

An Experimental Study of a Novel Prototype for Thermoelectric Power Generation from Vehicle Exhaust

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ABSTRACT

For a vehicle internal combustion engine, about 30% of the primary energy is discharged as waste heat in the exhaust gases. Waste heat recovery is a promising application of thermoelectric power generation (TEG). In this article, a novel prototype for TEG from vehicle exhaust has been proposed. After system modeling, an experiment structure has also been built and tested for further study. Results of theoretic analysis and experiment show the prototype employed for exhaust heat recovery is agreeable with the model. The prototype can generate a maximum power output of about 202W when hot side temperature is 473K with 4.04% of system thermal efficiency. System optimization and future improvement of the prototype has also been discussed. Finally, based on a vehicle made by our research funder, economic value for commercialization in diesel vehicles has been analyzed.

Keywords: thermoelectric power generation, thermoelectric module, exhaust heat recovery, thermal efficiency, waste heat recovery.

INTRODUCTION

According to the current assessment of vehicle engine, about 60% of the fuel energy is not used effectively [1]. If approximately 6% of the exhaust heat could be converted into electrical power, it would be possible to reduce the fuel consumption around 10% [2]. Increased concerns over vehicle fuel economy and exhaust emissions lead thermoelectric technology to be profitable in the automobile industry. Thermoelectric power generators (TEG) have many distinct advantages over other

technologies [3-6]: less maintenance, longer system life; the modularity makes application in a wide-scale range without significant losses in performance available; the absence of a working fluid avoids dangerous leakage into the environment; and silent operation also appears to be an important feature. Increased concerns over vehicle fuel economy leads thermoelectric technology to be profitable in the automobile industry.

Li Yan et al. [1] built a test rig to study the performance of TEG and did the economic analysis based on Dongfeng EQ14021 truck. Yodovard et al. [7] assessed the potential of waste heat TEG for diesel cycle and gas turbine cogeneration. It was shown that gas turbine and diesel cycle cogeneration systems can generate electricity at 33% and 40% of fuel input, respectively. The useful heat from stack exhaust of the system was estimated at 20% for a gas turbine and 10% for the diesel cycle. The Nissan Research Centre [8-10] has developed TEGs for different temperature ranges with a shape similar to Birkholz, U [11].

In previous studies [1-15], the TE module is mainly attached directly to the external of exhaust pipe. There are some disadvantages of such an approach:

- A. The different engine operating condition causes the exhaust temperature to vary widely, even at the same point of the exhaust pipe. This effects the performance of the TE modules, and hence the electrical power generated.
- B. Temperature range of the vehicle exhaust varies greatly from 500K to 1200K. But the normal TE module such as Bi₂Te₃ has a limited operating temperature range. Attaching TE module directly to the external exhaust pipe may increase the risk of burning TE modules.
- C. The closer to the muffler, the lower the exhausts temperature is. The exhaust pipe section used for TEG has uneven temperature distribution. That means it is usually need to purchase TE modules with a maximum operating temperature of 600K, but make some of them work at a temperature of 400K. And most TE materials exhibit peak performance at or near their maximum temperature limits. Thus, it is desirable to operate them near this limit and keep a steady hot side temperature.

To overcome disadvantages mentioned above, this article proposes

a novel TEG with a heat storage layer based on some performance tests of the TE module. This novel method has advantages as follows:

- A. The conducting oil can play a role of heat storage;
- B. Heat storage layer can minimize the impact of a sudden significantly exhaust temperature variation to the TE module and play a role of protection;
- C. This approach allows the pipe section used for TEG has a more even temperature distribution and all the mounted TE modules can work near their optimum performance for the most common working point of the engine.
- D. A more stable hot side temperature would make certain effort easier and more feasible. For example, multi-stage TE module or heat pipe can be employed in the system to improve the efficiency.

