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

Changxin Liu, Wei Zhong Li

ABSTRACT

In a vehicle's internal combustion engine, about 30% of the primary energy is discharged as waste heat in the exhaust gases. Waste heat recovery (WHR) is a noticeable promising application of thermoelectric power generation (TEG). This is essentially a case of mobile cogeneration where a vehicle utilizes a significant fraction of the fuel energy in the form of combined heat and power. 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 reasonably show this prototype can be employed for exhaust heat recovery. 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: exhaust heat recovery, mobile cogeneration, combined heat and power, thermal efficiency, thermal efficiency thermoelectric power generation, thermoelectric module, 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 vehicle's overall fuel consumption by 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 performance losses; 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 the 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 that:

A. The different engine operating condition causes the exhaust temperature to vary widely, even at the same point along the exhaust pipe. This affects 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 thermoelectric (TE) module such as Bi_2Te_3 has a limited operating temperature range. Attaching TE module directly to the external exhaust pipe may increase the risk of burning the 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 TE modules with a maximum operating temperature of 600K are needed, but some of them will be working at 400K. And most TE materials exhibit peak performance at or near their maximum temperature limits. Thus, for optimal efficiency it is desirable to operate them near this limit and keep a steady hot side temperature.

To overcome the disadvantages mentioned above, we propose 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 to operate at 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 makes the system easier to operate 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 (TE) modules with a load resistance R_L. T_H and T_L are temperature of high and low temperature heat reservoirs respectively. Q_H and Q_L represent the heat absorbed from conducting oil by the TEG and the heat released to the low temperature reservoir per unit time respectively. They can be expressed as follows [16, 17]:

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

$$Q_L = k_2 F_2 (T_2 - T_L) = n\left[\alpha I T_2 + K(T_1 - T_2) + 0.5 I^2 R\right] \tag{2}$$

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

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

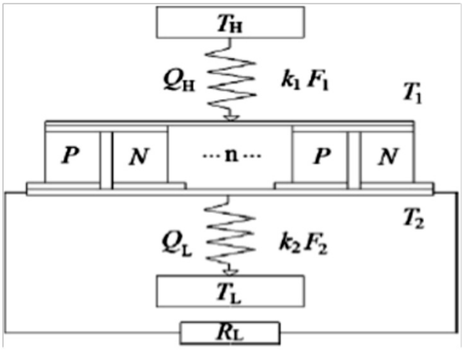

Figure 1: Schematic diagram of single stage TEG

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),

$$\begin{aligned} T_1 = {} & [k_1F_1k_2F_2T_H + nK(k_1F_1T_H + k_2F_2T_L) - n\alpha k_1F_1T_HI + \\ & (0.5nk_2F_2 + n^2K)RI^2 - 0.5\alpha Rn^2I^3] \times \\ & [k_1F_1k_2F_2 + nK(k_1F_1 + k_2F_2) + n\alpha(k_2F_2 - k_1F_1)I - n^2\alpha^2I^2]^{-1} \end{aligned} \tag{3}$$

$$\begin{aligned} T_2 = {} & [k_1F_1k_2F_2T_L + nK(k_1F_1T_H + k_2F_2T_L) - n\alpha k_2F_2T_LI + \\ & (0.5nk_1F_1 + n^2K)\, RI^2 - 0.5\alpha Rn^2I^3] \\ & \times [k_1F_1k_2F_2 + nK(k_1F_1 + k_2F_2) + n\alpha\, (k_2F_2 - k_1F_1)I - n^2\alpha^2I^2]^{-1} \end{aligned} \tag{4}$$

