An Experimental Study of a Two-stage Thermoelectric Generator Using Heat Pipe in Vehicle Exhaust

Changxin Liu and Wei Zhong Li

ABSTRACT

Heat recovery from vehicle exhaust is a promising application of thermoelectric power generation (TEG). In our previous study, a single stage TEG with 4.04% system thermal efficiency has been tested. To improve the power output and the efficiency, a novel prototype two-stage TEG employing heat pipe from vehicle exhaust has been proposed. After system model being established, an experimental set up has also been built and tested for further study. Results of both theoretic analysis and experimental results show the viability of the prototype TEG for exhaust heat recovery. The prototype can generate a maximum power of about 250W when the hot side operates at 473K. The system thermal efficiency reaches 5.37%; it is improved by 32% comparing to single stage TEGs 4.04% in the same operating conditions. Finally, system optimization and future improvement of the prototype are discussed.

Keywords: automotive cogeneration; exhaust heat recovery; energy conversion, heat pipe; thermoelectric generators; thermoelectric module.

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, about the same quantity of driving energy that demands the production of electrical power would be released and then, it would be possible to reduce the fuel consumption around 10%[2]. Increased concerns over vehicle fuel economy leads thermoelectric technology to be profitable in the automobile industry. Thermoelectric power generators (TEG) have many distinct advantages over other technologies [3-6]: The absence of moving components results in less maintenance, longer system life, and an increase of reliability; the modularity makes application in a wide-scale without significant losses in performance; the absence of a working fluid avoids dangerous leakage into the environment; and silent operation also appears to be an important feature. Because of the significant heat recovery converted to electrical power, a vehicle power plant with an internal combustion engine and TEG constitute an automotive cogeneration system.

We have studied single stage TEG on vehicle exhaust recovery and domestic thermoelectric cogeneration system. For vehicle exhaust recovery[7,8], the system thermal efficiency reaches 4.04% when the hot side temperature is about 460K. Yodovard, et al. [9] 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 waste 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 [10-12] has developed TEGs for different temperature ranges with a shape similar to Birkholz, et al. [13]. But only one stage TE module is employed in those TEGs.

Due to the performance limits of thermoelectric materials, TEG of two-stages or more should be applied to improve the level of thermodynamic performance. Based on our previous experimental study of single stage and two-stage TEG, enhancing cold-side heat transfer capacity (especially for the first stage) in a proper range is an effective way to promote system performance to a certain extent, though there is a limit on power improvement. For its advantages, such as large quantities of heat transported through a small cross-sectional area with no additional power input to the system, advanced maintainability, high reliability, simpler structure and smaller volume, heat pipe is chosen to strengthen the heat transfer between the two stages.

There are few experimental studies for the performance analysis and optimization of two-stage TEG employing heat pipe except for Zhou [14] and Chen, et al. [15]. They built a model of two-stage TEG and

analyzed the performance of it using the combination of finite-time thermodynamics and non-equilibrium thermodynamics.
In previous studies [10,16-20], the TE module is mainly attached directly to the external of exhaust pipe to generate power. There are some disadvantages of such an approach:

A. The different engine operating conditions cause the exhaust temperature to vary, even at the same point of 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 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 TE modules.

C. The exhaust pipe section used for TEG has uneven temperature distribution. The closer to the muffler, the lower the exhausts temperature is. 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.

In order to overcome disadvantages of the above, in this article, a novel two-stage TEG prototype employing heat pipe is addressed based on some performance tests of the TE module. Then, the feasibility is proved through experiments and performance is optimized through the theoretical model. This novel method has the following advantages:

A. The heat transfer oil can play a role of heat storage;

B. Heat storage layer can dampen the impact of a sudden exhaust temperature variation to the TE module and play a protective role;

C. This approach allows the pipe section used for TEG a more even temperature distribution and all the mounted TE modules can work near their optimum performance for the most common operating range of the engine.

D. Two stage TE modules can significantly improve the efficiency and power output.

TWO-STAGE TEG SYSTEM MODELING

Figure 1 is a schematic diagram of a two-stage TEG consisting of a top stage with m pairs of thermoelectric elements and a bottom stage with n pairs of thermoelectric elements. The total number of pairs is M, i.e. M = m + n[14,15].

