

Heat Recovery Technology of Automobile Using Thermoelectric Element and Its Effect on Fuel Economy

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ABSTRACT

Prior to the development of a heat recovery system using thermoelectric elements for automobile exhaust heat energy, simulation methods were developed to understand the current technical level and extract issues as well as key technologies.

Generated power not only has a positive effect on automobile fuel economy, but there are also the negative effects of increased weight and backpressure. Effects of fuel economy making full use of thermoelectric technology lie in optimum balance of these factors. Thus, guidelines for optimizing this balance were also developed.

The results showed that heat recovery using existing thermoelectric elements is nearly unable to enhance fuel economy. Elements that exhibit good performance within the temperature range of 100°C to 350°C should be employed, and development of new elements is found to be the key. Furthermore, investigations also showed that a heat recovery system provides approximately twice the fuel economy effects when the engine is operated at constant speed such as in a series hybrid, compared to an ordinary car. These findings provided the outlook that the combination of developing new elements, selecting the optimal car type, insulating the exhaust system, and adopting other technologies leads to enhance fuel economy by 3% or more compared to conventional levels.

1. Introduction

Technology for enhancing automobile fuel economy has become particularly important in recent years, and various heat recovery technologies are being developed. Of these, thermoelectric technology is gaining attention as a means of automobile heat recovery having a simple structure with no dynamic elements and ability to convert heat directly into valuable electrical energy⁽¹⁾.

However, while studies of automobile heat recovery have focused on the generated power^{(2),(3)}, or have taken into account only the generated power when evaluating fuel economy⁽⁴⁾, no studies so far have focused on realistic automobile fuel economy that accurately includes the negative effects of thermoelectric devices. Thus, at present the concrete steps needed to make thermoelectric technology a valuable means of enhancing automobile fuel economy have not yet been clarified.

Therefore, simulation technology focusing on fuel economy along with guidelines for determining optimal specifications were developed, and fuel economy effects

and development issues were clarified⁽⁵⁾.

This paper presents an overview of the simulations, and introduces issues for heat recovery using thermoelectric technology as well as concepts for making it a valuable technology.

2. Fuel Economy Simulations

Figure 1 shows a schematic diagram of the system used to perform the simulations. This thermoelectric power generation system uses the automobile exhaust gas as the heat source and automobile coolant as the cooling source. The effect on fuel economy assumes that fuel economy is enhanced by using the generated power to reduce the automobile generator load, which reduces the engine load. In addition, the effects of increased backpressure and weight due to system installation were also taken into account when calculating the automobile fuel economy effects. Table 1 shows the preconditions adopted for the simulation.

Figure 2 shows the simulation flow.

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Table 1 Preconditions adopted for simulation

Precondition factors		Adopted precondition
Target of exhaust condition to be optimized		Average mass flow and temperature in US combined driving cycle
Evaluated vehicle	Type and engine displacement	STREAM 2.0L
System configuration	Heating source	Exhaust gas
	Cooling source	Coolant (90°C:3L/min. constant)
	Efficiency of voltage converter	85% constant
Heat exchanger	Sectional area of exhaust path	Equivalent to sectional area of exhaust pipe
	Fin volume	10% relative to exhaust path
	Fin material	Exhaust: SUS Coolant: Copper
Thermoelectric unit	Sectional dimensions of element	5 mm × 5 mm
	Gap between elements	1 mm
	Electrode size and material	5 mm × 11 mm × 0.5 mm Copper
	Module efficiency	45% constant

- (1) Prior to evaluation, the automobile operating condition, to which the thermoelectric system is to be optimized, is defined.
- (2) Heat exchanger simulations were performed. The heat flux density per unit temperature difference and pressure loss generated by the heat exchanger are affected by the heat exchanger size and fin specifications. The effect of these specifications on the heat flux density was calculated using 3-dimensional CFD. The optimal heat exchanger specifications for fuel economy cannot be determined at this stage, so the characteristics were mapped without determining specifications.
- (3) To obtain output power effectively from the thermoelectric elements, the thermoelectric elements are connected in series to make a thermoelectric module, but this results in some loss. The loss to be taken into account when calculating the output power was clarified by actually assembling the thermoelectric elements into a module and measuring the output power.
- (4) The thermoelectric module output power was simulated. The element thickness dimension was optimized to maximize the output power for the heat conditions provided from the heat exchanger. The heat conditions

differ for each set of heat exchanger characteristics investigated in step (2), so the output power characteristics were mapped with the thickness dimension optimized for all specifications. The loss investigated in step (3) was also taken into account at this time.

