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The study of a thermoelectric generator with various thermal conditions of exhaust gas from a diesel engine

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ABSTRACT

It is well known that internal combustion engines have approximately 30% thermal efficiency, and the remaining energy is lost as heat through both exhaust gas and coolant. To improve upon this efficiency, technology for recycling waste energy is desirable. Increasing the thermal efficiency of engines would also reduce CO_2 emissions. Recently, waste energy recovery systems have drawn a great deal of attention for their potential ability to address stringent emission regulations as well as fossil fuel depletion. Thermoelectric generators (TEGs) can be applied to produce electricity from waste heat; however, there are still remaining many problems to be solved. It would be significant not only to improve the efficiency of the TEG, but also to optimize the operating conditions. Therefore, this study provides useful information on optimization of the TEG system, including optimization of the system layout, and configuration of TEG. In addition, the heat transfer characteristics of thermoelectric modules were predicted by theoretical analysis and compared to experimentally measured heat transfer characteristics. The performance of thermoelectric generators heated by exhaust gas from an actual engine was investigated. From these results, we clarified factors affecting the optimization of thermoelectric module according to operating conditions.

1. Introduction

Recently, the automotive industry in the world emphasizes more and more about the importance of CO_2 gas reduction as the global warming is sharply progressed. Besides, the fuel efficiency due to the oil price became the most important issue at present. It is well known that the thermal efficiency of internal combustion engines currently being used in the automobiles cannot exceed 30%, only one-third of the fuel or combustion energy is converted into power energy, and the rest is wasted. The greatest losses escape into the exhaust gas and coolant, and the most reliable way to improve fuel efficiency is to minimize these losses [1]. To improve the fuel efficiency and the combustion performance of engines, the earlier efforts were on the optimization of fuel mixing process or combustion system. Recently, a technology using waste heat from exhaust gas and coolant has drawn considerable attention. A waste heat recovery system is the technology needed to improve automotive fuel efficiency by recovering heat wasted in the form of engine coolant and exhaust gas and converting it back into useable power. The ability to improve fuel efficiency by recovering waste heat from automotive engines represents a major opportunity to reduce CO_2 emissions [2]. Therefore, it is necessary to develop a competitive and reliable key technology for the recovery of waste heat exhausted from engines [3]. As demand for cars with high gas mileage continues to increase as a result of fossil fuel depletion, the waste heat recovery system is the good way to improve fuel efficiency in the cars by recovering heat which otherwise disposed as an engine cooling water and exhaust gas [4]. However, earlier researches for improving fuel efficiency by recovering waste energy were mainly focused to the thermoelectric power generation system which uses a waste energy from iron works and incinerators. On the other hand, the researches about engine waste heat recovery system are not being so progressed. Up to now, many efforts were usually concentrated on the optimization of combustion phenomenon to improve the fuel efficiency of engines instead of this technology [5]. Among them, a steam generation is currently one of the main technologies used for waste heat recovery [6]. In this study, we focus on the thermoelectric generation technology, which can convert heat energy into electric energy, thereby simplifying the system [7].

In a thermoelectric module, when the temperatures of its opposite sides are different, power is produced by the Seebeck effect [8]. Conversely, if the module receives a power input, it actively moves

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Nomenclature

A	area [m^2]
A_B	area of heat sink base [m^2]
D	diameter of the exhaust pipe [m]
D_g	fin to fin spacing [m^2]
f	friction factor
H_f	fin height [m]
h	heat transfer coefficient [$W/m^2/K$]
k	thermal conductivity [W/m/K]
L	length of thermoelectric generator [m]
L_{HS}	length of heat sink [m]
P	overall generated electricity [W]
$\dot{q}$	internally generated heating per unit volume [W/m^3]
Q	thermal power [W]
W_{HS}	width of heat sink [m]
α	seebeck coefficient [V/K]
α^*	seebeck parameter of TEG [1/K]
γ	heat-transfer ratio of heat absorber to heat sink
δ	thickness of thermoelectric generator [m]
λ	Biot number of TEG
μ	viscosity coefficient
ρ	density
i,s	inner spread, i.e. of the spreader of the heat absorber
o,s	outer spread, i.e. of the spreader of the external heat sink

heat energy by means of the Peltier effect [9]. Keeping in mind the efficiency improvement of the TEG, we examine the thermoelectric module with regard to power generation [10]. Since power is generated by the temperature difference between the sides of the thermoelectric module without the need for any moving parts, the power generation device has a simple, structure and can have long life. However, thermoelectric modules presently have less generation efficiency than steam generation modules, presenting a hurdle for commercialization. Therefore, thermoelectric generation has mostly been used in specialized electric equipment in aerospace and military applications. Research has advanced the ability to use thermoelectric modules for power generation in automotive applications [3]. However, so far thermoelectric generators have rarely been applied in automobiles because the flow rate and the exhaust gas temperature change according to the engine's operating conditions. To implement thermoelectric modules in automobiles, first of all, analysis of the characteristics of thermoelectric module is required [4]. Also, performance improvements are needed that can enhance engine performance. However, data about optimum performance to implement thermoelectric module in the automobile is lacking. Besides, information about necessary elements required for performance improvement is quite poor. Thus, it is necessary to clarify the characteristics of thermoelectric modules and investigate the possibility of applying them to the engine system. In a previous study, basic data were obtained about the heat transfer characteristic of a thermoelectric module by means of theoretical analysis as a prerequisite stage to adopt it in automobile engines [11]. The effect of the thermoelectric module's shape upon heat transfer characteristics has been clarified [12]. Further, the exhaust system of an actual engine was equipped with thermoelectric modules, and their characteristics of were investigated under different drive conditions to evaluate the possibility of implementing thermoelectric modules in the engine was evaluated through these experiments [13]. Finally, by providing factors affecting the optimization of the thermoelectric module for various drive conditions, know-how was established that was needed to develop devices to converts waste energy from exhaust gas into electric energy. In addition, we also provide valuable information in terms of the optimization of the TEG system, including optimizing the system layout, exhaust manifold design, and configuration.

2. Experimental apparatus and procedure

2.1. Theoretical analysis of the thermoelectric module

In this study we investigated the principle and operation characteristics of the thermoelectric module, which is a most important part of the TEG. The Reynolds number can be determined based on the flow rate of exhaust gas and the diameter of the exhaust pipe, as expressed in the following Eq. (1).

$$\mathrm{RE} = \frac{\rho V D}{\mu} \tag{1}$$

Then, the friction coefficient can be calculated using Eq. (2) if The Reynolds number is less than 100,000.

$$f = \frac{0.3164}{RE^{1/4}} \tag{2}$$

The pressure loss, which strongly affects the heat transfer, can be determined by using the friction coefficient as given in Eq. (3).

$$\Delta p = f \frac{L}{D} \frac{\rho V^2}{2} \tag{3}$$

Since flow rate increases with decreased friction loss and engine load increases according to drive conditions, pressure loss shows an increasing trend.

In the case of incompressible fluid, the pressure drop that occurs in the circular cylinder can be applied in the energy equation as below.

$$\frac{V_1^2}{2g} + \frac{p_1}{\rho} + z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\rho} + z_2 + h_L \tag{4}$$

here, h_L is the pressure drop. In this case, because the sectional area of circular cylinder is constant,

$$V_1 = V_2 \tag{5}$$

Therefore, Eq. (4) simplifies to

$$h_L = \frac{\Delta(p + \gamma h)}{\rho} \tag{6}$$

assuming that the front and rear ends of the exhaust pipe are of the same height ($Z_1 = Z_2$). The energy loss can be expressed in proportion to Δp. In other words, the lost energy is the difference between inflow energy and outflow energy. It is considered that this energy is transferred to thermoelectric module through heat sink because this energy has an effect on the heat transfer. Therefore, the characteristics of the thermoelectric module were analyzed based on pressure difference in this study.

Also, characteristics of heat transfer were calculated using the mechanism of the Seebeck effect as shown in Fig. 1.

The heat conduction equation can be derived based on the internal energy generation of the thermoelectric module [14].

$$\frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}}{k_{TEG}} = 0 \tag{7}$$