

Concept for Improving Cost Effectiveness of Thermoelectric Heat Recovery Systems

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ABSTRACT

The practical application of heat recovery using thermoelectrics requires the realization of reasonable cost effectiveness. Therefore, a thermoelectric generator (TEG) structure that can compatibly increase efficiency and reduce cost was investigated with the aim of enhancing cost effectiveness. To increase efficiency, a method of using a vacuum space structure to reduce the TEG size was investigated to enable installation just after the close-coupled catalyzer, which is subject to many space restrictions. It was found that by making it possible to use high temperature exhaust heat, power generation efficiency can be increased to approximately twice that of the typical under floor installation. In addition, coupled simulation of heat transfer and power generation using FEM, 1D cost effectiveness simulations, and bench tests were performed with the aim of reducing cost. These results clarified that use of a TEG with a heat concentration structure enabled to reduce the number of elements used to 1/4 and the system cost to approximately 1/2 that of the previously studied Honda system, while still maintaining approximately the same size and power output.

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1. INTRODUCTION

Various entities have actively investigated heat recovery technology in the past with the aim of enhancing automobile fuel economy. Many of these studies have reported that heat recovery technology helps to enhance automotive fuel economy.[1,2] Honda has also investigated heat recovery technology such as use of a Rankine cycle or thermoelectrics, and has verified that heat recovery is possible in each case.[3,4] However, heat recovery technology has not yet been practically applied to automobiles. A major reason why practical application has not been achieved is that prospects could not be obtained for achieving effects at a suitable cost. Among the studied heat recovery technologies, heat recovery systems using thermoelectric elements feature a simple structure with no moving parts. For this reason, these systems were thought to be advantageous from the viewpoint of cost effectiveness, particularly for small-scale power generation with an average power generation output of less than 1 kW such as heat recovery in a passenger car. Even so, there were still no prospects for obtaining reasonable cost effectiveness. Compatibly achieving a high balance between cost and recovery efficiency is an effective way to enhance cost effectiveness. Therefore, realistic measures that can compatibly increase efficiency and reduce cost were investigated.

performance to increase the figure of merit ZT , and the other method is to increase the difference between T_h and T_c , that is to say the temperature difference applied to the thermoelectric element.

$$\eta = \left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + T_c/T_h} \right) \cdot \left(\frac{T_h - T_c}{T_h} \right) \quad (1)$$

η : conversion efficiency

ZT : figure of merit

T_h, T_c : Temperature of TE element at hot and cold side

High expectations are placed on increasing ZT , that is to say enhancement of element performance. However, technical advances are extremely challenging to predict, and the future cannot be known for certain. At present the method for most reliably increasing the recovery efficiency is to increase the temperature difference applied to the thermoelectric element. Therefore, utilization of a high exhaust gas temperature was considered.

2. METHODS FOR INCREASING EFFICIENCY

2.1. Approaches for Increasing Efficiency

Equation (1) gives the power generation efficiency using thermoelectrics. There are mainly two methods for increasing efficiency. One method is to enhance thermoelectric element

2.2. Relationship between Installment Location and Exhaust Gas Temperature

Automobile exhaust gas is higher temperature farther upstream in the exhaust system, and the temperature becomes lower due to heat radiation as the exhaust gas moves downstream. Figure 1 shows the results of measuring the average exhaust gas temperature during US 5 cycles at various locations in the exhaust system of a 13MY US

Accord having 2.4L L4 engine with MT. The measurement locations express the distance downstream from the reference position 30 mm from the inlet of the close-coupled catalyzer substrate. The average exhaust gas temperatures during US 5 cycles measured at the position just after the close-coupled catalyzer and at the under floor position differed by approximately 180°C. This shows that a higher exhaust gas temperature can be utilized by installing the thermoelectric generator (TEG) just after the close-coupled catalyzer.

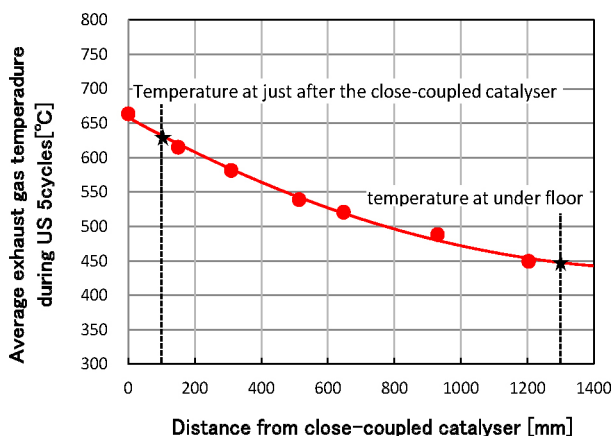


Figure 1. Relation between installment locations and exhaust temperature

2.3. Issues and Measures for Location just after the Close-coupled Catalyzer

Installing the TEG in a location that enables to use a higher exhaust gas temperature is a very natural idea when considering heat recovery. However, TEG is typically installed under floor where the exhaust gas temperature is lower. Figure 2 shows an example of installment by GM.[5] furthermore, as seen in other cases of development by BMW, Ford, Fiat and Renault[6,7,8,9], past development of heat recovery systems using thermoelectrics mainly uses under floor installment.