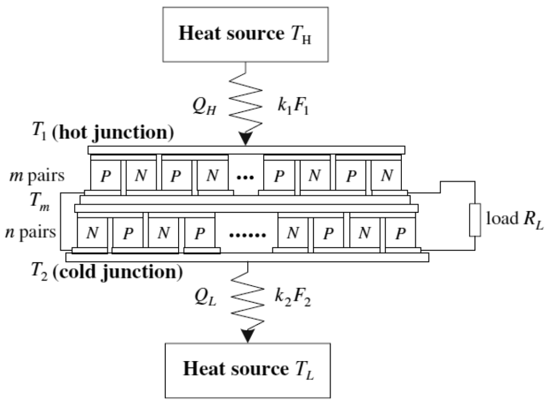

Figure 1. A schematic diagram of a two-stage TEG

Assuming that the heat-transfers between the hot and cold junctions of the TEG and their respective reservoirs obey Newton's law, the following equations apply at the three junctions:

$$Q_H = k_1F_1(T_H - T_1) = maIT_1 - mI^2R/2 + mK(T_1 - T_m) \quad (1)$$

$$Q_m = maIT_m - mI^2R/2 + mK(T_1 - T_m) = naIT_m - nI^2R/2 + nK(T_m - T_2) \quad (2)$$

$$Q_C = k_2F_2(T_2 - T_C) = naIT_2 - nI^2R/2 + nK(T_m - T_2) \quad (3)$$

Where a = $a_p - a_n$, a_p and a_n , and are the Seebeck coefficients of the p-and n-type semiconductor legs for each TE modules, Q_m is the rate of heat flow between the two-stages in the system. T_1 is the hot-junction temperature, T_2 is the cold-junction temperature, and Tm is the temperature of the junction between the two stages. T_H and T_L are the temperatures of the heat source and cold source, respectively. For the generator, the rate of heat transfer at the hot junction is Q_H, and the rate of heat transfer at the cold junction is Q_C. The power output is P. The electrical resistance of the external load is R. Assume that the two heat exchangers between the hot and cold junctions of the TEG and their respective reservoirs are for counter flows, and the heat conductance of the heat exchangers are k_1F_1 and k_2F_2, respectively, where k_1, k_2 (W/m^2K), F_1, and F_2 are heat transfer coefficients and heat-transfer surface-areas of the two heat-exchangers, respectively. K is thermal conductance of the semiconductor couple (W/K). *m, n* presents the number of *P&N* junctions for the first and the second stage, respectively.

From Eq. (2), T_m is:

$$T_m = \frac{(m+n)I^2R/2 + mKT_1 + nKT_2}{aI(n-m) + K(m+n)} \tag{4}$$

The conduction heat losses are K x ($T_1 - T_{HP-H}$) for the first stage and K x ($T_{HP-C} - T_2$) for the second stage, respectively. Where T_{HP-H} and T_{HP-C} is hot end and cold end temperature of the heat pipe (the maximum temperature difference between them is about 4K in this experiment). To simplify the model, T_m is used to replace T_{HP-H} and T_{HP-C} in this study.

Substituting Eq. (4) into Eq. (1) and (3), then combining these equations yields. The power output and thermal efficiency of the TEG as follows:

$$\begin{aligned} P &= Q_H - Q_C \\ &= (\{[aI(n-m)+K(m+n)][(mk_1F_1k_2F_2 + mnKk_1F_1 - mnk_1F_1aI)(aIT_L - 0.5I^2R + KT_H) \\ &- (nk_1F_1k_2F_2 + mnKk_2F_2 + mnk_2F_2aI) \times (aIT_C - KT_C + 0.5I^2R)] \\ &+ 0.5(m+n)KR[(n-m)k_1F_1k_2F_2 + mnK(k_1F_1 - k_2F_2) - mn(k_1F_1 - k_2F_2)aI]I^2 \\ &- (n-m)(mT_H + nT_C)k_1F_1k_2F_2K^2 + mn(n-m)K^2(k_1F_1T_H - k_2F_2T_C)aI \\ &+ mn(n+m)K^3(k_1F_1T_H - k_2F_2T_C)\}) / (mk_1F_1\{[aI(n-m)+K(m+n)] \\ &\times (k_2F_2 + nK - naI)(aIT_H + KT_H - 0.5I^2R) - 0.5(m+n)KI^2R(k_2F_2 + nK - naI) \\ &- (nK)^2(aI+K)T_H - K^2[k_2F_2(mT_H + nT_C) + mn(K - aI)T_H]\}) \end{aligned} \tag{5}$$

$$\begin{aligned}\eta = P/Q_H = 1 - (&nk_2F_2\{[\alpha I(n-m)+K(m+n)](k_1F_1+mK+m\alpha I)\\ &\times(\alpha IT_C - KT_C + 0.5I^2R) + 0.5(m+n)KI^2R(k_1F_1+mK+m\alpha I)\\ &+(mK)^2(K-\alpha I)T_C + K^2[k_1F_1(mT_H+nT_C)+mn(K+\alpha I)T_C]\})\\ &/(mk_1F_1\{[\alpha I(n-m)+K(m+n)](k_2F_2+nK-n\alpha I)(\alpha IT_H+KT_H-0.5I^2R)\\ &-0.5(m+n)KI^2R(k_2F_2+nK-n\alpha I)-(nK)^2(K+\alpha I)T_H\\ &-K^2[k_2F_2(mT_H+nT_C)+mn(K-\alpha I)T_H]\})\end{aligned} \quad (6)$$

P and η are an important theoretical basis for analysis and optimization of the TEG system performance. In this experiment, the same TE modules are used for both stages and m = n = 127.