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:

$$\begin{aligned} P & = Q_H - Q_L = n\,[\alpha I(T_1 - T_2) - I^2R] \\ & = \{0.5\alpha Rn^2I^3\,(k_1F_1 - k_2F_2) - [nRk_1F_1k_2F_2 + n^2KR(k_1F_1 + k_2F_2) \\ & + n^2\alpha^2\,(k_1F_1\,T_H + k_2F_2\,\mathrm{T_L})I^2 + n\alpha k_1F_1k_2F_2(T_H - T_L)\,I\}\times \\ & [k_1F_1k_2F_2 + nK(k_1F_1 + k_2F_2) + n\alpha\,(k_2F_2 - k_1F_1)I - n^2\alpha^2I^2]^{-1} \end{aligned} \tag{5}$$

$$\begin{aligned} \eta = {} & P\,/\,Q_H = \{0.5\alpha Rn^2I^3\,(k_1F_1 - k_2F_2) - \\ & [nRk_1F_1k_2F_2 + n^2KR(k_1F_1 + k_2F_2) + n^2\alpha^2 \\ & (k_1F_1\,T_H + k_2F_2\,\mathrm{T_L})I^2 + n\alpha k_1F_1k_2F_2(T_H - T_L)\,I\} \\ & \times \{k_1F_1[0.5\alpha Rn^2I^3 - (0.5nk_2F_2R + n^2KR + n^2\alpha^2T_H)I^2 \\ & n\alpha k_2F_2T_HI + nKk_2F_2(T_H - T_L)]\}^{-1} \end{aligned} \tag{6}$$

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.

EXPERIMENT SET UP

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.

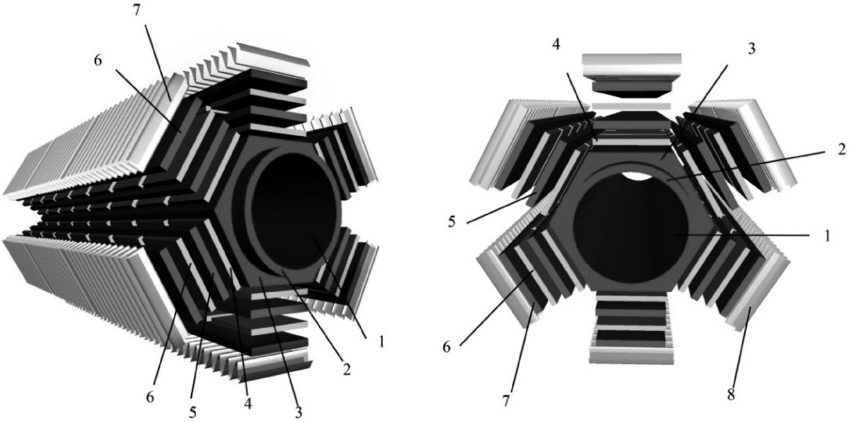

Figure 2: Design of the Prototype
(1) Inner side of the tube, (2) Central support tube, (3) Conducting oil, (4) TE module, (5) Cooling plate, (6) The second stage TE module, (7) The second stage cooling plate, (8) Cooling fin. This is the final design for two-stage TE generator employing heat pipe (elements 1 to 5 apply to the experiment reported in this paper).

This prototype has a length of 355mm and side length of the hexahedral structure is 75mm.

The structure can support two kinds of common size and low cost commercial Bi_2Te_3 TE modules provided by our funder, which are 40mm 40mm 4.2mm and 60mm 60mm 4.2mm. In this article, the structure employs eight (8) TE modules (size 40mm 40mm 4.2mm) on each side and forty eight (48) TE modules for total. The diameter of the inner tube is = 100mm, 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.

Experimental Structure Setup

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

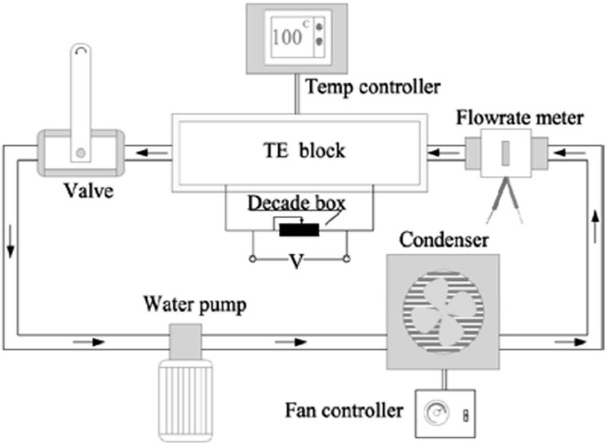

Figure 3: Block diagram for exhaust heat recovery power generation test rig

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 it 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. In order 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.