THERMOELECTRIC POWER GENERATION SYSTEM MODELING

Figure 1 shows a general TEG composed of several thermoelectric modules (TE modules) with a load resistance R_L connected. T_H and T_L are temperature of high and low temperature heat reservoirs respectively. Q_H and Q_L presents the heat absorbed from conducting oil by the TEG and the heat released to low temperature reservoir per unit time respectively. They can be expressed as follows [16, 17]:

$$Q_H = k_1 F_1 (T_H - T_1) = n [\alpha I T_1 + K(T_1 - T_2) - 0.5 I^2 R] \quad (1)$$

$$Q_L = k_2 F_2 (T_2 - T_L) = n [\alpha I T_2 + K(T_1 - T_2) + 0.5 I^2 R] \quad (2)$$

Where $a = a_p - a_N$, α_p and α_N are the Seebeck coefficients of the P and N type semiconductor legs respectively; I is electric current; T_1 and T_2 are hot-side and cold-side temperature of the generator; R is the semiconductor couple resistance; K is thermal conductance of the semiconductor couple (W/K); k_1 , k_2 are heat transfer coefficients in hot side and cold side heat exchangers respectively (W/m^2K); n presents the number of

P&N junctions; F_1, F_2 are heat transfer surface areas of hot side and cold side heat exchangers respectively.

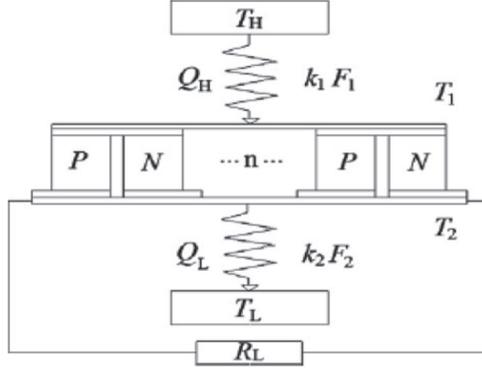


Figure 1. Schematic diagram of single stage TEG

This study focuses on low-temperature system, and the temperature difference between two reservoirs is relatively small accordingly. Therefore, the influence of Thomson effect could be ignored in this analysis[17]. For the purpose of facilitating the calculation, thermoelectric element is assumed to be insulated thermally, from its surroundings, except at the junction–reservoir contacts.

Combining (1) and (2),

$$T_1 = [k_1 F_1 k_2 F_2 T_H + nK(k_1 F_1 T_H + k_2 F_2 T_L) - nak_1 F_1 T_H I + (0.5nk_2 F_2 + n^2 K) R I^2 - 0.5aRn^2 I^3] \times [k_1 F_1 k_2 F_2 + nK(k_1 F_1 + k_2 F_2) + na(k_2 F_2 - k_1 F_1) I - n^2 a^2 I^2]^{-1} \quad (3)$$

$$T_2 = [k_1 F_1 k_2 F_2 T_L + nK(k_1 F_1 T_H + k_2 F_2 T_L) - nak_2 F_2 T_L I + (0.5nk_1 F_1 + n^2 K) R I^2 + 0.5aRn^2 I^3] \times [k_1 F_1 k_2 F_2 + nK(k_1 F_1 + k_2 F_2) + na(k_2 F_2 - k_1 F_1) I - n^2 a^2 I^2]^{-1} \quad (4)$$

Substituting Eqs. (3) and (4) into Eqs. (1) and (2), then combining these equations yields. The power output P and the thermal efficiency η of the TEG can be obtained as follow:

$$\begin{aligned} P &= Q_H - Q_L = n[aI(T_1 - T_2) - I^2 R] \\ &= \{0.5aRn^2 I^3(k_1 F_1 - k_2 F_2) - [nRk_1 F_1 k_2 F_2 + n^2 K R(k_1 F_1 + k_2 F_2) \\ &\quad + n^2 a^2(k_1 F_1 T_H + k_2 F_2 T_L)] I^2 + nak_1 F_1 k_2 F_2 (T_H - T_L) I\} \\ &\quad \times [k_1 F_1 k_2 F_2 + nK(k_1 F_1 + k_2 F_2) + na(k_2 F_2 - k_1 F_1) I - n^2 a^2 I^2]^{-1} \end{aligned} \quad (5)$$

$$\begin{aligned}
\eta = P / Q_H = & \{0.5\alpha R n^2 I^3 (k_1 F_1 - k_2 F_2) - [n R k_1 F_1 k_2 F_2 + n^2 K R (k_1 F_1 + k_2 F_2) \\
& + n^2 \alpha^2 (k_1 F_1 T_H + k_2 F_2 T_L)] I^2 + n \alpha k_1 F_1 k_2 F_2 (T_H - T_L) I\} \\
& \times \{k_1 F_1 [0.5 \alpha R n^2 I^3 - (0.5 n k_2 F_2 R + n^2 K R + n^2 \alpha^2 T_H) I^2 \\
& + n \alpha k_2 F_2 T_H I + n K k_2 F_2 (T_H - T_L)]\}^{-1}
\end{aligned} \tag{6}$$

Power output and thermal efficiency of the TEG in Equations (3) and (4) are the important theoretical basis for analysis and optimization of the generator system performance.