THE EXPERIMENTAL SYSTEM SETUP

System Design

In this article, a new design inspired by Hi-z company's small prototypes is proposed. Their small prototypes all could be used inside the space available in a vehicle [21-25]. The proposed structure is an aluminum central support tube, circular in its inner part and hexagonal in its outer surface, between them, there are conducting oil which would play the role of heat storage and minimize the impact which the exhaust temperature variation to the TE modules, as shown in Figure 2. The TEG structure is mounted behind 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 a hexagonal structure side length of 75mm. Then the structure can support two kinds of common size and low cost commercial Bi_2Te_3 TE modules, which are 40mm x 40mm x 4.2mm and 60mm x 60mm x 4.2mm. In this article, the structure employs a total 96 TE modules with the size of 40mm x 40mm x 4.2mm and 16 TE modules on each side are employed in the structure. The diameter of the tube is $D_{tube} = 100mm$, which is close to the average of most commercial vehicle exhaust pipes. The sides of the support structure were fabricated from flat aluminum strips with small fins machined on the tube's inner side. They are welded together configuring the polygonal shape. After the space between outer hexagonal structure and inner tube is checked for no leak, there is only a

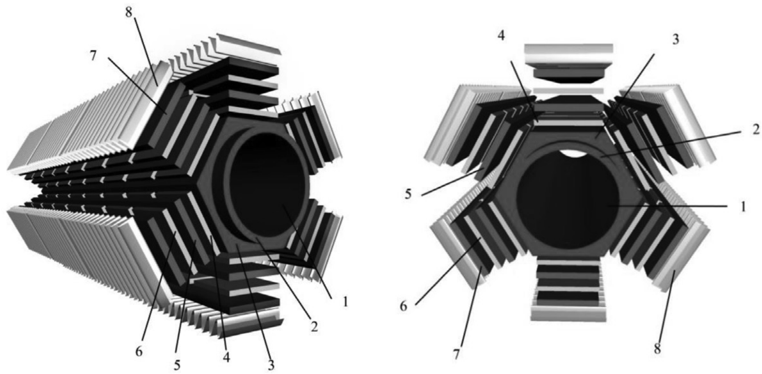

Figure 2. Design of the Prototype.
1. Inner side of the tube 2. Central support tube
3. Conducting oil 4. TE module
5. Thin aluminum plate 6. The second stage TE module
7. Cooling plate 8. Or Fin (If choose air-cooling)

port left to perfuse conducting oil and then it is sealed by a leak-proof screw. Outside the TE modules, a second stage TE module and their cold fluid loop will be mounted depends on our experimental demand.

Structure Setup

The experimental system consists of four main parts: the hot side, thermoelectric converter, the cold side and the data acquisition system. A block diagram is shown in Figure 3.

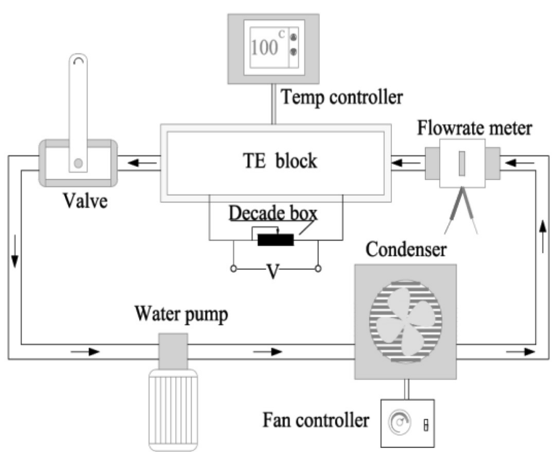

Figure 3. Block diagram for exhaust heat recovery power generation test rig

The Hot Side

The proposed hexagonal structure and its inner part is the hot side. 16 TE modules are mounted on each side by two layers. Before completing the prototype and mounting it in the vehicle, an alternative design is chosen based on our experiment in order to save costs. The hexagonal structure is replaced by a flat structure in the experiment test. The size of the flat structure is 450mm x 350mm x 15mm, exactly the same as commencement of the hexagonal structure. There is conducting oil with a maximum safe temperature of 620K in the cavity of flat 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 to heat without exposure to the conducting oil, 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 on the outside by insulation board super wool with the thickness of 5mm.

