

Simulation of Fuel Economy Effectiveness of Exhaust Heat Recovery System Using Thermoelectric Generator in a Series Hybrid

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ABSTRACT

Simulation was employed to estimate the fuel economy enhancement from the application of an exhaust heat recovery system using a thermoelectric generator (TEG) in a series hybrid. The properties of the thermoelectric elements were obtained by self-assessment and set as the conditions for estimating the fuel economy. It was concluded that applying exhaust system insulation and forming the appropriate combination of elements with differing temperature properties inside the TEG could yield an enhancement of about 3% in fuel economy. An actual vehicle was also used to verify the calculation elements in the fuel economy simulation, and their reliability was confirmed.

INTRODUCTION

Methods for optimizing TEG specifications have begun to be proposed in recent years with a view to TEG application in automobiles [1,2]. One such method that has been proposed is simulation capable of optimizing the TEG specifications so that it will yield maximum power or maximum efficiency [2]. When installing exhaust heat recovery systems employing TEG in automobiles, not only are factors that enhance fuel economy engendered by power generation, but at the same time, factors that result in deterioration in fuel economy, such as increased pressure loss in the exhaust system and increased vehicle weight, are also created. Obtaining the optimum fuel economy enhancement requires configuring the system specifications so that these factors are in optimal balance. It is not necessarily the case that optimization of TEG output or efficiency will yield the optimal fuel economy benefit.

For that purpose, it was decided that the object to consider for optimization should be expanded from the TEG alone to the vehicle system. Not only was a simulation created to calculate fuel economy effectiveness with positive and negative factors regarding fuel economy taken into account, but a scheme was also created to optimize the system as installed on a vehicle [1]. A method of use was also proposed to further enhance the fuel economy by installing the system on series hybrid vehicles that have higher exhaust gas temperatures and more stable exhaust gas flow rate than ordinary gasoline vehicles [3]. Meanwhile, measures to insulate the exhaust ports, exhaust manifold, and other such parts so as to reduce dissipation heat loss and increase the amount of heat input to the waste heat recovery unit were also proposed as methods of increasing heat recovery efficiency [4].

For this report, specific series hybrid specifications and engine operating conditions were assumed and fuel economy simulation was employed to estimate the fuel economy enhancement from application of the TEG to the assumed series hybrid. The reduction in fuel consumption that can be obtained by applying insulation to the exhaust system was also examined. The estimation was made by subjecting the properties of multiple sample thermoelectric elements with differing temperature characteristics to self-assessment, and choosing from among them those elements with higher conversion efficiency in each temperature range. Those properties were then taken as the set conditions for the calculation. In order to determine more effective methods for utilizing the thermoelectric elements, estimates were produced for the various cases that arise when the elements selected for each temperature range are used independently

and when they are used in combination with elements that have differing temperature ranges. An actual vehicle was also used to conduct accuracy verification of the relationship between pressure loss and the power generation output of the TEG, as well as weight, as computed from the calculation elements in the fuel economy simulation, and the reliability of the calculation elements was evaluated.

SET CONDITIONS FOR FUEL ECONOMY SIMULATION

In estimating the TEG fuel economy enhancement with a series hybrid as the set conditions, the specifications in [Table 1](#) were assumed. The exhaust temperature at the TEG inlet was set to two types of configuration, one with no particular means of insulation applied and the other with double-layered piping used to insulate the exhaust system. Regarding the effectiveness of insulating the exhaust system, the results of verification tests of insulation effectiveness in exhaust systems conducted in the past were referred to, and it was assumed that an increase in exhaust gas temperature of 120°C could be expected relative to the TEG inlet temperature when no insulation is applied. Regarding the engine operating conditions, two sets of conditions were configured, one a low-power operation with low brake specific fuel consumption (BSFC), and the other a high-power operation with somewhat higher BSFC. The high-power operation is used when a high-load manner of driving is required in which the necessary energy cannot be supplied by the low-power operation. The assumption of the fuel economy simulation carried out here was that priority would be assigned to use of the low-power operation, in response to the driving load, while switching over to the high-power operation as necessary in order to obtain the electric power necessary for operating the vehicle. [Figure 1](#) shows the operating points of low-power operation (Low) and of high-power operation (High) in the BSFC map. The operating point for the high-power operation was selected to yield approximately two times the power of the low-power operation while holding the increase in BSFC down to a minimum. [Table 2](#) shows the operating times of high-power and low-power operation and engine stop time when operating with the assumed engine on US fuel economy driving cycles.

