

Development of State of the Art Compact and Lightweight Thermoelectric Generator Using Vacuum Space Structure

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ABSTRACT

Exhaust heat recovery units that use a thermoelectric element generate electricity by creating a temperature difference in the thermoelectric element by heating one side and cooling the other side of the thermoelectric circuit (module). In this case, the general structure does not directly join the thermoelectric module with the heat sink, and instead presses the thermoelectric module against the heat sink using bolts or other means in order to prevent thermoelectric element damage due to the difference in linear expansion between the cooled and heated sides of the thermoelectric module. However, this poses the issues associated with a complex, heavy and expensive structure. Therefore, a new vacuum space structure was devised that houses the thermoelectric module in a vacuum chamber and presses the module against the heat sink using atmospheric pressure. The results of electric generation validation tests showed that the new vacuum space structure can provide electric generation performance equivalent to that of the conventional structure, and was also confirmed to effectively prevent thermoelectric element damage, enabling significant reduction of the thermoelectric generator size.

CITATION: Matsumoto, M., Mori, M., Haraguchi, T., Ohtani, M. et al., "Development of State of the Art Compact and Lightweight Thermoelectric Generator Using Vacuum Space Structure," *SAE Int. J. Engines* 8(4):2015, doi:10.4271/2015-01-1691.

INTRODUCTION

Sharply rising fuel costs, shortages of natural resources, and the global warming problem are being watched with concern in various industries. There is no question that these are also critical concerns in the automobile industry. Growing importance is being attached to raising energy efficiency in order to resolve these problems, and the automobile industry has been engaged in efforts to improve engine efficiency as a way to raise energy efficiency. The approaches used include measures to reduce friction loss and pumping loss, and to improve combustion efficiency. It is clear, however, that even if methods like these to improve efficiency are carried on and improvements are carried further, at some point a limit to efficiency improvement will be reached. In order to pursue further reductions in CO₂ emissions, therefore, technical development from different perspectives is being sought.

Even if further engine efficiency is sought, however, waste heat will be left over because the engine is a heat engine. [Figure 1](#) shows the automobile energy budget published by the United States Department of Energy [1]. About 70% of the energy in the fuel input to automotive gasoline engines is being discarded into the atmosphere in the form of waste heat from coolant and exhaust gas.

For reasons like these, new initiatives to reduce CO₂ emissions in the future are likely to include recovery of waste heat as one measure. Waste heat recovery technology includes a number of

techniques, among them thermoelectric waste heat recovery technology [2,3,4,5], the turbosteamer [4], the Rankine cycle [6], and the Stirling engine [7]. As these examples of development indicate, while using the exhaust energy of a motor vehicle in a useful manner and recovering it is technically possible, it has not yet been applied in a practical manner. The results from investigation of the Rankine cycle at Honda [6] suggest that it cannot readily achieve a size and cost that are commensurate with its fuel economy effectiveness, and the key to practical application will be making it reasonable enough in cost and compact enough in size to be installed in a vehicle. Technology using a thermoelectric element, which has no moving parts and has a simple structure, was judged to be a strong candidate for waste heat recovery. Several studies using prototype TEG systems have been reported [2,8]. However, these systems were not suitable for installation in passenger vehicles because of their large and heavy structures. The practical application of waste heat recovery technology using a thermoelectric element has been the aim of the present research, which has therefore not sought improved fuel economy or maximized recovery amount, but instead has sought comprehensive increases in compactness and cost reductions [9] in order to achieve a size and cost commensurate with the effectiveness of this technology. The focus in this paper will be on measures for greater compactness.