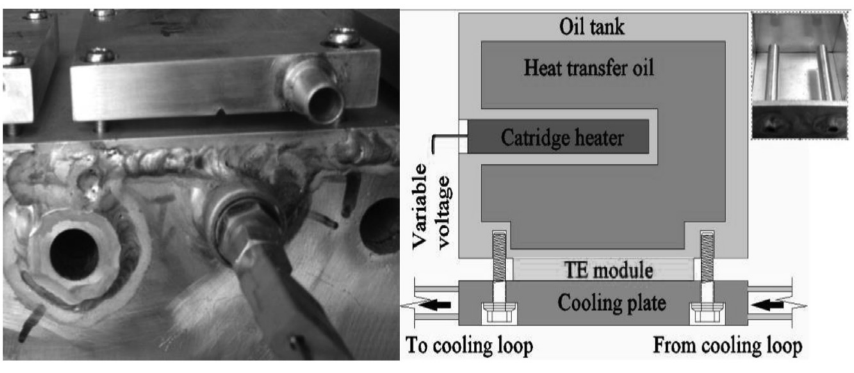

Figure 4. Heating Rods and their structure

The Thermoelectric Converter

All 96 TE modules, arranged in six lines by two layers, are fixed on upper surface of the flat structure. They are connected electrically in series, but thermally in parallel. TE module of the first stage is sandwiched between the upper side of the structure and the copper plates which are used to fix the hot end of heat pipe. They are fixed together with screws as shown in Figure 5. TE module of the second stage is sandwiched between the cooling plate and the copper plates which are used to fix the cold end of heat pipe.

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, a fiber washer and a flat metal washer is used with each screw.

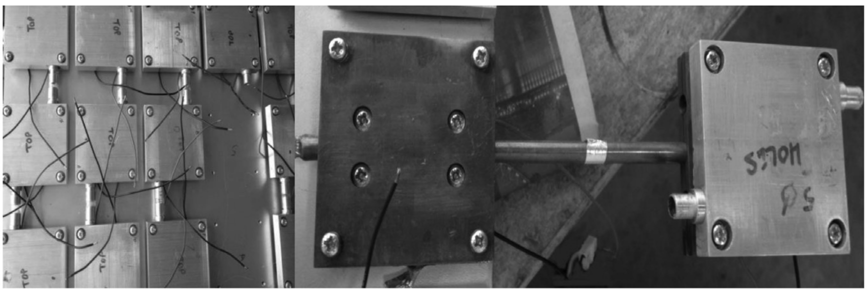

Figure 5. Installation of TE modules

The Heat Pipe

Two kinds of copper-water heat pipe, conventional capillary-driven heat pipe and flat-plate heat pipe were designed and built for the experiment. Conventional copper-water heat pipes were used first to verify prototype feasibility. Table 1 lists the basic specifications of a single heat pipe. Special copper plates are designed to fix the heat pipe and connect it with both two stages TE modules as shown in Figure 6.

The Cold Side

A water-cooling method is proposed firstly in this study to keep the temperature difference. To provide a uniform temperature distribution and a uniform pressure across the surface of the TE modules, 48 single aluminum cooling plates are chosen as the thermal spreader between the hot and cool sinks in this study. There is flow channel in the aluminum cooling plate to enhance the heat transfer, as shown in Figure 7.

Table 1. P Specifications of a single heat pipe

Material of pipe	Copper
Working fluid	Water
Outer diameter of pipe	20 mm
Pipe thickness	1.5 mm
Pipe length	210 mm
Length of evaporator section	100 mm
Length of condenser section	100 mm
Preformed length for the splitter plate	5 mm
Preformed assembled length for the end of the condenser section	5 mm

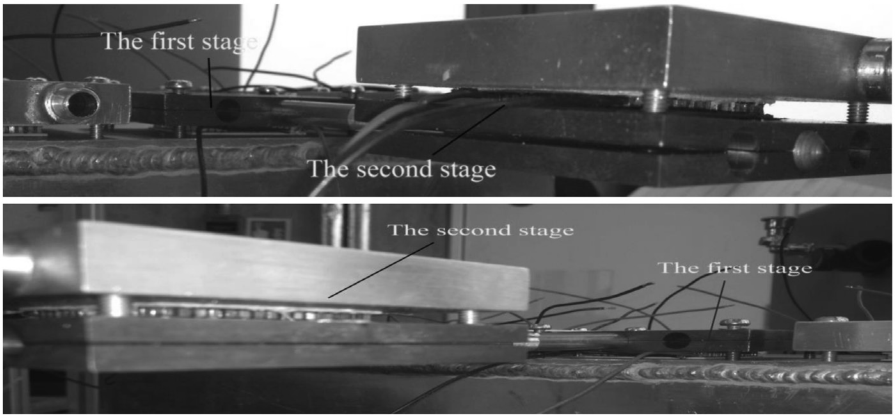

Figure 6. Mounting method for heat pipe and TE modules

Measurement System

All performance parameters are sampled every 5s, for about 2 hours until a steady operation is reached. 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). To reduce the thermal bypass losses, (for example, between the heat source and the cold sink), the