[Figures 2](#) and [3](#) show the respective performance of P-type and N-type elements, set as the conditions for calculating the TEG fuel economy benefit. The thermoelectric elements can be classified under the three general categories of low-temperature type elements that have high performance at 200°C or below, middle-temperature type elements that demonstrate high performance at around 350°C, and high-temperature type elements that have high performance at around 450°C. Multiple element samples were obtained for the various element categories and self-assessment of the performance of those elements was performed. Among the

various elements assessed, those found to have the optimal properties in each category were adopted.

Table 1. Assumed specification of series hybrid

Vehicle type		1000kg Compact size passenger vehicle
Engine displacement		440cc
Exhaust condition at TEG inlet without exhaust insulation	High-power operation	Exhaust mass flow: 15.2g/s Exhaust temperature: 716°C
	Low-power operation	Exhaust mass flow: 8.8g/s Exhaust temperature: 625°C
Exhaust condition at TEG inlet with exhaust insulation	High-power operation	Exhaust mass flow: 15.2g/s Exhaust temperature: 836°C
	Low-power operation	Exhaust mass flow: 8.8g/s Exhaust temperature: 745°C

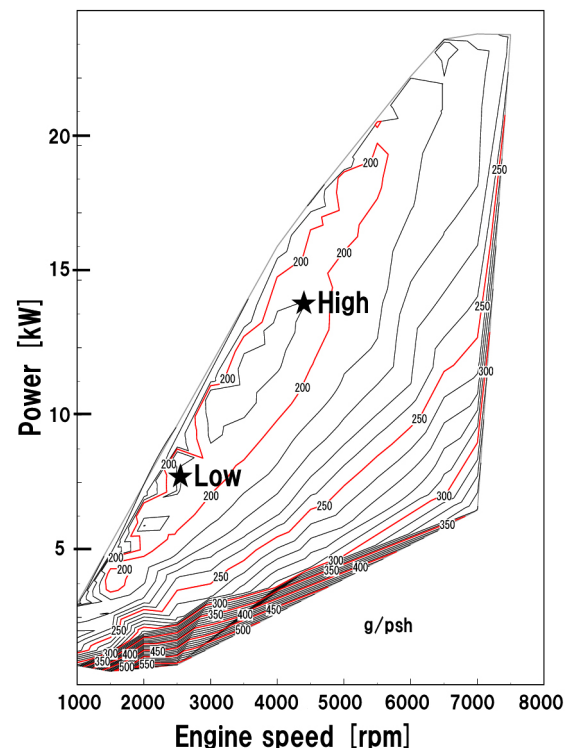


Figure 1. BSFC map of engine adopted for simulation

Table 2. Assumed engine operation schedule

Item	Unit	LA4 City	LA4 Highway	US06
Total energy necessary to run the driving cycle	Wh	1.030	1.923	2.085
Duration of drive cycle	sec.	1,372	765	600
Time of low-power operation	sec.	412	702	186
Time of high-power operation	sec.	0	63	414
Time of engine stop	sec.	960	0	0