THE EXPERIMENT SYSTEM

The System Design

In this article, a new TEG design prototype is proposed. It is inspired by designs of Hi-z Company [14, 18-20]. The proposed structure is an aluminum central support tube, cylindrical for its inner part and hexahedral for its outer surface; between them, there are conducting oil which can play the role of heat storage and minimize the impact of exhaust temperature variation, as shown in Figure 2. The TEG structure is proposed to be mounted after the catalyst converter, where the temperature range of the exhaust gases is between 450K and 670K. One important advantage is that it decreases the pressure drop across the generator and results in a lower back pressure on the engine.

This prototype has a length of 355mm and side length of the hexahedral structure is 75mm. Then the structure can support two kinds of common size and low cost commercial Bi₂Te₃ TE modules provided by our funder, which are 40mm x 40mm x 4.2mm and 60mm x 60mm x 4.2mm. In this article, the structure employs eight TE modules (size 40mm x 40mm x 4.2mm) on each side and forty-eight TE modules for total. The diameter of the inner tube is $D_{\text{tube}} = 100\text{mm}$, which is around the average diameter of most coach and lorry's exhaust pipe. After leak detection for the structure, there is only a port left to perfuse conducting oil, it is sealed by leak-proof screw. Upon the TE modules, the cold fluid loop or a second stage TE modules and their cold fluid loop will be mounted depends on the experimental demand.

The Setup of Structure

The experiment system is mainly consisted of four parts: the hot side, thermoelectric converter, the cold side and the data acquisition system. The experiment block diagram is shown in Figure 3.

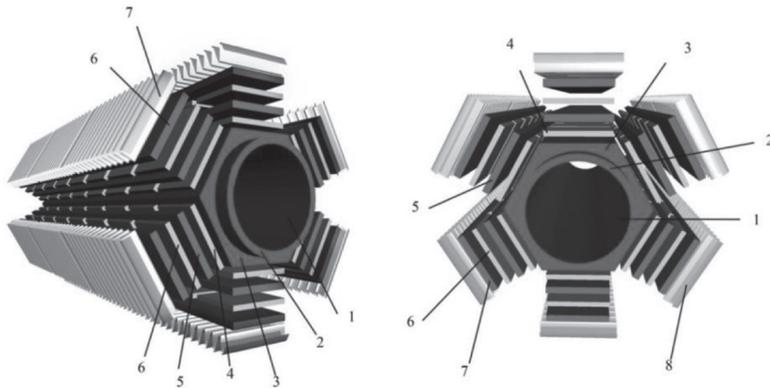


Figure 2. Design of the Prototype

1. Inner side of the tube
2. Central support tube
3. Conducting oil
4. TE module
5. Cooling plate
6. The second stage TE module
7. The second stage cooling plate
8. Fin

*This is the final design for two-stage TE generator employing heat pipe. Just 1 to 5 is for this article.

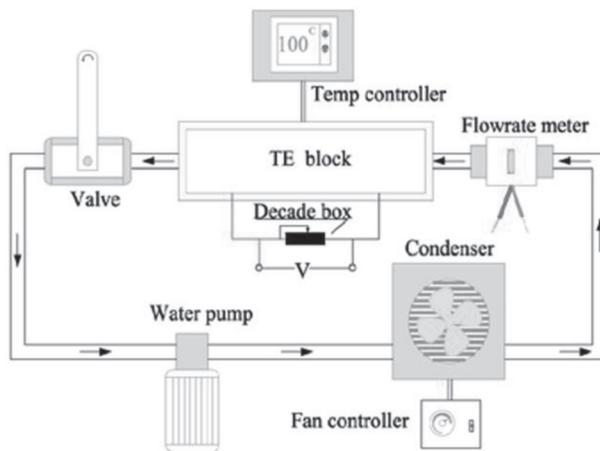


Figure 3. Block diagram for exhaust heat recovery power generation test rig

The Hot Side

The proposed hexahedral structure and its inner part is the hot side. Eight TE modules are mounted on each side. Before the hexahedral structure is mounted in the vehicle, an alternative structure is chosen to test feasibility in a lower cost. The size of the flat structure is 450mm 350mm 15mm, exactly the same as commencement of the hexahedral structure. There is conducting oil with a maximum safe temperature of 673K in the cavity of the structure. For minimum heat diffusion to the environment and a more accurate calculation on heat transfer to the hot side, electric heating rods are chosen. Special jacks are reserved for them to insert the structure, as shown in Figure 4. The power of electric heating rods is adjustable, so the hot side temperature can be controlled upon experiment needs. In order to reduce side heat losses from the heat exchanger and thermoelectric converter, the fully assembled unit is surrounded by insulation board with the thickness of 5mm.