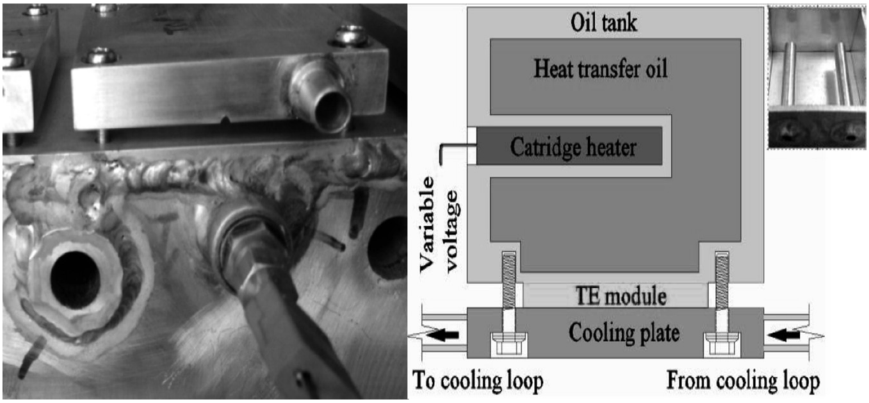

Figure 4: Heating Rods and the structure for them

The Thermoelectric Converter

All forty-eight 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 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.

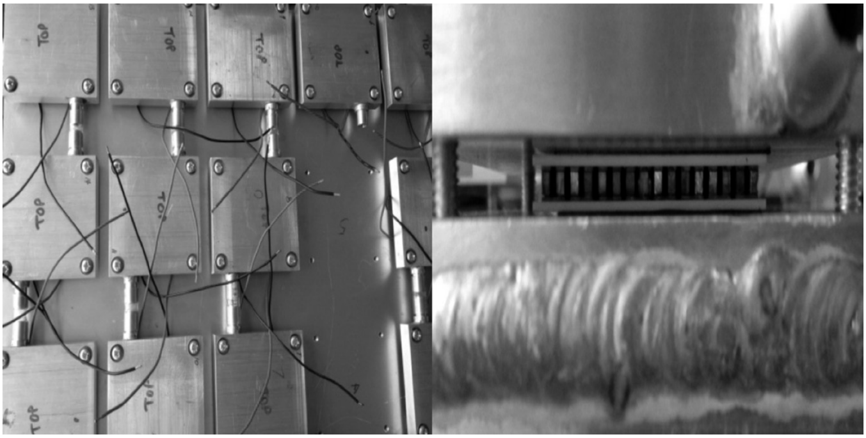

Figure 5: Installation of TE modules

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.

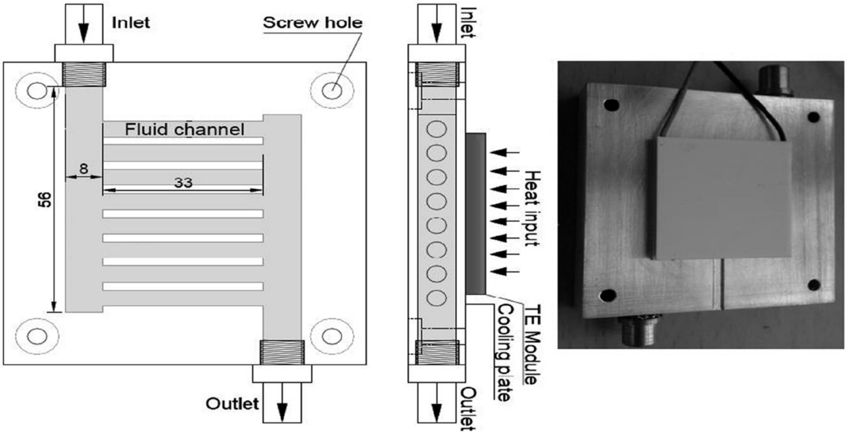

Figure 6: Installation of aluminum cooling plate

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 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 superwool. 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 are in good agreement with the experimental data. TH refers to hot side temperature.