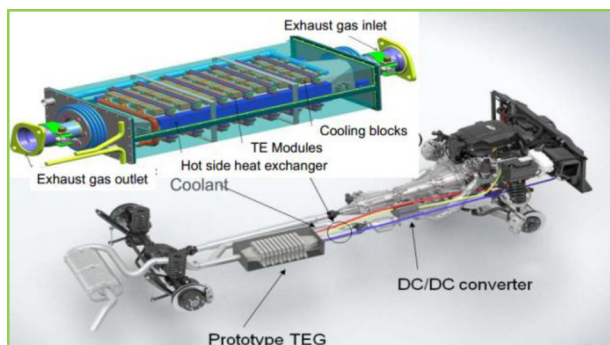


Figure 2. Example of TEG installation

Figure 3 shows an example of packaging around close-coupled catalyzer in a Honda Civic.

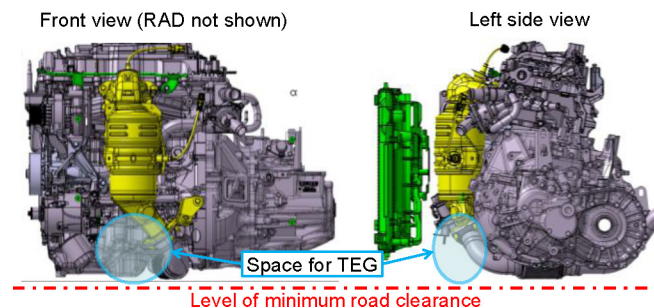


Figure 3. Packaging of 16MY Civic around close-coupled catalyzer

A close-coupled catalyzer is located just after the engine. In order to satisfy emissions regulations, the TEG needs to be located downstream from the catalyzer, so the space available for the TEG is extremely limited. The major reason why an under floor layout is the most common despite it being desirable to use a high exhaust gas temperature to increase recovery efficiency is thought to be the challenge of securing sufficient installment space upstream. Therefore, a method was devised of using a vacuum space structure to reduce the TEG size in order to facilitate installment in even a small space. The feasibility of this method was reported at the 2015 SAE World Congress.[10]

When thermoelectric module is mechanically jointed with hot and colds side heat exchanger, difference in thermal expansion between hot and cold side causes large stress to thermoelectric elements leading to crack to the thermoelectric element as shown in Fig. 4.

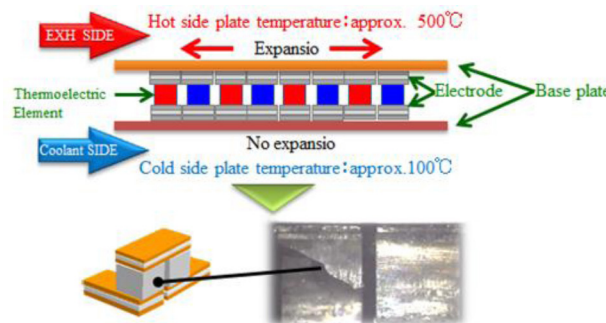


Figure 4. Issue need to be avoided in TEG

To resolve this issue, structure shown in Fig. 5 is typically adopted. Heat exchanger is mechanically disjointed from thermoelectric module to reduce stress of thermoelectric element. However, to conduct heat, heat exchangers need to be strongly pressed against module to acquire good contact, and fasteners were used to press heat exchanger against module as shown in Fig. 5. This complicates structure inhibiting TEG to become compact.

For vacuum space structure, it allows compact size having equivalent ability to reduce stress as the conventional structure. As shown in Fig. 6, cold side heat exchanger is disjointed from thermoelectric module

similar to conventional structure. However, space around module is vacuumed, and cold side heat exchanger is pressed against thermoelectric module by atmospheric pressure through flexible plate instead of force created by fasteners. In this structure, fasteners are no longer necessary and it simplifies structure enabling compact TEG.