- (5) To effectively utilize the power output from the thermoelectric module, electric power should be supplied at the voltage required by the car. Therefore, the DC-DC conversion loss was measured using an actual conversion circuit to clarify the loss to be taken into account in fuel economy calculations.
- (6) The fuel economy enhancement effects of supplying electric power to the car and the increase in fuel consumption due to backpressure were measured using an actual car to clarify the sensitivity of each factor to fuel economy.
- (7) The information obtained from the above investigations was reflected to the existing fuel economy simulation code so that all factors affecting fuel economy were taken into account. This enabled the optimum specifications

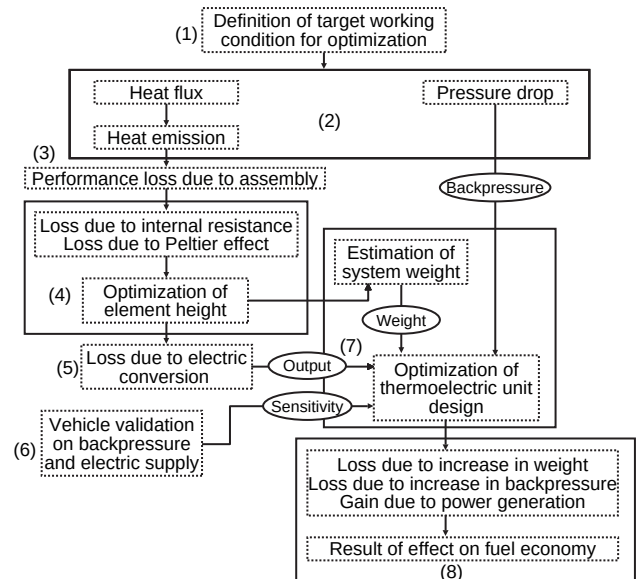


Fig. 2 Flow and factors considered in simulation

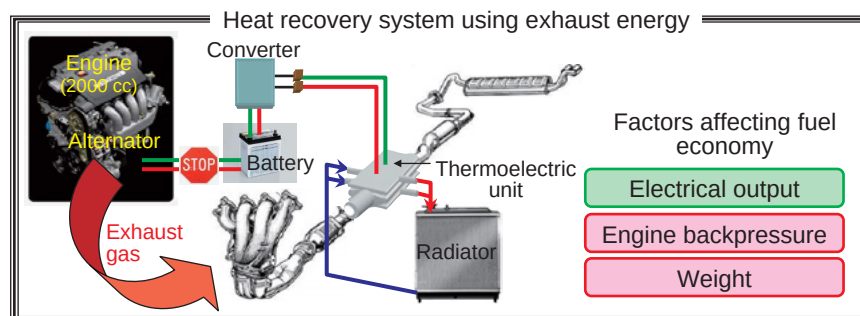


Fig. 1 General configuration of heat recovery system

Table 2 Effect of unrestrained specifications on factors affecting fuel economy

○: Has effect ×: No effect

Unrestrained specifications		Elements affecting fuel economy		
		Engine backpressure	Generated power	System weight
Heat exchanger	Fin pitch and thickness	○	○	×
Thermoelectric unit	Number of elements	○	○	○
	Element thickness	×	○	○

exhibiting the maximum fuel economy effects under the targeted operating condition to be determined.

- (8) The fuel economy effects for various driving cycles were calculated using the determined optimum specifications, and the effects of thermoelectric technology to enhance automobile fuel economy were clarified.

As mentioned previously, automobile fuel economy is calculated according to the three factors of power generated by the thermoelectric elements, exhaust pressure loss, and system weight. Table 2 summarizes the specifications that can be varied in the simulations, and their effects on each factor.

Each specification is affecting multiple factors determining fuel economy effect, and consequently, cannot be optimized one by one in any particular order. Therefore, it is necessary to map the effects on each factor without predetermining any specification. The constructed map is used to calculate the fuel economy effects for all combinations of specifications, and the optimum specifications are determined by finding the combination that provides the greatest fuel economy effects.

First, the heat exchanger, which affects the pressure loss factor, was mapped. The heat flux performance of the heat exchanger is determined by the exhaust pressure loss (fin thickness and pitch) and the number of elements

(dimensions of heat exchange area). Figure 3 shows a map of the heat exchanger performance simulation results using CFD. This shows that allowing an increase in exhaust pressure loss enhances heat flux performance, but this eventually reaches an equilibrium state. In addition, increasing the number of elements tends to lower the heat flux per unit area.