As shown in Figure 8, the maximum voltage output (V_{out}) increases with a boost of temperature difference (ΔT) in a linear trend. What is more, 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

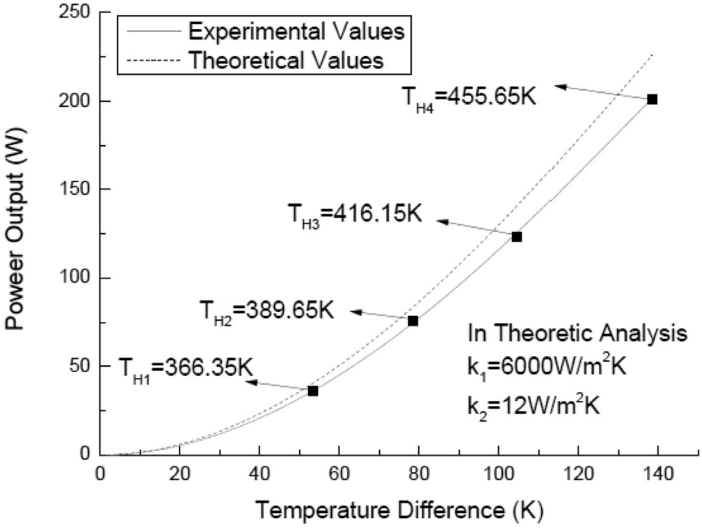

Figure 7: The variation of the power output with temperature difference for nature water cooling

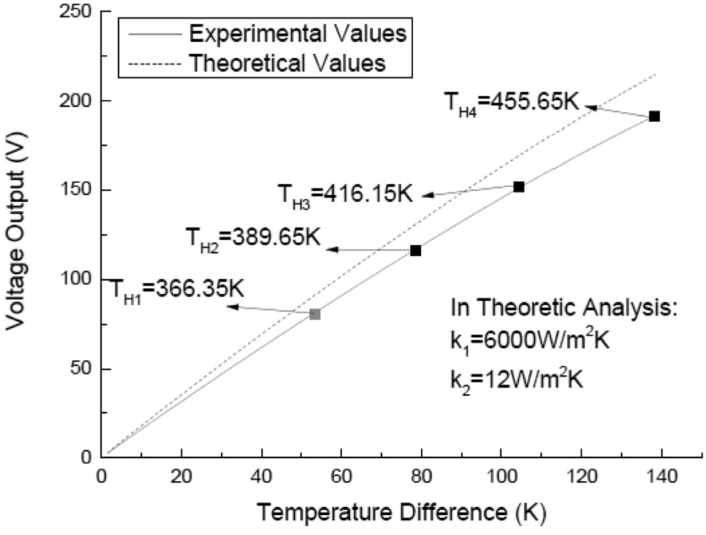

Figure 8: The variation of the voltage output with temperature difference for nature water cooling

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 is the summarized experimental data obtained when the system operating 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 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 T_H reaches 455.65 K), and the efficiency increases slightly with a boost of temperature difference.

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.