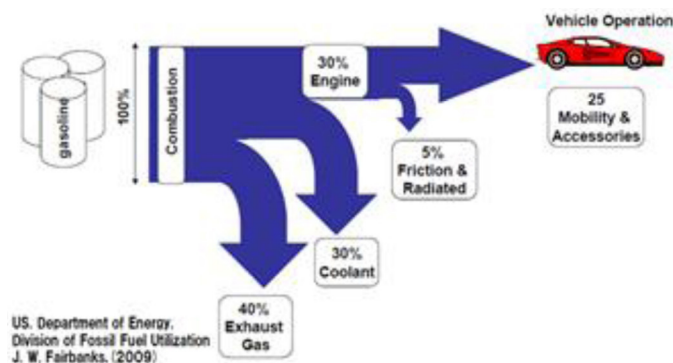


Figure 1. Automobile energy budget

1. ISSUES IN THE DESIGN OF THERMOELECTRIC GENERATION UNITS

As shown in Figure 2, a thermoelectric element generates electricity when a temperature difference is applied across the two sides of a thermoelectric element, causing the electron density in the thermoelectric element to vary so that a difference in electric potential is created. There are two types of thermoelectric element, the P-type and the N-type [10]. As shown in Figure 3, the properties of these two types are opposite in nature. However, a thermoelectric element on its own creates only a small electromotive force, so it cannot be used just as it is. Therefore P-type and N-type elements are connected in series by electrodes, as shown in Figure 4, to create a usable voltage and put it to use. The unit consisting of thermoelectric elements connected in series in this way is called a module. A module of this kind that joins a passage for exhaust gas to flow through and a passage for coolant to flow through is called a thermoelectric generator (TEG). By channeling high-temperature exhaust gas on one side and coolant on the other side, the TEG creates a temperature difference in the thermoelectric element and generates electricity. As shown in Figure 5, the plate on the high-temperature side that is in contact with exhaust gas experiences greater stretching, while the plate on the low-temperature side that is in contact with coolant experiences little stretching. Consequently, if all the parts are mechanically fixed in place, the elements cannot withstand the stress caused by the difference in linear thermal expansion in the two plates, and cracking occurs. The structure in Figure 5 has the high-temperature side of the thermoelectric element and the low-temperature side joined together and both fixed in place, and it is therefore called a structure that is rigidly fixed on both sides (both sides ridged structure). A both sides ridged structure is thus unable to release the thermal stress generated by the thermoelectric element, and cracking of the thermoelectric element becomes an issue. In general, the structure of a thermoelectric generator (TEG) has the thermoelectric element sandwiched between a heat sink and a heat source. In this structure, the high-temperature side and low-temperature side are not joined together but are pressed together, creating a structure that floats freely at both sides (both-side floating structure). This structure is shown in Figure 6. This both-side floating structure has the thermoelectric element sandwiched between the heat source and heat sink without being joined together, so that the thermal stress generated in the thermoelectric element can be released. Since the parts are not joined together, however, the electric generation efficiency of the module will be lowered if heat is not

transmitted because the close contact of surfaces cannot be maintained, and a temperature difference therefore cannot be applied to the thermoelectric element. In a both-side floating structure, the close contact between surfaces becomes an issue. The structure generally adopted to resolve this issue uses bolts or a highly rigid retainer plate, as shown in Figure 7, to sandwich the thermoelectric element between the heat source and the heat sink, and it secures close contact by applying a large load. This method not only involves a complex structure, but also necessitates a framework strong enough to withstand the pressure of being sandwiched in this way, making the device larger. A TEG needs to achieve a balance between the stress release structure and heat transfer performance by technical means, and compactness will be sought for putting it to practical use in automobiles.