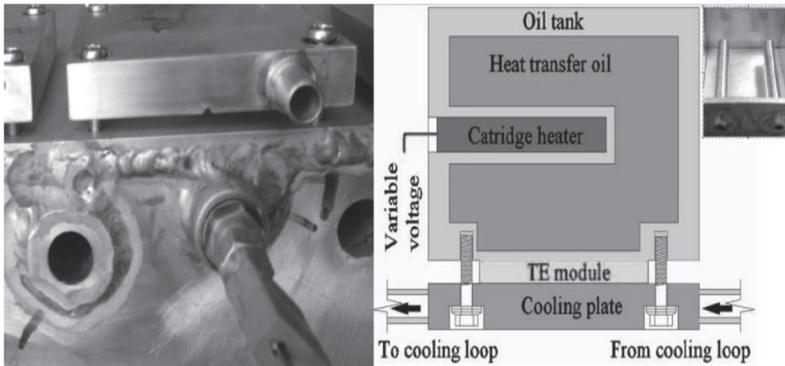


Figure 4. Heating Rods and the structure for them

The Thermoelectric Converter

All 48 TE modules, arranged in six lines, are fixed on upper surface of the flat structure. They are connected electrically in series, but thermally in parallel. TE modules are sandwiched between the upper side of the structure and the aluminum cooling plates, they are fixed together with screws as shown in Figure 5. Different cooling methods will be tested in the experiments, but here only water-cooling is used to demonstrate the mounted method. For the pressure on TE modules is an very important factor affecting the efficiency of power generation, to ensure every TE module works in the same operating conditions and obtain a

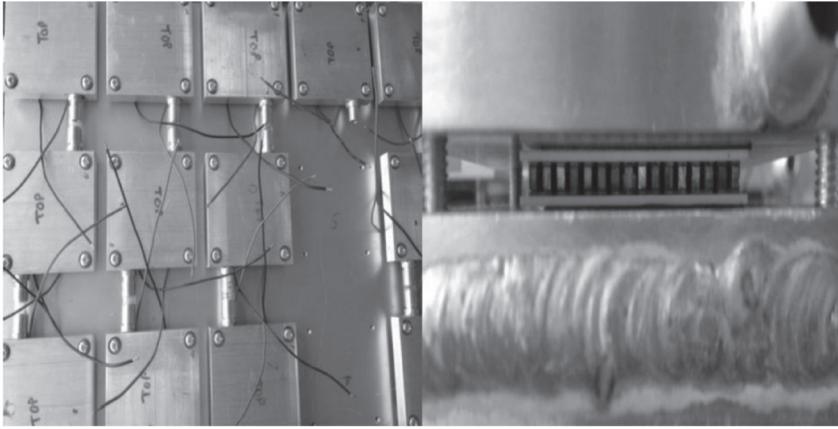


Figure 5. Installation of TE modules

more accurate data, all TE modules are mounted individually, so their cold junctions. Meanwhile, to minimize thermal diffusion through the screws and make the system be elastic to compensate the different thermal expansion coefficients, crinkle washer, fiber washer and flat metal washer are used with each screw.

The Cold Side

Water-cooling method is proposed in this study to keep the temperature difference. In order to provide a uniform temperature distribution and a uniform pressure across the surface of the TE modules, forty eight aluminum cooling plates are chosen as the thermal spreader in this study. There are flow channels in the aluminum cooling plate to enhance the heat transfer as Figure 6 shows.

Measurement System

All the parameters are sampled every 5s, over a period of about 2 hours until the steady operation. All the temperature-measuring devices have the accuracy of 0.01K. The power outputs of TEG are obtained by measuring the TEG voltage outputs on the adjustable load resistor at various load resistances.