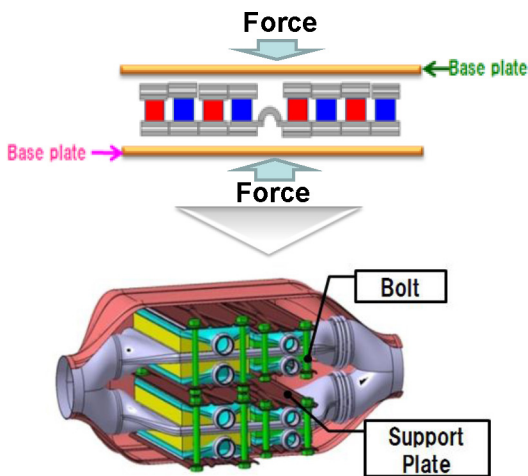


Figure 5. Example of Conventional TEG structure

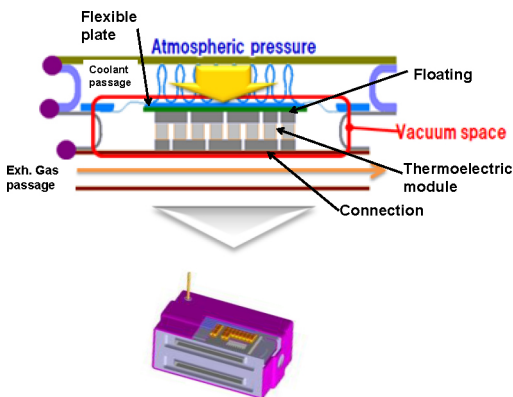


Figure 6. Example of TEG adopting vacuum space structure

2.4. Possibility and Effects of Installment just after the Close-coupled Catalyzer

This study newly created a concrete design for applying a TEG with a vacuum space structure to an actual vehicle, and investigated the packaging capability. Figure 7 shows the packaging that assumes installment in a 16MY US Civic. In addition to the generator, the TEG unit packaging also assumed installment of a bypass valve and actuator as shown in Fig. 8. This valve system is purposed to suspend heat recovery by bypassing exhaust gas when water temperature is too high. It is intended to be operated only in special circumstances when vehicle is operated under severe condition and water temperature becomes close to overheat. Therefore, it is not used normally including entire duration of driving cycles evaluating fuel economy since water temperature will not become high enough to operate bypass valve.

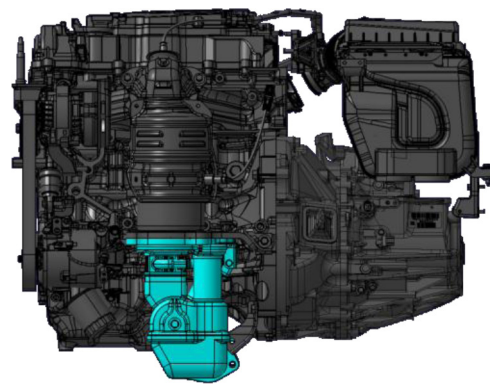


Figure 7. Installment of TEG unit to just after the close-coupled catalyzer

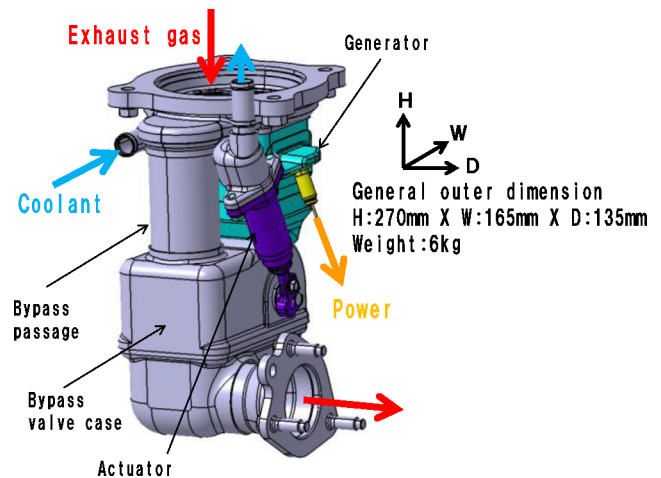


Figure 8. TEG unit

Table 1 lists the specifications of the generator used in the installed TEG unit. The use of a vacuum space structure results in an extremely compact TEG, so it was found that although there is size restrictions to generator, the TEG can fit in the space just after the close-coupled catalyzer.

Table 1. General specification of TEG

Number of exhaust heat exchanger	2
Sectional dimension of exhaust heat exchanger	72mm X 10mm
Length of exhaust heat exchanger	57 mm
Fin thickness and pitch of exhaust heat exchanger	t:0.3mm fp:3mm
Sectional dimension of TE elements	2mm X 2mm
Gap between TE elements	4mm
Total number of TE elements	432

Figure 9 shows the results calculated by simulation of the regenerative power output relative to the exhaust gas temperature at the TEG inlet.