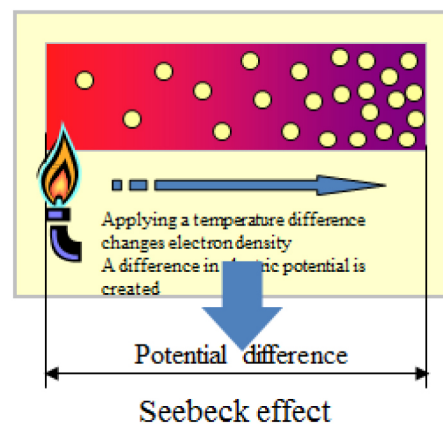


Figure 2. Seebeck effect

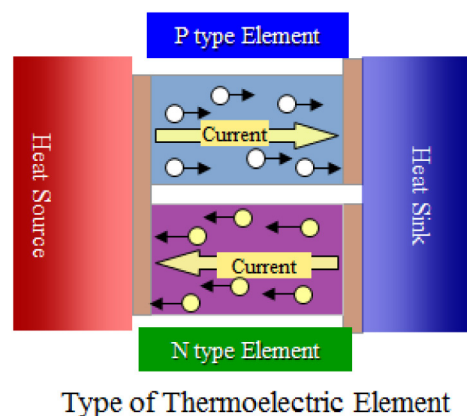


Figure 3. Two thermoelectric elements that perform oppositely

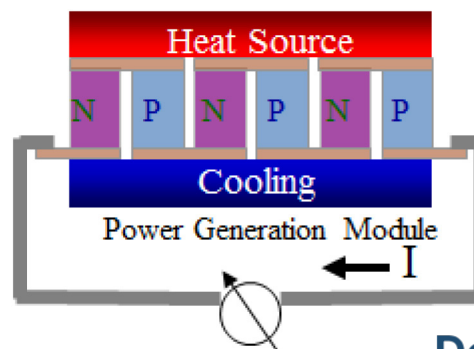


Figure 4. Modularized thermoelectric element

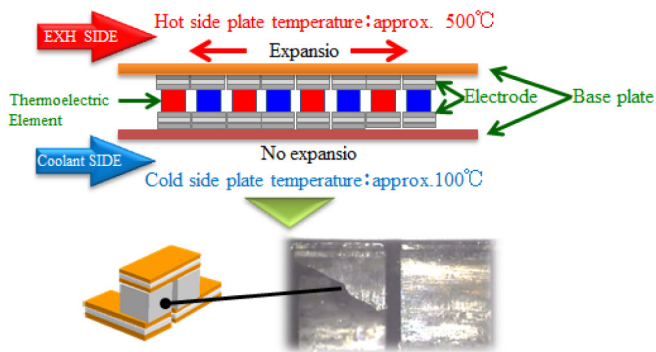


Figure 5. Both sides ridged structure TEG

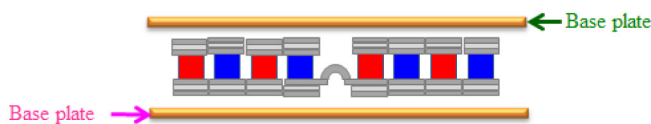


Figure 6. Both-side floating structure TEG

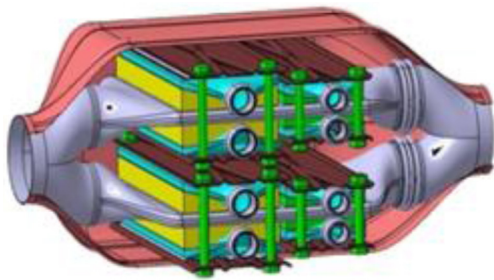


Figure 7. Conventional structure TEG

2. TEG STRESS RELEASE STRUCTURE AND SIZE REDUCTION

2.1. Concept of One Side Floating Structure Adopted in Vacuum Space Structure

The concept of a one side floating structure adopted in vacuum space structure was developed to resolve the increased TEG size that is an issue in the common type of TEG structure. Figure 8 shows the vacuum space structure [11]. The vacuum space structure forms a vacuum in the TEG space for the thermoelectric element and uses the resulting pressure difference between the vacuum and atmospheric pressure to press the high- and low-temperature sides together and assure their close contact. This vacuum space structure maintains the close contact with a smaller load than the conventional structure, and it uses a thin plate with good following properties and flexibility to change shape readily (the flexible plate to be described later) to form the structure that holds the pieces in place. With the conventional method, the effort to assure close contact required bolts or a retainer plate and the device became larger, but here those things become unnecessary and the TEG becomes more compact. Simple stainless sheet is adopted as flexible plate. Therefore, cost is made very at a low price. Next there is the structure that is floating freely at one side (one-side floating structure) shown in Figure 9. As opposed to the both-side floating structure TEG, this one-side floating structure joins either the high-temperature side or the low-temperature side, and the

