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Effects of heat transfer characteristics between fluid channels and thermoelectric modules on optimal thermoelectric performance

Wei He [a], Shixue Wang [a,b,*], Yulong Zhao [a], Yanzhe Li [a]

[a] School of Mechanical Engineering, Tianjin University, Tianjin 300072, PR China
[b] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, Tianjin 300072, PR China

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ABSTRACT

Semiconductor thermoelectric generation technology has a promising application for waste heat recovery and is becoming a noticeable research field. This paper presents a mathematical thermoelectric generator (TEG) model applicable to engine exhaust gas heat recovery. This model considers the conduction along the heat exchanger and the contact thermal resistance of the exchanger plate between the fluid channel and the thermoelectric modules, which were neglected in a previous numerical analysis. Considering that there is an optimum module size corresponding to the maximum power output in a TEG system, the effects of heat transfer characteristics between the fluid channel and the thermoelectric modules on the optimal thermoelectric performance are investigated by using an engineering equation solver (EES) program. Numerical results show that there is a larger optimal area and a lower peak power when considering the conduction and contact thermal resistance factors mentioned above compared to traditional results, which are determined by considerably different factors such as internal heat transfer and temperature distributions. Moreover, an optimal thermal conductivity coefficient that corresponds to the peak power output exists when the conduction along the exchanger is considered. In the case when conduction along the exchanger is not considered, higher the thermal conductivity, the better is the thermoelectric performance. A thin-plate exchanger is recommended in the TEG system owing to its high power output. The optimal module area increases linearly, and the maximum power output exhibits an obvious decrease with an increase in the contact thermal resistance.

1. Introduction

As a significant cause of fuel crisis and environmental pollution, an internal combustion engine drives vehicles with only 30% of the total heat generated by the gasoline used. During this process, about 40% of fuel energy is discharged from the exhaust pipe and about 30% is lost to the coolant for a typical gasoline engine vehicle. It is meaningful to recycle the considerable waste heat generated from internal combustion [1]. As a solid-state energy converter, a thermoelectric material can directly convert thermal energy into electrical energy without additional power generation devices. Therefore, many automotive manufacturers are exploring thermoelectric power generators (TEGs) to convert some of the waste heat from the exhaust gas into useful electric power [2]. A thermoelectric generator is a static heat engine that generates voltage when a temperature difference is created across its hot and cold sides based on the Seebeck effect [3]. Thermoelectric generators have various advantages compared to the other devices used for similar applications. First, thermoelectric generators utilize low-grade thermal energy, which is cheap and easily available. Second, thermoelectric generators are environment friendly because they do not emit pollutants during operation. Third, thermoelectric devices have a longer lifetime because there are no moving parts compared to conventional thermal systems [4]. Therefore, the TEG using automobile waste exhaust as the heat source is believed to be a new method to decrease fuel consumption and environmental pollution [5].

With the development of advanced thermoelectric materials, a direct energy conversion of waste heat into electric power has become a popular research topic that has recently attracted considerable attention [6]. To perform a better analysis of the performance and heat transfer of the TEG, considerable efforts in system modeling and TEG optimization have been proposed [7–9]. Chen et al. revealed the influences of external irreversibility and operative conditions on a multi-couple thermoelectric generator [10]. Lee developed the optimal design of thermoelectric

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* Corresponding author at: School of Mechanical Engineering, Tianjin University, Tianjin 300072, PR China. Tel.: +86 22 27402567; fax: +86 22 27402567.
E-mail address: wangshixue_64@tju.edu.cn (S. Wang).

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devices in connection with heat sources using dimensional analysis [11]. Kim proposed an analytic model to measure the internal temperature difference of a TEG [12]. Wang et al. considered a general model with the coupling of the electric potential field and the temperature field [13]. Yilbas et al. discussed the influence of the slenderness ratio and the external load parameter on the thermoelectric power and device efficiency. Chen and Gou analyzed the effects of a finite-rate heat transfer between a thermoelectric device and its external heat reservoirs on the performance of a single-element thermoelectric generator [14,15]. Gou et al. developed a low-temperature waste heat thermoelectric generator system model and indicated that the addition of TE models in series would lead to further system improvement [16].

When TEG technology is used for recycling the heat energy from engine exhaust gas, which has a high temperature and a low mass flow mate, there is a temperature decrease across the TEG surface in the fluid flow direction. This is because of the continual recovery of heat energy from a high temperature into the atmosphere. Some authors have paid attention to the temperature gradient and proposed a new TEG model. Yu et al. presented a numerical model on the basis of an elemental approach. They demonstrated its ability to simultaneously analyze the temperature change in a thermoelectric generator, and its performance under operation conditions. Simulation results showed that the variations in the temperature of the fluids in a TEG are linear [17]. Weng et al. explored the influence of the number and the coverage rate of TE couples on the heat exchanger of a TEG via simulations [18]. Simon et al. optimized the design of a TEG that was placed in the wall of a crossflow heat exchanger using a numerical model. This numerical model took the total power output as an objective function, and the number of modules and the current at each control volume of the mesh as the design variables [19].