Table 1: Generation power and efficiency of the prototype

Generator	Test No. 1	Test No. 2	Test No. 3	Test No. 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			

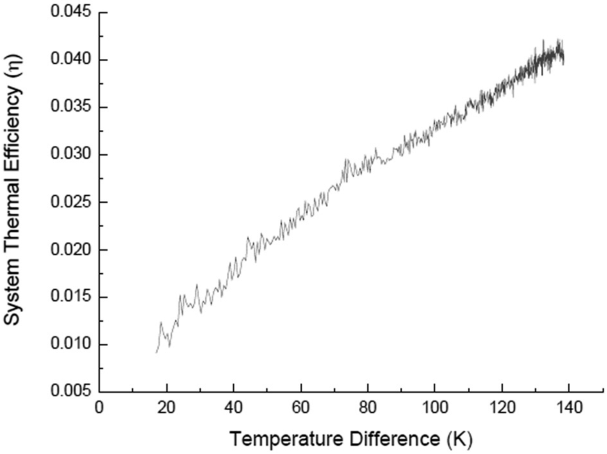

Figure 9: The variation of thermal efficiency with temperature difference

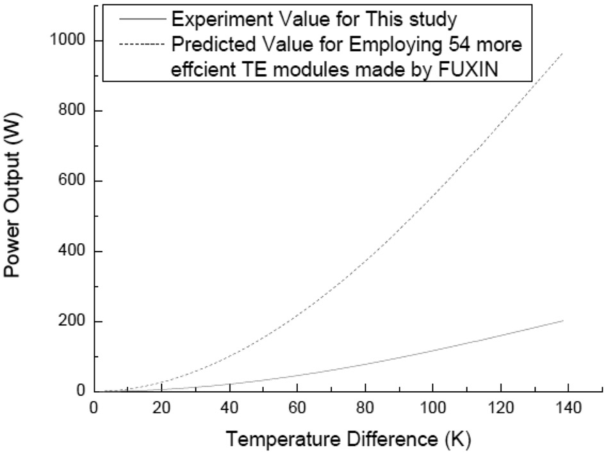

Figure 10: Predicted power output for a more efficient system

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 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

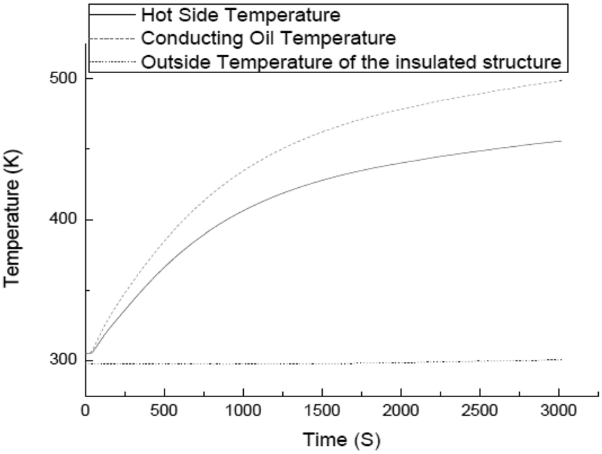

Figure 11: Temperature variations in the experiment

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.

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:

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

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:

$$1264/1.5 \text{ x } 0.05 \text{ x } 12 \text{ x } 330 \approx 4.25 \text{ year}$$

CONCLUSION

To recover the heat from vehicle exhaust gas, a novel TEG prototype is proposed is 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

Table 2: Cost of the Prototype

Item	**Price(£)**	**Numbers**	**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**		

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.

Acknowledgements

The author wishes to sincerely thank: China FAW Group Corporation for funding the research; Guangdong FuXin Corporation for the kind help for providing various TE modules.

References

[1] Xu, L., et al., Experimental study of thermoelectric generation from automobile exhaust. *Journal of Tsinghua University* (Science and Technology), 2010. 2: p. 031.

[2] Vázquez, J., et al. State of the art of thermoelectric generators based on heat recovered from the exhaust gases of automobiles. in Proc., 7th European Workshop on Thermoelectrics. 2002. IEEE Piscataway, NJ.

[3] Omer, S.A. and D.G. Infield, Design and thermal analysis of a two stage solar concentrator for combined heat and thermoelectric power generation. *Energy conversion and management*, 2000. 41(7): p. 737-756.

[4] Yadav, A., K. Pipe, and M. Shtein, Fiber-based flexible thermoelectric power generator. *Journal of Power Sources*, 2008. 175(2): p. 909-913.