Next, thermoelectric performance, which affects the output power factor, was mapped. Output power performance is determined by the temperature difference and internal resistance occurring in the thermoelectric elements. The important point here is the element thickness. Increasing the element thickness increases the temperature difference of the thermoelectric elements, which produces greater electromotive force, but at the same time the internal resistance also increases, which is a factor reducing the output power that can be obtained from the elements. There is an optimum thickness for each heat exchanger specification, and Fig. 4 shows a map of output power performance with the element thickness set to the optimum value for each heat exchanger specification.

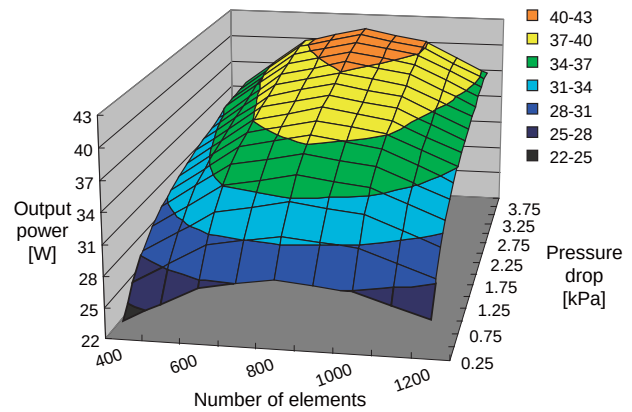


Fig. 4 Performance map of thermoelectric unit

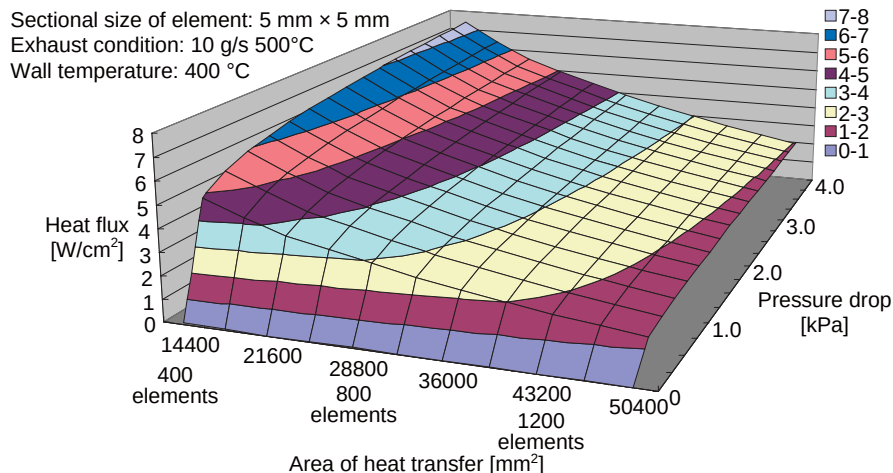


Fig. 3 Performance map of heat exchanger

There is also an optimum value for the number of thermoelectric elements. Increasing the number of thermoelectric elements has effects to increase the electromotive force. However, the heat flux supplied per unit area falls due to the heat exchanger characteristics, so the rate of increase in the electromotive force slows as the number of elements increases. On the other hand, the internal resistance continues to increase proportionally to the number of elements, so an optimal solution exists at the balance between the positive effect of a rise in electromotive force and the negative effect of increased internal resistance. In addition, from the viewpoint of pressure loss, fining off the fin tends to increase the output power. However, this rate of increase tends to slow as the pressure loss increases.

Finally, the system weight, which affects the weight factor, was mapped. The system weight is determined by the number and thickness of the elements, the weight of the heat exchanger needed for the number of elements, and the weight of the power conversion unit, piping and coolant, and other items. Figure 5 shows the system weight according to number and thickness of

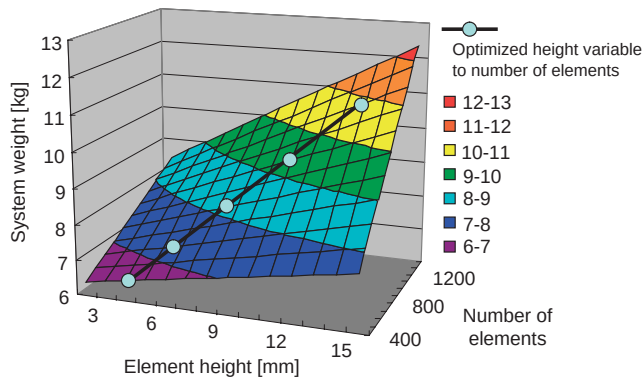


Fig. 5 Weight map of heat recovery system

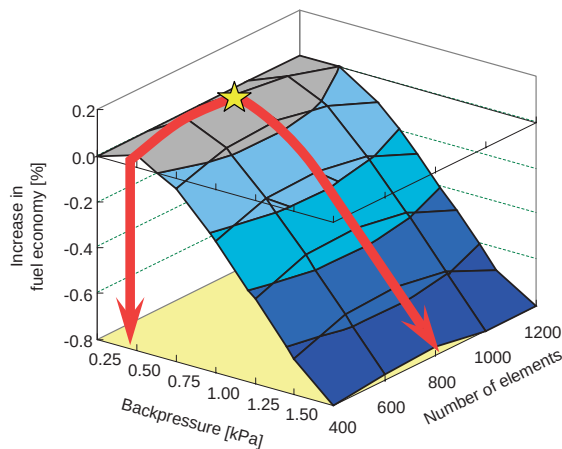


Fig. 6 Effect on fuel economy at target exhaust condition under various specifications

Table 3 Optimized specifications of thermoelectric unit

Hot side heat exchanger	Sectional size: 7 mm x 294 mm Fin specifications Fin thickness: 0.175 mm Fin pitch: 0.88 mm
Cold side heat exchanger	Sectional size: 2.5 mm x 294 mm x 2 paths Fin specifications Fin thickness: 0.03 mm Fin pitch: 0.2 mm
Element size	5 mm x 5 mm x 8.6 mm x 800 pieces
Unit weight	4.2 kg
System weight	8.3 kg

Table 4 Effect of thermoelectric generator on fuel economy

	Increase in fuel economy	Reduction of CO ₂ per km
	%	g/km
LA4	0.13	0.2
HWY	0.36	0.42
SC03	0.15	0.24
US06	0.08	0.14

thermoelectric elements. The system weight increases together with both the element thickness and the number of elements.

Mapping the heat exchanger performance, thermoelectric output power performance and system weight without predetermining any specification enabled the fuel economy effects of optional combinations of the three fuel economy factors of pressure loss, output power and weight to be verified. Figure 6 shows the results of calculating the fuel economy effects for various specification combinations under the average exhaust gas conditions in the U.S. combined cycle. These results show that there is an optimal value for pressure loss. This is because when the fin pitch and thickness is too large, heat cannot be recovered, so sufficient power cannot be generated. Conversely, when the fin pitch and thickness are too small, the backpressure rises, and the resulting drop in engine efficiency exceeds the effect of generated power. Likewise, there are also optimal specifications for the number of elements. Table 3 shows the optimized specifications. The system weight is 8.3 kg, which makes it a compact device suitable for installation in a car. Table 4 shows the results of calculating the fuel economy effects when a thermoelectric power generation system with the optimized specifications is applied to various driving cycles. This shows that while good installation capability in a car can be expected, heat recovery using current thermoelectric technology provides almost no fuel economy effects.

3. Loss Analysis based on Energy Balance

Figure 7 shows the energy balance in the LA4 driving cycle.

First, the conversion efficiency of the elements is low [Fig. 7 (6)]. Figure 8 shows the temperature characteristics of the elements used in this study, as well as the element temperatures used in the driving cycle. This shows that the elements are used in a temperature range lower than that which yields the maximum element performance. This is because as shown in Fig. 6, when the heat exchanger fin pitch and thickness is reduced to increase the element temperature, the thermoelectric unit power output increases, but the exhaust pressure loss rises by even more, with the result that fuel economy is not enhanced. Elements that exhibit sufficient performance between 100°C and 350°C are needed, but elements that can secure performance in

that temperature range do not currently exist. Therefore, the development of elements suited to this lower temperature range is the key to automobile heat recovery.

In addition, experiments conducted separately from this simulation showed that element damage occurring when joining the elements also accounts for a large part of the loss. Elements are joined together into a thermoelectric module by brazing. However, diffusion of the brazing materials onto the elements, vaporization of components during brazing, and other factors reduce element performance by approximately 45%, so preventing these is effective [Fig. 7 (7)]. Furthermore, measurements of exhaust system temperatures in an actual car showed that approximately 18% of the energy is lost due to heat radiation before reaching the thermoelectric unit, so countermeasures to help prevent this are also thought to be effective [Fig. 7 (1)].