Many new characteristics of the thermoelectric behavior of a TEG system were reported when temperature variation was considered in previous studies. In our previous work, the functional relationship between the thermoelectric power generation and the TEG module geometric parameters based on the exhaust gas parameters was formulated [20,21]. Results showed that a large temperature gradient exists in the engine exhaust gas TEG system; therefore, there is a peak power output value when the module is designed at the optimal size. However, the previous numerous promising results were obtained under the modeling assumption that the heat transfer caused by conduction along the heat exchanger could be neglected along with the contact thermal resistance between the heat exchanger and the TEG module. In fact, with respect to the existing large temperature gradient along the fluid flow direction in an engine exhaust TEG system, the heat transfer caused by conduction along the heat exchanger seems obvious. Further, contact thermal resistance is inevitable in an actual application at the interface between the heat exchanger and the fluid channel. Therefore, in this study, a new TEG model that considers the conduction along the heat exchanger and the contact thermal resistance between the heat exchanger and the fluid channel is built for possible applications in engine exhaust gas waste heat recovery. The new heat transfer characteristic and its function with respect to the optimal thermoelectric conversion performance are studied using a plate heat exchanger.

2. Numerical implementation

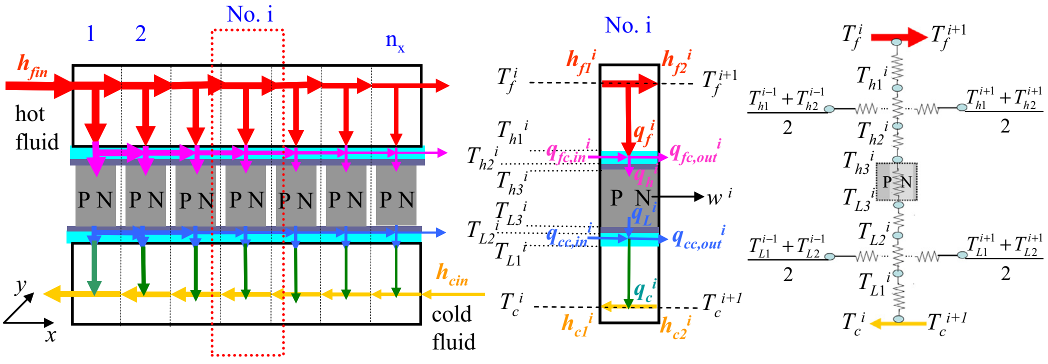
2.1. Mathematical model

2.1.1. Model description

A thermoelectric module can function between hot and cold fluid channels because of the temperature difference between the two sides. A counterflow plate heat exchanger, which has the opposite flow direction for cold and hot fluids, is adopted in this study for its good heat transfer performance. Fig. 1 shows a schematic representation of a mathematical model of TEG.

Fig. 1(a) shows the overall TEG module layout. The entire TEG module is divided into a total of $n_x \times n_y$ calculation units, where a single P–N element is one TE unit. Here, n_x P–N elements are aligned with the fluid flow (x direction), and n_y *P–N* elements are placed across the fluid flow (y direction). For each *P–N* element, the *P* and *N* units are connected along the y direction. All *P–N* elements are connected in series. The temperatures of each small calculation unit along the fluid flow direction are considered to be same; thus, each line of TE elements can be used as a new calculation unit containing n_y *P–N* elements, which is marked by the superscript i for all corresponding variables, where i ranges from 1 to n_x.

Fig. 1(b) shows the heat transfer and conversion process for one calculation unit, and with the corresponding thermal resistance distribution shown in Fig. 1(c). Here, the inlet enthalpy values for the hot and cold fluids are denoted as h_{fin} and h_{cin}, respectively. When the hot fluid flows along the heat exchanger, the released heat q_f^i is first transferred from the fluid channel to the heat exchanger's surface by convective heat transfer. In addition, the hot fluid temperature drops from T_f^i to T_f^{i+1} and the exchanger outside surface temperature heats to ${T_{h1}}^i$. Similarly, when the cold fluid flows along the heat exchanger, the absorbed heat q_c^i is equal to the heat released from the exchanger's outside surface by convective heat transfer, when the cold fluid temperature increases



(a) (b) (c)

Fig. 1. Schematic representation of mathematical model of TEG: (a) overall TEG module layout, (b) heat transfer and conversion process for one calculation unit, and (c) thermal resistance distribution.