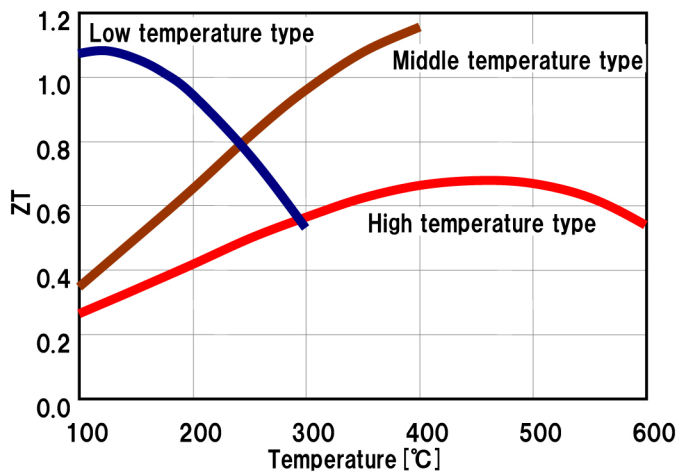


Figure 2. Figure of merit of P type thermoelectric element

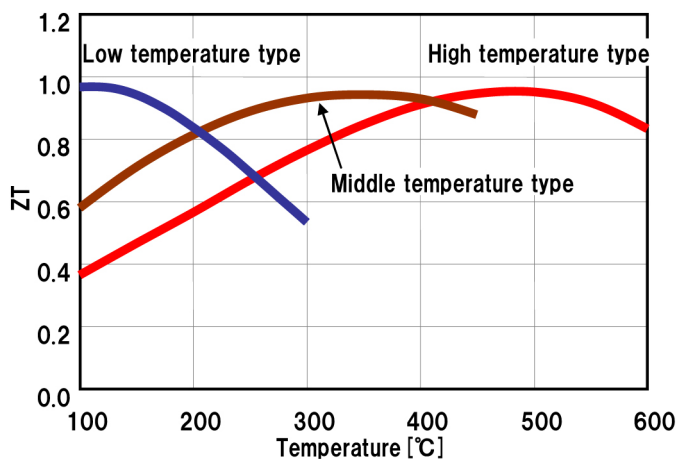


Figure 3. Figure of merit of N type thermoelectric element

SET CONDITIONS FOR ACCURACY VERIFICATION OF FUEL ECONOMY SIMULATION CALCULATION ELEMENTS

Figure 4 shows the composition of the fuel economy simulation process. The fuel economy simulation is composed of three basic calculation elements, which are heat exchanger performance, power generating performance, and system weight. The heat exchanger performance calculation, which is highest upstream, carries out computation for certain exhaust gas conditions to determine what heat exchanger involves what extent of pressure loss, in order to calculate what extent of heat flux density will be possible. The power generating performance calculation is carried out to determine what extent of power generation is possible using that heat. The system weight calculation estimates how much the resulting TEG will weigh. The fuel economy simulation

takes as inputs the generated power, increase in exhaust pressure loss, and weight increase that are obtained from the three upstream calculations, and then uses the fuel economy sensitivity of those factors obtained using the actual vehicle to convert them into fuel economy [1]. The calculation accuracy in the heat exchanger performance calculation, power generating performance calculation, and system weight calculation described above was verified on an actual vehicle. Since the series hybrid assumed as the object for the present fuel economy simulation does not actually exist, the verification was performed using an existing vehicle as a substitute. A simulation conducted in advance was used to predict the state with TEG installed, and then the accuracy of those results was verified by comparing them with the measurement results obtained from the actual vehicle with TEG installed.

Table 3 shows the test conditions used in verifying the accuracy of the calculation elements of the fuel economy simulation. The test employed a current production model CIVIC that was placed on a chassis dynamo where loads equivalent to actual driving were applied and measurements of the steady states at multiple vehicle speeds were taken. Table 4 shows the actual measurement results for flow and temperature of the exhaust gas and coolant supplied to the TEG as taken at the measurement points. Figure 5 shows the structure of the TEG used in verifying accuracy, and Fig. 6 shows the TEG as installed. The testing was conducted with the TEG placed in the center tunnel under the floor and downstream from the catalyst.

Table 3. Test condition

Vehicle type	1.3 litter Civic
Test facility	Chassis dynamo
Load condition	Road load 0% clime
Gear	3 rd Gear fixed

Table 4. Measured inlet condition of TEG

Engine speed [rpm]	1000	2000	3000	4000
Exhaust mass flow [g/s]	2.29	5.33	13.57	28.31
TEG inlet exhaust gas temperature [°C]	312.4	433.0	565.4	696.8
Coolant volume flow [l/min]	10.5	25.0	38.9	51.6
TEG inlet coolant temperature [°C]	92.5	90.1	91.2	91.7

FUEL ECONOMY SIMULATION RESULTS

Figure 7 shows the generated power obtained by the TEG using low-temperature type, middle-temperature type, and high-temperature type elements, with each type used alone as