Electrical Insulation and Thermal Insulation

The electrical insulation between the heat source and TE modules is provided by a mica foil (0.1 mm thick). In order to reduce the thermal

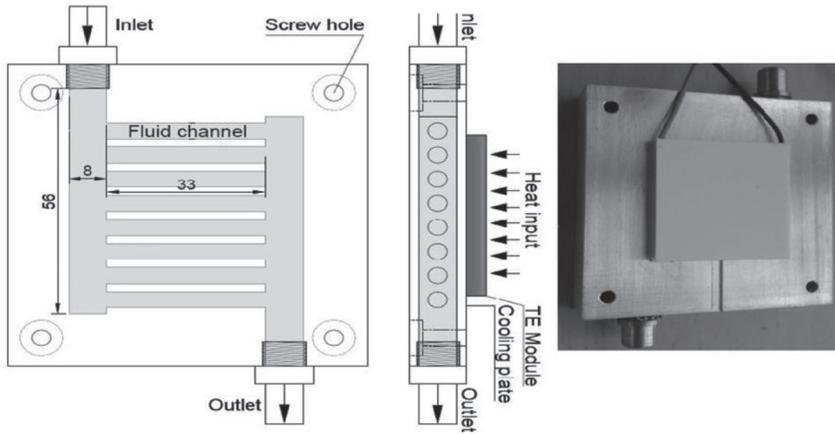


Figure 6. Installation of aluminum cooling plate

bypass losses, all the space, for example, between the heat source and the cold sink, the free space between the pellets of the thermoelectric pair and the space among the TE modules is stuffed with the super-wool. Thermal grease is also placed between all TE modules and their interfaces to minimize the thermal contact resistance.

EXPERIMENTAL RESULTS AND DISCUSSION

For this test rig, hot-side temperature is relatively controllable and stable. Based on different engine operating state, measurements are carried out for four values of the electric power supplied to the heater. System performance is subject to temperature difference and cold-side heat transfer. System maximum power output can be attained when load resistance is equal to inner resistance (here, 3.8Ω for single TE module and 182.4Ω for total).

Then, a series of system voltage output and power output (P_{out}) changing with temperature difference (ΔT) for water cooling are measured under the 4 different heater powers set before.

Figure 7 shows the trend of maximum power output versus temperature difference. The P_{out} increases with increasing ΔT . The data distribution is typical of a second order polynomial of ΔT . The theoretical data is in good agreement with the experimental data. TH refers to hot side temperature. Next, Figure 8 shows the maximum voltage output

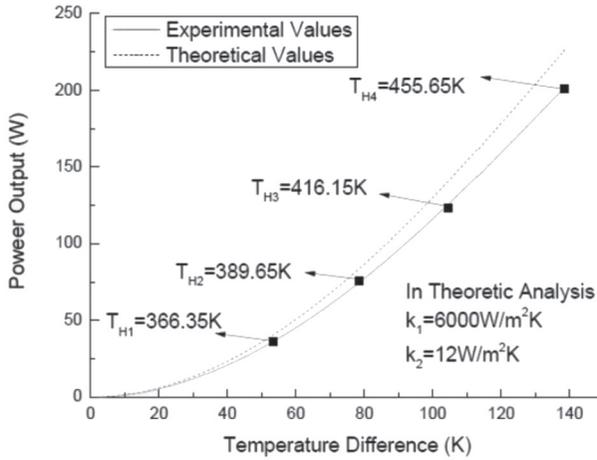


Figure 7. The variation of the power output with temperature difference for nature water cooling

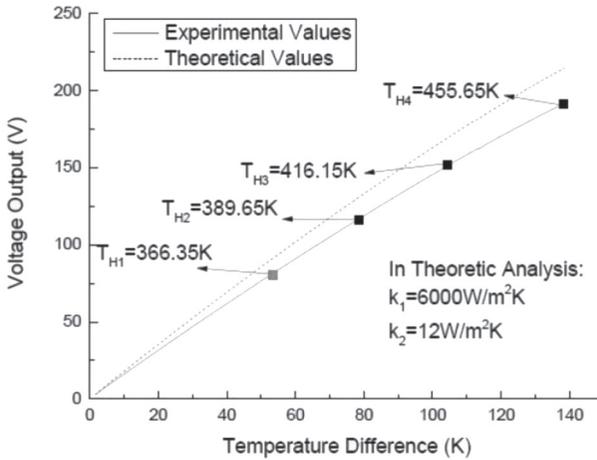


Figure 8. The variation of the voltage output with temperature difference for nature water cooling

(V_{out}) increases with a boost of temperature difference (ΔT) in a linear trend. Moreover, each addition of 10 K to ΔT will result in 15V addition to V_{out} . The results given by the theoretical model coincide with experimental ones, whether in the qualitative aspect or the quantitative one.