4. Concepts for Further Increasing Fuel Economy Effects

The previous section presented locations to be modified from the viewpoint of energy balance, but fuel economy effects can also be enhanced by changing the way in which the thermoelectric system is used. When applying a thermoelectric system to an ordinary gasoline car as mentioned previously, three issues arise.

Figure 9 shows the exhaust temperature and its effect on thermoelectric power output for an ordinary gasoline car in the LA4 driving cycle and a series hybrid that assumes high-load constant speed operation. The 2-liter STREAM evaluated in this study requires average power output of approximately 10 kW for the LA4 driving cycle. The series hybrid was assumed to obtain the average output power required for driving by using a 0.65-liter displacement engine operated at constant speed while maintaining the point of maximum engine efficiency. In addition, the ordinary gasoline car used the average exhaust temperature measured by actually driving a 2-liter STREAM. The results showed that high-load constant-speed operation has a higher exhaust temperature and enabled efficient conversion of heat to electrical energy.

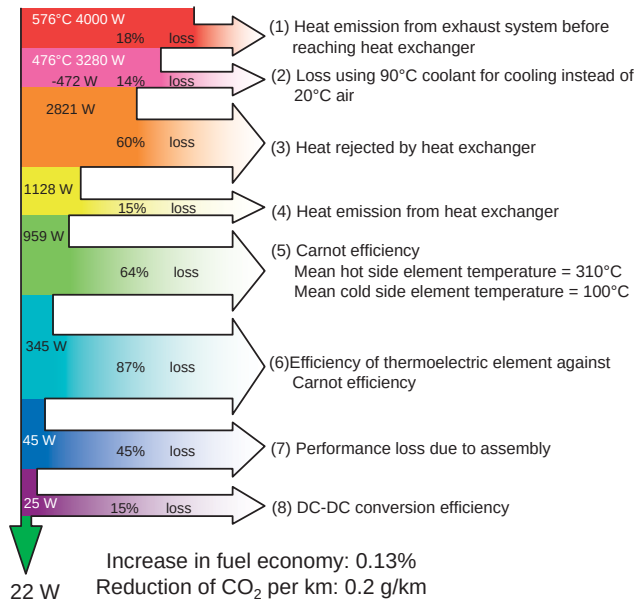


Fig. 7 Analysis of energy flow in LA4 driving cycle

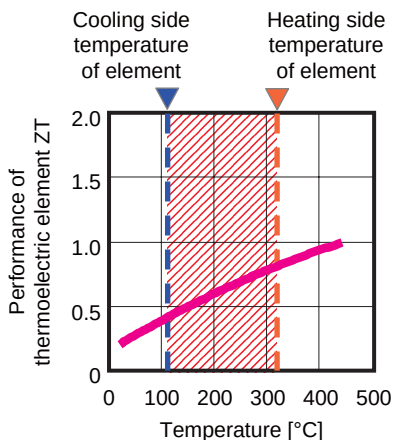


Fig. 8 Performance of thermoelectric element relative to temperature

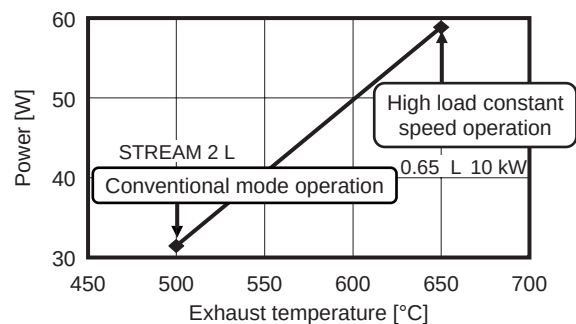


Fig. 9 Effect on output of thermoelectric unit due to difference in exhaust temperature

Figure 10 shows the effects of fluctuating exhaust gas conditions on fuel economy. This shows that the thermoelectric unit exhibits the maximum fuel economy effects under the optimized exhaust mass flow. The exhaust gas conditions of an ordinary gasoline car fluctuate during the driving cycle, so optimization was performed to match the most frequently occurring conditions. However, it is a challenge to constantly