[5] Jinushi, T., et al. Development of the high performance thermoelectric modules for high temperature heat sources. in Materials science forum. 2007. Trans Tech Publ.

[6] Ismail, B.I. and W.H. Ahmed, Thermoelectric Power Generation Using Waste-Heat Energy as an Alternative Green Technology. Recent Patents on Electrical Engineering, 2009. 2(1).

[7] Yodovard, P., J. Khedari, and J. Hirunlabh, The potential of waste heat thermoelectric power generation from diesel cycle and gas turbine cogeneration plants. *Energy sources*, 2001. 23(3): p. 213-224.

[8] Ikoma, K., et al. Thermoelectric module and generator for gasoline engine vehicles. in Thermoelectrics, 1998. Proceedings ICT 98. XVII International Conference on. 1998. IEEE.

[9] Shinohara, K., et al., Application of thermoelectric generator for automobile. *Journal of the Japan Society of Powder and Powder Metallurgy*, 1999. 46(5): p. 524-528.

[10] Ikoma, K., et al., Thermoelectric Energy Conversion Materials. Thermoelectric Generator for Gasoline Engine Vehicles Using Bi2Te3 Modules. *Journal of the Japan Institute of Metals*, 1999. 63(11): p. 1475-1478.

[11] LaGrandeur, J., et al. Automotive waste heat conversion to electric power using skutterudite, TAGS, PbTe and BiTe. in Thermoelectrics, 2006. ICT'06. 25th International Conference on. 2006. IEEE.

[12] Woo, B.C. and H.W. Lee, Relation between electric power and temperature difference for thermoelectric generator. *International Journal of Modern Physics* B, 2003.

17(08n09): p. 1421-1426.
[13] Birkholz, U., et al. Conversion of waste exhaust heat in automobiles using FeSi2 thermoelements. in Proc. 7th International Conference on Thermoelectric Energy Conversion. 1988.
[14] Kushch, A.S., et al. Thermoelectric development at Hi-Z technology. in Thermoelectrics, 2001. Proceedings ICT 2001. XX International Conference on. 2001. IEEE.
[15] Meleta, Y.A., et al. Truck co-generation system based on combustion heated thermoelectric conversion. in Energy Conversion Engineering Conference, 1997. IECEC-97., Proceedings of the 32nd Intersociety. 1997. IEEE.
[16] Gou, X., H. Xiao, and S. Yang, Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system. *Applied energy*, 2010. 87(10): p. 3131-3136.
[17] Chen, J. and C. Wu, Analysis on the performance of a thermoelectric generator. *Journal of energy resources technology*, 2000. 122(2): p. 61-63.
[18] Pramanick, A. and P. Das, Constructal design of a thermoelectric device. *International journal of heat and mass transfer*, 2006. 49(7): p. 1420-1429.
[19] Bass, J.C., N. Elsner, and F. Leavitt. Performance of the 1 kW thermoelectric generator for diesel engines, in AIP Conference Proceedings. 1994.
[20] Bass, J., A. Kushch, and N. Elsner. Development of a self-powered pellet stove. in Proc. 19th International Conference on Thermoelectrics. 2000.

ABOUT THE AUTHORS

Weizhong Li (1955) is Professor of Dalian University of Technology. His Ph.D. is from Nottingham Trent University (1998-2002). Prof. Li's research activities and expertise include: evaluation of the heat exchanger and heat transfer enhancement mechanism, sustainable energy and waste heat recovery. He can be reached at Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116023, P.R. China. E-mail: wzhongli@dlut.edu.cn, Tel: +86 (0) 411 84708774

Changxin Liu (1981) is a Ph.D. candidate of Dalian University of Technology and was a Joint-Ph.D. student in University of Nottingham. Mr. Liu's research activities and expertise include: Sustainable energy, waste heat recovery and thermoelectric power generation. He can be reached at (a) Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116023, P.R. China, and (b) Energy and at Sustainability Research Division, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK.