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Optimal heat exchanger dimensional analysis under different automobile exhaust temperatures for thermoelectric generator system

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Abstract

An entirely numerical thermoelectric generator model is formulated by taking the heat transfer and flow resistance characteristics of exhaust fluid with different exchanger scales into consideration. Applied to automotive exhaust heat recovery, this study mainly focused on the effect of exhaust temperature on exhaust exchanger structure optimization, the objective being maximal net power output. Results show that the optimal height was unchanged at different exhaust temperatures, unlike the optimal length and width, which increased and decreased at higher temperatures, respectively. A small TEG module is necessary at high exhaust temperatures.

Keywords: Thermoelectric generator; net power; automotive; exhaust exchanger; scale optimization

1. Introduction

The number of automobiles is increasing continuously with peoples' progressing lifestyles; although convenient for people, this affects the environment negatively. According to statistics, 40% of the heat generated by automobiles is discharged into the atmosphere through automobile exhaust. Effectively reusing the waste heat from automobiles will not only improve energy efficiency, but also reduce emissions and improve environmental quality. The thermoelectric generator (TEG) can directly convert

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heat into electricity according to the Seebeck effect in semiconductor materials and is advantageous in terms of simplicity, ruggedness, silent operation, and the absence of compression-expansion moving parts or working fluid; it is regarded as one of the most promising ways of recovering waste heat in the future. Many automotive manufacturers are exploring thermoelectric power generators to convert some of the waste heat from exhaust gas into useful electric power. However, this technology has not yet been installed in the current production of cars and is still in the concept stages because of its low efficiency. Therefore, the analysis and modeling of an effective TEG system is an important consideration for its application in waste heat recovery systems.

Analytical models have been developed by many authors. Yilbas et al. [1] presented the effect of the slenderness ratio and external load parameter on thermoelectric power and device efficiency. With reference to the TEG structure, a significant increase in the module's power output can be achieved by modifying the geometry of the thermoelectric elements using conventional non-equilibrium thermodynamics. Chen et al. [2] investigated the characteristics of a multi-element thermoelectric-generator with the irreversibility of finite-rate heat transfer, Joulean heat generated inside the thermoelectric device, and heat leaks through the thermoelectric couple. Gou et al. [3] established a low-temperature waste heat thermoelectric generator system using modeling and experiment and found that aside from increasing waste heat temperature and TEG modules in series, expanding heat sink surface area and enhancing cold-side heat transfer capacity within proper ranges can also be employed to enhance system performance. As most studies were modeled under the assumption that every thermoelectric element operates at the same temperature, in our previous study [4], we developed a mathematical model that considered a large temperature gradient across the TEG module surface in the fluid flow direction via the finite element method and explored some new features of TEG optimization. However, we had assumed a constant value for the convective heat transfer coefficient when exhaust gas flows through the exchanger and neglected flow resistance characteristics along with their effect on its additional pump power consumption. To obtain a more accurate result for optimal thermoelectric performance by an exhaust TEG system, in this study, we formulate an entirely numerical TEG model by calculating the specific exhaust fluid heat transfer and flow resistance characteristics for different exchanger structure scales. Considering the various working conditions of automotive engines in practice, we mainly focus on studying the optimization simulation and analysis of the exhaust exchanger structure when exhaust gas temperature varies within a certain range. Assuming the maximal net power output as the optimal objective, and with the aid of the new model, optimal performance conditions for the TEG system were determined using numerical simulations.

2. Mathematical model

The general schematic structure of the TEG system is shown in Fig.1(a). In the figure, two modules of the TEG semiconductor layer are attached both on the upper and lower sides of exhaust heat exchangers. L, w, and h are the exhaust exchanger's total length, width, and height, respectively; two parallel flow coolant heat exchangers are employed to cool each TE module. A water cooling type is considered by introducing the engine cooling water into two coolant exchangers, and the convective heat transfer coefficient of cold water (h_c) is held constant. The mathematical model of a TEG module is illustrated in Fig.1(b). The entire TEG module is divided into a total of $n_x \times n_y$ calculated particles, considering a single P–N semiconductor couple as one unit. The coordinates (i, j) represent the numbers of lines and rows, respectively, where $i = 1$ to n_x and $j = 1$ to n_y.

In the model calculations, the original inlet temperatures for hot and cold fluids are T_{fin} and T_{cin}, respectively. In a TEG module, the P–N couples are connected in series with the external load resistance R_L, which is equal to the total internal resistance for each module. Then the two modules are connected in parallel. Because the temperatures of each small calculation unit across the fluid flow direction are the same, each line of TEG elements can be used as a new calculation unit containing n_y P–N elements. This