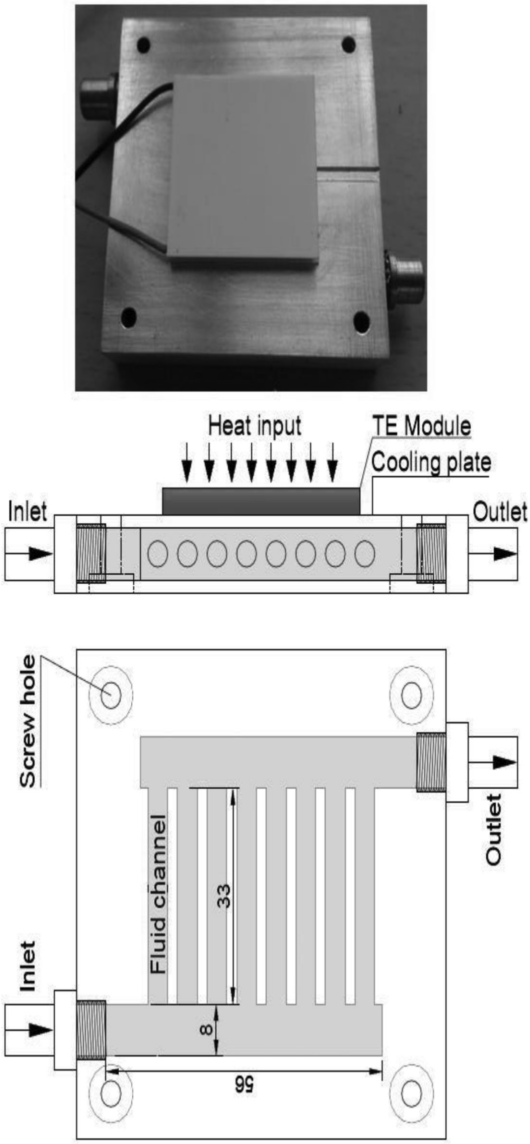

Figure 7. Cooling plate for each thermoelectric module

free space between the pellets of the thermoelectric pair and the space among the TE modules is filled with the super-wool. Thermal grease is also placed between all of the TE modules and their interfaces to minimize thermal contact resistance.

EXPERIMENTAL RESULTS AND DISCUSSION

For this test rig, hot-side temperature is relatively controllable and stable. Based on different engine operating condition, 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 364.8Ω for total).

Then, a series of system voltage output and power output changing with temperature difference for water cooling are measured under the 4 different heater powers set before. The results for these 4 test conditions are depicted in Figures 8 through 11.

Test 1: Figure 8 shows the trend of maximum power output (P_{out}) versus temperature difference. The P_{out} increases with increasing of ΔT. The data distribution is typical of a second order polynomial of ΔT. The predicted P_{out} is also a parabolic function of ΔT. The theoretical data is in good agreement with the experimental data. T_{H1} refers to hot side temperature of the first stage TE and T_{C2} refers to cold side temperature of the second stage TE.

Test 2: The maximum voltage output (V_{out}) increases with a boost of temperature difference (ΔT) in a linear trend as shown in Figure 9. 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.

Figures 8 and 9 show that the theoretical model over-predicts performances of TEG in the entire temperature range. At low T_{H1} and ΔT, the predicted performances and the measurements are relatively in good agreement. However, at high temperatures, the deviation of the prediction arises largely with increasing T_{H1} and ΔT. The deviation between the theoretical and experimental values results from the fact that not all the heat losses are taken into account in the theoretical model.

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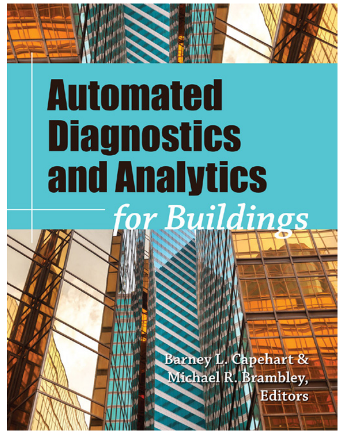

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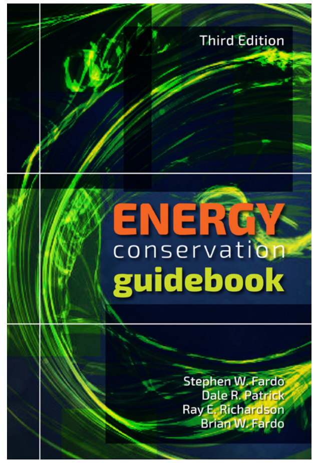

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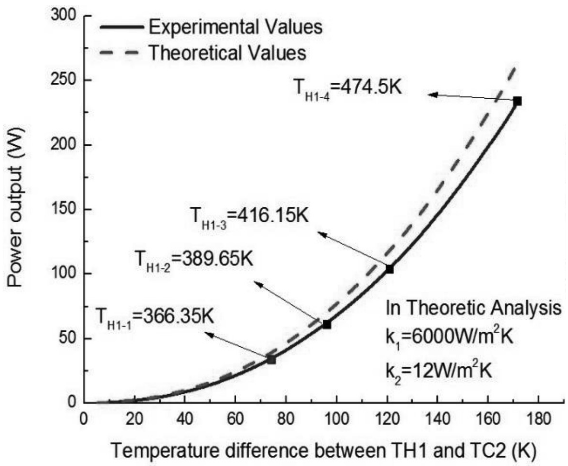

Figure 8. The variation of the power output with temperature difference for water cooling.

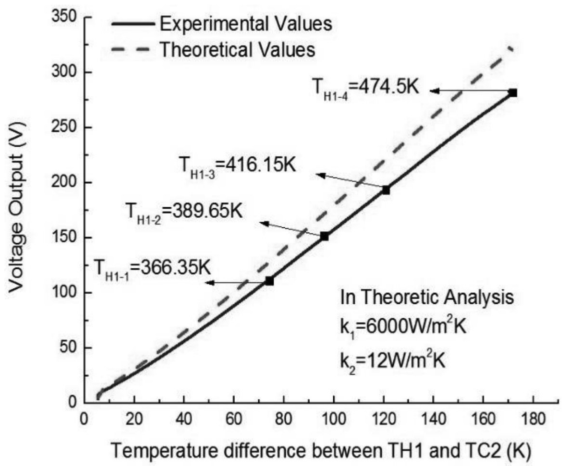

Figure 9.The variation of the voltage output with temperature difference for water cooling.

In fact, the heat losses that have been observed experimentally increase significantly with increasing T_{H1}, 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.

Test 3: The maximum power outputs of two-stage TEG and single stage TEG are compared in Figure 10. It arises with increasing of T_{H1}

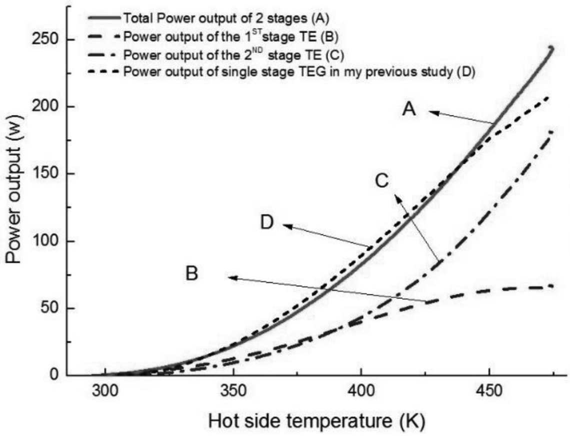

Figure 10. The comparison of power output variation with hot side temperature for nature water cooling between two-stage and single stage TEG.

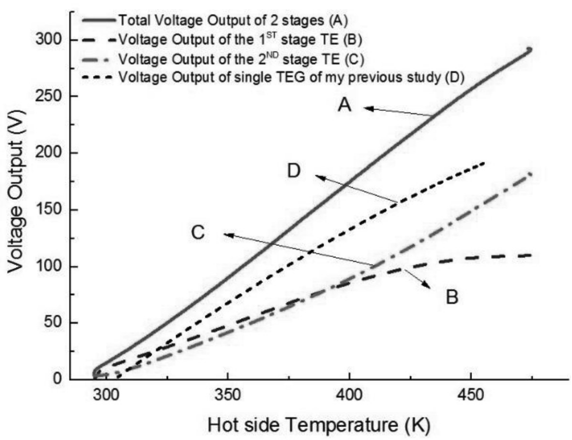

Figure 11. The comparison of voltage output variation with hot side temperature for nature water cooling between two-stage and single stage TEG.

in both TEGs. When the temperature of the hot side is less than about 430K, both two kinds of TEGs have similar power output and the same increasing trend, but single stage TEG's is a little more. After T_{H1} exceeds 430K, the two-stage TEG has a more P_{out} and a lager increasing rate on it comparing to the single stage TEG. Each stage in two-stage TEG has lower P_{out} than single stage TEG. With T_{H1} increasing to 440K, the P_{out} of the 1^{ST} stage TE in two-stage TEG turns to increase very slowly for ΔT of the 1^{ST} stage TE is almost constant.

Figure 11 compares the maximum V_{out} of two-stage TEG with single stage TEG. The performance of single stage TEG is still better than that of individual stage in two- stage TEG. However, in the whole temperature range, the two-stage TEG produces much higher voltage output than one of the single stage TEG. When T_{H1} is 473K, the maximum voltage output of two-stage TEG is about 293V while it is only about 200V for single stage TEG.

