keep the cold end at a lower temperature and a relative high temperature difference can be achieved.

At the same time, it is also found that the temperature of the radiation fins is different at different parts, especially for the part away from the TEG chips and the part connected to the TEG chips. It means the there is some improvement can be done for the radiation system.



a)Side view b)Front view

Fig.8 Temperarure filed of the radiation system

3.3 Experiment validation

In order to validate the model the TEG is installed into the exhaust system, which means the outlet and inlet of the TEG heat collector was connect to the exhaust system respectively as shown in Fig. 1. The experimental test bed was composed of EQ491 engine, eddy current dynamometer, dynamometer control system, measurement equipments, and sensors. The specification of the EQ491 engine is listed in table1 and the measurement equipments and sensors are list in table 2 including the K-type thermocouple, the data acquisition system, dynamometer control system, and multi-meter. The precision of the measured parameters are list in table 3.

Table 1

Parameters of the EQ491 engine

Parameters	value	Parameters	value
Type	Four stroke and four cylinder	Rated power(kW)/speed(rpm)	76/5200
Bore× stroke(mm)	76.95×90.82	Compression ratio	8.7:1
Displacement /mL	1993	Cooling method	Water cooling

Table 2

Equipments of experiment

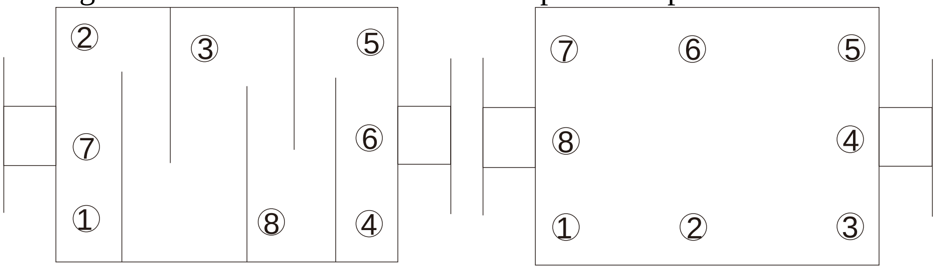
Name	Type	Company
Thermocouple	K	Sincera piezotronics INC
Dynamometer control system	ET2000	Sichuan Chengbang Sciences and technology
Multi-meter	FLUKE-115C	Fluke Corporation

Table3

Accuracy and error of the sensor

Sensor(unit)	Range	Accuracy	Error
Temperature/℃	0~800	0.1	±0.5%
Voltage/V	0~60	0.01	±1%
Currency/A	0~ 10	0.01	1.5 %

Then the surface temperature of the heat collector was measured based on the measuring points show in figure 9 for the separated structure and hollow structure. And the engine was at idle condition with the speed 800rpm.



(1) Separated with spacer (2) Inner hollow structure

Fig.9 Diagram of the temperature mearment

The surface temperature of the heat collector with spacer was listed in table 4. It could be seen that the highest temperature was 200℃ located at measuring point 1 while the lowest temperature was 150℃ located at measuring point 4.

The difference in table 4 and 5 is calculated by the division of (Experiment results-Simulation results)/ Experiment results. From the difference of experiment and simulation results, it can be seen that the maximum value 7.39% appears in point 6. This difference might be the results of fluid hypothesis and error of small fluid area. However, the trend of temperature distribution is the same. So the model was able to simulate the heat collector.