other is left floating free. For the present research, the high-temperature side was joined and the cooling side was left floating in order to release the stress.

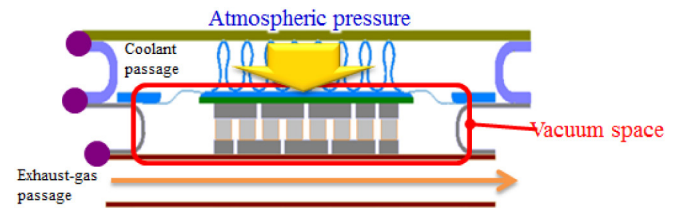


Figure 8. Vacuum Space Structure

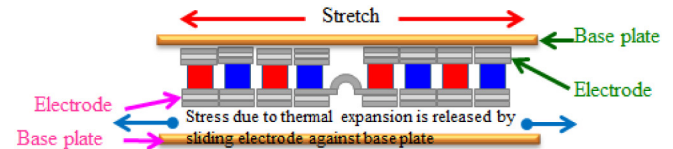


Figure 9. One-side floating structure TEG

2.2. Configuration of One Side Floating Structure Adopted in Vacuum Space Structure

Figure 10 shows an exterior view of the TEG of one side floating structure adopted in vacuum space structure. Figure 11 shows a section view of it. Table 1 shows the specifications and parts structure. This TEG was designed for concept verification, and although the basic structure is the same, the dimensions differ from a TEG for installation in an actual vehicle. Going from the heating side, in order, the one side floating structure adopted in vacuum space structure is connected to a tube, three-layer electrodes, thermoelectric element, and single-layer electrode. There is no mechanical joining between the flexible plate and the single-layer electrode, but rather has sandwiched between them a cushioning material that absorbs minute variations in the height of the module and an insulating film that prevents electrical conduction between the thermoelectric element and flexible plate.

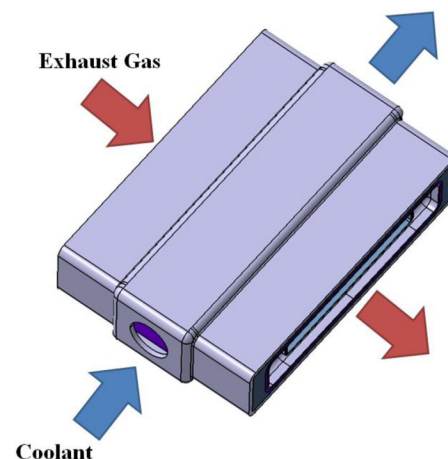


Figure 10. TEG exterior view

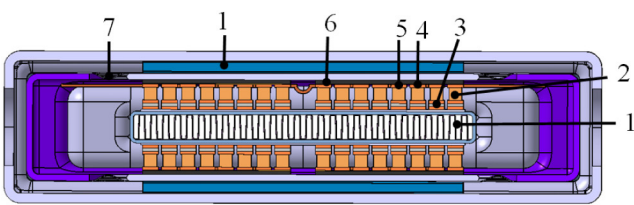


Figure 11. TEG Section View

Table 1. TEG specifications and parts structure

1	Heat Exchanger	Size	54mm × 28mm × 4mm
		Fin Pitch	1.8mm
		Material	SUS
2	Thermoelectric Element	Number of Element	256 elements (P128 and N128)
		Size	2mm×2mm×2mm
3	Three-Layer Electrodes	Material	Cu-Al2O3-Cu
		Size	2.5mm×5mm ×1.5mm
4	Single-Layer Electrode	Material	Copper
		Size	2.5mm×5mm×0.5mm
5	Insulating Material	Low-Temperature Side	Polyimide
6	Contacting material	Material	Oriented Graphite
7	Flexible Plate	Material	SUS t0.1

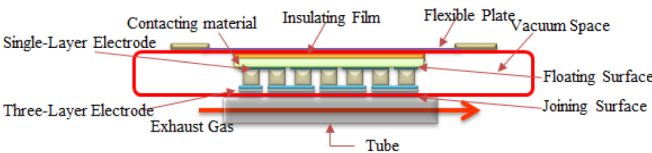


Figure 12. One side floating Structure adopted in Vacuum Space Structure



Figure 13. Flexible plate

2.3. Stress Release in One Side Floating Structure Adopted in Vacuum Space Structure

An analysis of the stress occurring in elements in the structure described above and an examination were made of the mechanism of stress release in a one-side floating structure.

2.3.1. Analytical Model and Flow

Figure 14 shows the area of the TEG one side floating structure adopted in vacuum space structure that was modeled together with that analytical model. Table 2 shows the specifications of this analytical model. In the case of a one-side floating structure, the low-temperature-side electrodes would be single-layer electrodes, but the low-temperature side was changed to three-layer electrodes. A both sides ridged structure cannot adopt an insulating structure with an interleaved polyimide sheet as in the one-side floating structure. In order to obtain a pure comparison just of the difference in stress generation caused by the difference in structure, the electrode structures were unified as three-layer electrodes for evaluation. For the model of the both sides ridged structure used in this analysis, a structure joining the three-layer electrodes on the low-temperature side was adopted, as shown in Figure 15. Apart from that, it is the same model as for the one-side floating structure. Since the TEG for proof of the concept has an axially symmetrical shape longitudinally, laterally, and vertically, the generation of stress is also symmetrical. Making use of that symmetry, therefore, the TEG as a whole was divided into eight equal parts (into shapes divided into two equal parts in each of the X, Y, and Z directions and the minimum necessary range for determining stress distribution was modeled. The fins on the interior of the exhaust tube were modeled simply as a structure of perpendicular plates in a row. Analysis was conducted according to the following analytical flow.

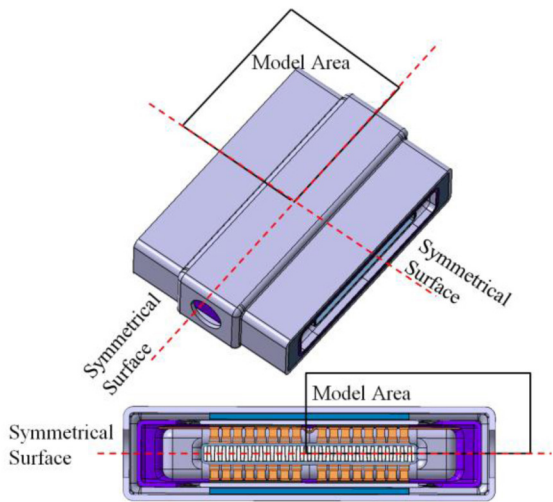


Figure 14. Model Area of the Analytical Model

1. Heat conduction analysis

For the fins on the interior of the exhaust tube that come into contact with exhaust gas, the gas temperature was set at a fixed 380°C. The coolant temperature for the area of wall and fins that come into contact with coolant was set at a fixed 40°C. Steady-state temperature distribution was then calculated.

2. Stress analysis

The model was configured so that when the temperature of the TEG as a whole is a uniform 40°C, the stress in each part will be zero. Evaluation was conducted of the deformation and stress distribution that occur when the temperature distribution determined by the above heat conduction analysis is applied. The flexible plate on the inside of the tube is subjected to a downward