Table 2 summarizes the experimental data obtained when stable system operation is reached in the four different test conditions explained above. The two-stage TEG employing heat pipe obtains its best results under the condition when the power into the TE modules is 6646.1W in this study. The electric power generated was 249.06W, being that the electric power generated 5.37% of the heat flux through the generator.

Table 2. 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)	2448.3	3997.4	4996.8	6646.1
Conducting Oil Temperature T_{Oil} (K)	385.72	413.72	447.08	525.62
The 1^{ST} stage of two-stage TEG				
Hot side temperature of 1^{ST} stage TE T_{H1} (K)	366.431	389.69	416.105	473.54
Cold side temperature of 1^{ST} stage TE T_{C1} (K)	327.33	342.11	358.92	405.92
Temperature Difference of 1^{ST} stage TEΔT_1 (K)	39.101	47.58	57.185	67.62
Maximum Power Output of 1^{ST} stage TE P_1(W)	20.91	34.13	50.25	68.03
Maximum Voltage Output of 1^{ST} stage TE V_1 (V)	61.76	78.9	95.74	111.39
The heat pipe				
Temperature of evaporator section	327.11	341.83	358.68	404.98
Temperature of condenser section	325.85	340.46	357.02	403
The 2^{ND} stage of two-stage TEG				
Hot side temperature of 2^{ND} stage TE T_{H2} (K)	324.97	340.02	356.87	402.76
Cold side temperature of 2^{ND} stage TE T_{C2} (K)	291.023	292.37	293.916	301.27
Temperature Difference of 2^{ND} stage TEΔT_2 (K)	33.947	47.65	62.954	101.49
Maximum Power Output of 2^{ND} stage TE P_2(W)	16.33	33.78	62.83	181.03
Maximum Voltage Output of 2^{ND} stage TE V_2(V)	54.576	78.495	107.052	181.71
Two-stage TEG				
Hot side temperature T_H	366.431	389.69	416.105	473.54
Cold side temperature T_C	291.023	292.37	293.916	301.27
Temperature Difference T_D	75.408	97.32	122.189	172.27
Maximum Power Output P	37.24	67.91	113.33	249.06
Maximum Voltage Output V	116.336	157.395	203.26	293.1

(Continued)

Table 2 (*Cont'd*). Generation power and efficiency of the prototype

Generator	Test No. 1	Test No. 2	Test No. 3	Test No. 4
Cooling Water				
Water- in Temperature (K)	289.03	289.61	290.73	293.3
Water- out Temperature (K)	289.37	290.83	292.51	295.11
Flow Rate (m^3/S)	0.00138	0.00138	0.00138	0.00139
Efficiency				
Single Module Efficiency of 1^{ST} stage TE	8.71%	14.22%	20.94%	28.18%
Single Module Efficiency of 2^{ND} stage TE	6.81%	14.08%	26.18%	75.43%
Average Module Efficiency	7.76%	14.15%	23.56%	51.81%
Thermal Efficiency of two-stage TEG	1.85%	2.7%	3.14%	5.37%
Power area of modules' surface (m^2)	0.1536			
***Experimental data of single TEG from our previous study for comparison**				
Maximum Power Output $P_{Single\ stage}$	45.14	79.26	126.39	201.58
Maximum Voltage Output $V_{Single\ stage}$	90.74	120.24	151.84	191.75
Module Efficiency	18.8%	33.1%	52.6%	83.8%
Thermal Efficiency of single stage TEG	2.31%	2.98%	3.29%	4.04%
Power area of modules' surface (m^2)	0.0768			

From the data in Table 2, it should be noted that, in the low temperature range (Test No. 1-Test No. 2), the two-stage TEG generates lower power output than the single stage TEG. The reason is, in that temperature range, both the first and second stage of two-stage TEG has small temperature difference, and the ZT value of the Bi_2Te_3 is also low. When T_{H1} rises to above 440K, the first and second stage of two-stage TEG both operates in a relatively high ZT value temperature. Even having the similar total temperature with single stage TEG, the two-stage TEG generates more power output. It is also an important factor should be considered for system optimization in further study. In the aspect of total efficiency, more attention is paid to the thermal efficiency of the TE generator, as expressed by Eq. (6), not the whole energy 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 cost free. Experimental results indicate that the thermal efficiency of this two-stage TEG is only a few percent (5.37% when T_H reaches 473 K) as shown in Figure 12, and the efficiency value increases slightly with a boost of temperature difference. However, the system thermal efficiency has been improved by 32% comparing to single stage TEG.

SYSTEM OPTIMIZATION

TE Module Optimization

On the basis of the above discussion, employing more efficient TE modules and adding TE modules in series are good measures for system improvement. The predicted value for employing 96 TE modules (Type No. TEG1-127-2.8-1.6-250, size 62mm×62mm, Matched Load Output Power 21.3W) is indicated in Figure 13. About 1100W power output can be obtained when the temperature difference is about 175K. However, the cost of adding TE modules is relatively high and the space limitation need to be considered.

Heat Transfer Optimization

It is important to observe the high values of the temperature of the conducting oil 525K compared to the hot side temperature of the TE modules, 473K, as shown in Figure 14. The difference between the two grows as the temperature increases. Possibly, this fact is related to the material used to build the inner shell, and with the system used to join the TE modules on the outer surface of it, increasing the thermal resistance. Reduce 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.

Optimization of the Number of Thermoelectric-Element Pairs

Based on the system model in section 2, some calculations were done to probe the optimum allocation of the number of thermoelectric-element pairs[14,15]. Figure 15 shows the effect of the second stage thermoelectric-element pairs number (n) on the power output (P) versus the electric-current (I) when M = m + n = 400. For a fixed M, there exist an optimum number of thermoelectric-element pairs for the second stage which leads to a greatest power-output. The maximum of the optimum power output increases with the increase of M.

Figure 16 shows the effect of the total number of thermoelectric-element pairs of the two-stage TEG (M) on the optimum power-output

(P_{opt}) versus the number of thermoelectric-element pairs of the second stage (n). For a fixed number of thermoelectric-element pairs of the second stage (n), the power output versus working electric-current (I_{opt}) characteristic behaves like a parabola, and there exists an optimum I_{opt} which leads to an optimum power-output (P_{opt}). When the number of thermoelectric-element pairs of the second stage (n) increases, both I_{opt} and P_{opt} increase first and then decrease. The greatest power output is obtained when n=m.

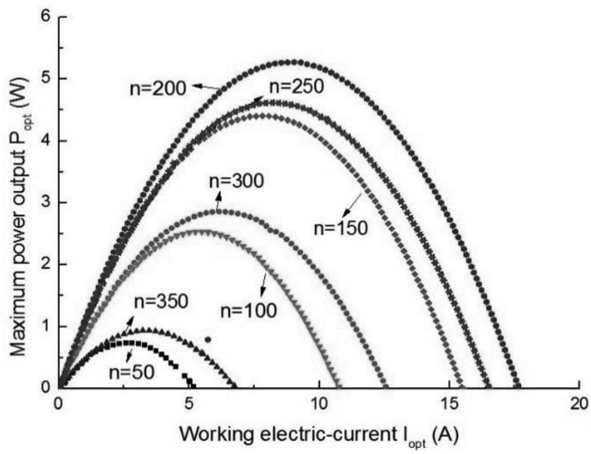

Figure 15. The effect of n on P versus I characteristics

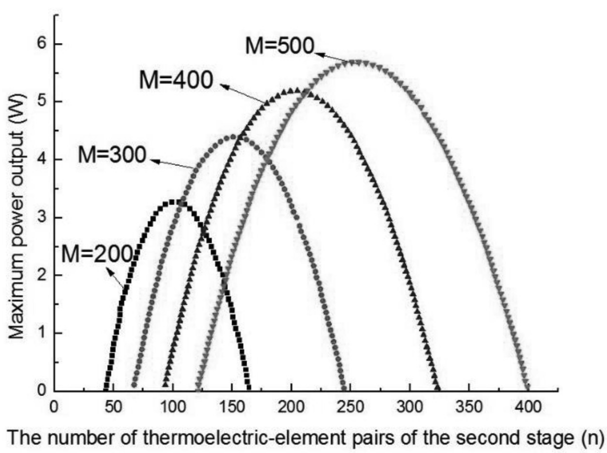

Figure 16. The effect of M on P versus n characteristics

CONCLUSION

To recover the heat from vehicle exhaust gas, a novel TEG prototype employing heat pipe is proposed is this article. After a theoretical system model based on basic TE effects and the heat transfer irreversibility is established, 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 250W when operating stably in hot side temperature 473K. The system thermal efficiency reaches 5.37%, it is improved by 32.9% compared to single stage TEG's 4.04% in the same operating conditions.

By means of system modeling, optimum allocation of the number of thermoelectric-element pairs is analyzed. There exist an optimum number of thermoelectric-element pairs for the second stage (m=n) which leads to a greatest power-output. The maximum of the optimum power output increases with the increase of M. Besides increasing waste heat temperature and TE module quantity in series, reducing thermal resistance between the structure upper surface and module, using more efficient TE modules in a proper range and enhancing cold-side heat transfer capacity can also be employed to enhance performance of this setup.

We will do further optimization studies at the system level, focusing on system power capacity and energy efficiency. Other experimental structures will be explored and constructed using different cooling methods to improve waste heat recovery.

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