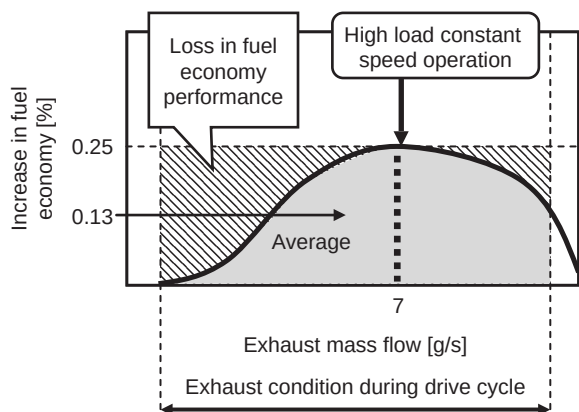


Fig. 10 Effect on fuel economy relative to exhaust mass flow

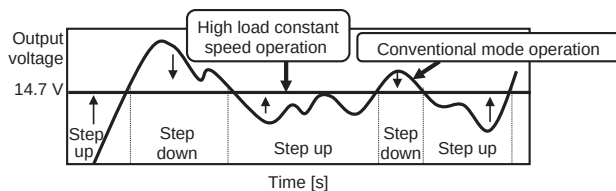


Fig. 11 Image of output voltage of thermoelectric unit during drive cycle

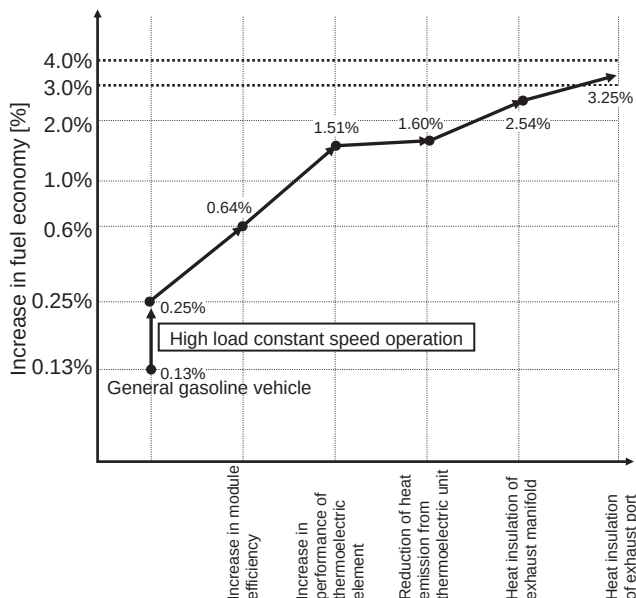


Fig. 12 Future potential of thermoelectric technology for fuel economy

maintain the optimized conditions, so the efficiency drops. In contrast, the exhaust conditions do not fluctuate during high-load constant-speed operation, which constantly enables to operate under the optimized conditions.

Figure 11 shows an image of thermoelectric output power during the driving cycle. The exhaust conditions of an ordinary gasoline car fluctuate during the driving cycle, so the output voltage from the thermoelectric unit also fluctuates accordingly. The voltage required by the car is constant, so when a voltage mismatch occurs, step-up or step-down voltage conversion is required, so power loss occurs during conversion. On the other hand, the exhaust conditions do not fluctuate during high-load constant-speed operation, so the approximately 15% conversion loss can be eliminated by presetting the thermoelectric power output to the voltage required by the car.

Figure 12 shows the enhancement in fuel economy effects when comprehensive measures are taken for locations to be enhanced from the viewpoint of energy balance, and the method of use. Simulations were performed using the conditions of high-load constant-speed operation such as in a series hybrid, a high exhaust temperature, optimized exhaust pressure loss, and constant output voltage. The results showed that approximately twice the fuel economy effects were obtained compared to when applied to an ordinary gasoline car. Furthermore, this provided the outlook that developing elements capable of securing ZT1 or more on average within the temperature range of 100°C to 350°C, establishing methods for reducing assembly loss to 15% or less, modifying the system usage method, and taking heat insulation measures could be combined to enhance fuel economy by approximately 3%.

5. Conclusion

Fuel economy simulation technology and guidelines were developed for an automobile heat recovery system that uses thermoelectric elements.

- (1) Effects and issues when using current thermoelectric technology were clarified.
- (2) Key technologies and enhancement methods were extracted, and optimal methods of use were determined. Estimates of increased driving cycle fuel economy when these measures are taken showed that enhancement of approximately 3% can be expected.

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