It can be seen that the theoretical model over-predicts performances

of TEG in the entire temperature range. At low hot side temperature and temperature difference, there is relatively good agreement between the predicted performances and the measurements. However, at high temperatures, the deviation of the prediction arises largely with increasing hot side temperature and temperature difference. The deviation between them is result from the fact that not all the heat losses are taken into account in the theoretical model. In fact, the heat losses that have been observed experimentally increase significantly with increasing hot side temperature, although the TEG is thermally insulated outside. On the other hand, the properties of the thermoelectric materials are assumed to be constants in the model. In practice, all thermoelectric properties of the modules vary with temperature. So this assumption has been found to introduce errors into the model.

Table 1 summarizes the experimental data obtained when the system operates stably in the four different conditions.

The TEG obtains its best results when the power into the system is 6140W in this study. The generated electric power is 201.58W. We pay

Table 1: Generation power and efficiency of the prototype

Generator	Test No.	Test No.	Test No.	Test No.
	1	2	3	4
Power into the heater (W)	2496	3744	4656	6240
Conducting Oil Temperature T_{Oil} (K)	385.35	413.59	447.2	498.36
Hot side temperature T_H (K)	366.625	389.65	416.19	455.65
Temperature Difference ΔT (K)	59.81	80.99	104.818	138.41
Maximum Power Output (W)	45.14	79.26	126.39	201.58
Maximum Voltage Output (V)	90.74	120.24	151.84	191.75
Heat Output (W)	1798.02	2415.04	3473.31	4430.62
Heat Loss (W)	66.80	88.46	114.02	150.82
Cooling Water				
Water- in Temperature (K)	303.303	303.9	305.201	309.127
Water- out Temperature (K)	303.46	304.127	305.597	309.679
Flow Rate (m^3/S)	0.0015	0.0015	0.0015	0.0015
Efficiency				
Single Module Efficiency	18.8%	33.1%	52.6%	83.8%
Thermal Efficiency of the TEG	2.31%	2.98%	3.29%	4.04%
Power area of modules' surface (m^2)	0.0768			

more attention to the thermal efficiency of the TEG, as expressed by Eq. (6), not the conversion efficiency at present. This is not only because the amount of waste heat in this study is more difficult to measure and evaluate than electric power, but also because the waste heat utilized here is assumed to be no-cost. However, experimental results shown in Figure 9 indicate that the thermal efficiency of this TEG is only a few percent (4.04% when TH reaches 455.65 K), and the efficiency increases slightly with a boost of temperature difference.