Table 4

Temperature comparison of the surface of heat collector

Points	Experiment results/℃	Simulation results/℃	Difference/%	Points	Experiment results/℃	Simulation results/℃	Difference/%
1	200.1	196	2.05	5	155.1	165	-6.38
2	198.3	195	1.66	6	158.3	170	-7.39
3	160.8	170	-5.72	7	198.2	197	0.61
4	150.3	160	-6.45	8	160.4	175	-5.99

Table 5

Temperature comparison of the surface of heat collector

Points	Experiment results/℃	Simulation results/℃	Difference/%	Points	Experiment results/℃	Simulation results/℃	Difference/%
1	184.4	190	-3.04	5	183.2	190	-3.71
2	188.5	190	-0.80	6	187.3	189	-0.91
3	187.1	192	-2.62	7	184.2	189	-2.61
4	199.3	197	1.15	8	199.3	197	1.15

3.4The connection of TEG chips

The connection of the TEG chips has direct impact on the power output, so the number, external loads, and TEG chip output power should be considered. For this TEG system designed in our work, there are 40 F30345 TEG chips with maximum temperature 210°C and the temperature difference is generally between 120°C and 140°C. So the hybrid connection is selected which means four groups with 10 series connection TEG chips are connected in parallel. Then in order to ensure the output power is constant the charging circuit should be designed using commercial regulator module.

4. Energy recovery experiment

The TEG system was measured at idle speed and the output power was measured with natural air cooling method. The experiment results are listed in table 6. It can be found that the output voltage was 1.8V and the currency was 0.28A when the hot end temperature was 200°C and cold end was 74°C.So it can be concluded that it can be realized energy recovery with TEG system.

Table 6

Experiment results for different cooling methods

Cooling method	Hot end temperature/℃	Cold end temperature /℃	Voltage/V	Currency/A
Natural air	200.5	74.3	1.80	0.28

4.1TEG economy analyses

Based on the design and analysis of the TEG energy recovery system the TEG is manufactured and installed in the exhaust system of the engine which is shown in figure 1. Then the TEG economy is analyzed based on the experiment results.

It should be noted that as we all known the exhaust pressure drop increases and the motor power decreases and the consumption increases, in the experiment the pressure drop is so small that the engine fuel consumption increase can not be measured. So this part of energy decrease is not considered.

According to the above structure and analysis results, the temperature difference across the TEG ends can be maintained at around 140°C for the all engine operation conditions and the output voltage is 12V after a regulator. So the output power P is 12 ×2.5= 30W for this TEG structure.

Assuming the engine fuel consumption is b_e g / (kW • h), fuel density is ρ kg/m^3, the entire TEG output power is P W, vehicle work hour per day is t hour, annual days of working is d, the price of fuel a is RMB/L, and the TEG cost *m* is RMB, then the TEG saving rate b can be calculated by $b=\frac{b_e \times P}{\rho}\times 10^{-3}$ L/h and the cost recovery period y is computed as $y=\frac{m}{t\times d\times a\times b}$ years.

The TEG is comprised of TEG chips, radiation system, regulator, and other wire, where the TEG chips are the main cost and the total cost is 850RMB. The fuel consumption of the E491 is 310g/(kW·h) and the fuel density is 720 kg/m^3 then the saving rate b can be calculated as following.

$$b=\frac{b_e \times P}{\rho}\times 10^{-3}=\frac{310\times 30}{720}\times 10^{-3}=0.013 \text{ L/h}$$

If the vehicle is for transportation and assume *b* is 8 hours, *t* is 330 days, and the price of gasoline is 6.5 RMB/L, then the cost recovery period y can be calculated by:

$$y=\frac{m}{t\times d\times a\times b}=\frac{850}{8\times 330\times 6.5\times 0.013}=3.8 \text{ years.}$$

The result can be explained that it is possible to recycle energy using the TEG based on commercial TEG chips and structure designed in our wok, but the cost recovery period is a little longer.

5. Conclusion

Based on commercial TEG chips one TEG recovery system is designed for the IC engine exhaust system and some researches have also been done based on it. The conclusions are given as follows.

(1) For the heat collector, the inner structure with hollow is better for temperature uniform and pressure lose.

(2) The radiator composed with radiation fins can achieve temperature difference between the hot end and cold end of the TEG.

(3) It is possible to realize energy recovery using the TEG system based on commercial TEG chips and inner hollow structure, but the cost recovery time is a little bit longer.

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