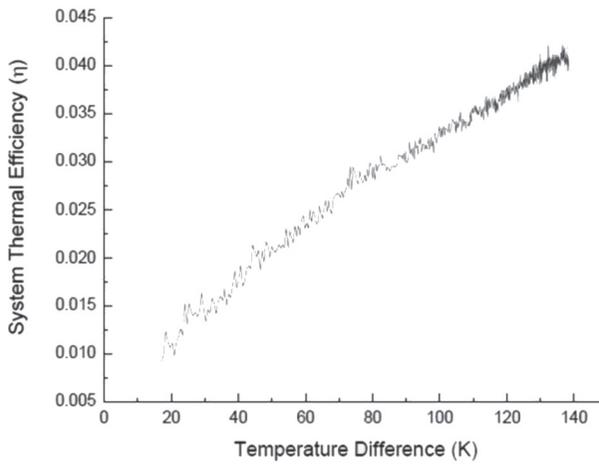


Figure 9: The variation of thermal efficiency with temperature difference

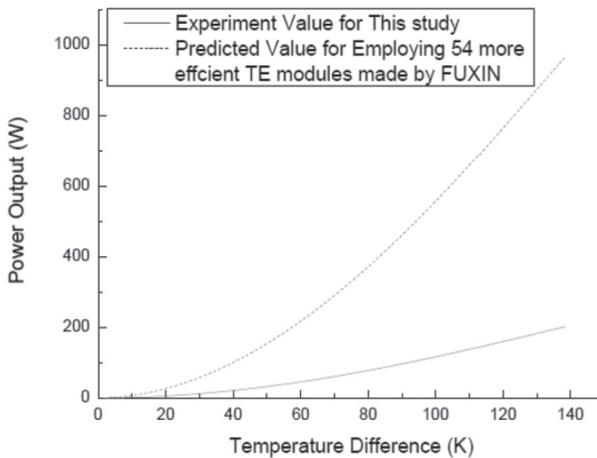


Figure 10: Predicted power output for a more efficient system

Employing more efficient TE modules and adding TE modules in series are good measures for system improvement. The predicted value for employing 54 TE modules (Type: TEG1-127-2.8-1.6-250, size 62mm × 62mm, Matched Load Output Power 21.3W) is indicated in Figure 10. A 966W power output can be obtained when the temperature difference is about 140K. However, the cost of adding TE modules is relatively high and the space limitation need to be considered.

It is important to observe the high temperature of the conducting oil, 499K, compared to the hot side temperature of the TE modules, 455K, as shown in Figure 11. The difference between the two grows as the temperature increases. Possibly, this fact is related to the material of the structure, thermal grease between all TE modules and their interfaces. They increase the thermal resistance. Reducing the thermal resistance between them will effectively improve the system performance. However, the outside temperature of the insulated structure is very stable, which means the structure is in a good insulation condition.

ECONOMIC VALUE AND COMMERCIALIZATION

A vehicle produced by China FAW Group Corporation is set as the example for economic analysis. The diesel fuel consumption is 22.5 L/100km. Diesel generator fuel consumption is 210 -240 g/(kWh). The

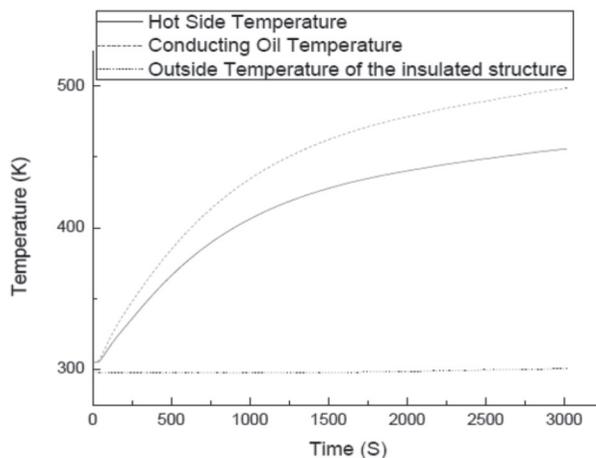


Figure 11: Temperature variations in the experiment

density of diesel fuel is 0.86 g/ml. The exhaust temperature at the exports of catalytic converter is about 673K, it meets the requirements and there is enough space for the proposed structure to be mounted. Table 2 can show the economic value of this prototype in a certain extent.

Table 2: Cost of the Prototype

Item	Price(£)	Number	Total (£)
The support structure (Materials and manufacture)			300
TE modules	8	48	384
Aluminum cooling plate (including inside copper tube)			100
Labor cost			400
Other material and tools (super wool, connection pipe, screws, conducting oil, thermal plastic, special screwdriver and so on)			80
In Total (£)			1264 pounds

Considering the different output power in vehicle's different operating condition, we set 180 W is the rough average output power of the system. The fuel-saving of the system is:

$$240 \times 180 \times 10^{-3} / 0.86 \times 10^3 = 0.05 \text{L/h}$$

Assume that the vehicle working twelve hours a day, 330 days a year and the price of diesel fuel in UK is 1.5 pounds/L. The cost recovery period is:

$$1264 / 1.5 \times 0.05 \times 12 \times 330 = 4.25 \text{ year}$$

CONCLUSION

To recover the heat from vehicle exhaust gas, a novel TEG prototype is proposed in this article. The experiment structure is also constructed and tested for further studies. Through the results of theoretical analysis and experiment, reasonability of this prototype employed for exhaust heat recovery has been verified. The prototype can generate a maximum power output of about 202W when hot side temperature is

473K with the system thermal efficiency of 4.04%.

In the next step, we will do further studies on system optimization, mainly focus on system power capacity and energy efficiency. Another two experiment structure will be constructed in a more effective manner for the potential of waste heat power recovery. One will employ two stage TE modules, and the other will employ heat pipe on the cold side.

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