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# Structural size optimization on an exhaust exchanger based on the fluid heat transfer and flow resistance characteristics applied to an automotive thermoelectric generator

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ABSTRACT

In practice, for effective exhaust waste heat recovery, a heat exchanger must exhibit a high heat transfer performance and a reasonable pressure drop to achieve a high net power output. Therefore, a complete numerical thermoelectric generator (TEG) model used for engine exhaust gas heat recovery is presented in this paper, based on a common plate-type exhaust heat exchanger. The model not only considered the temperature gradient along the fluid flow direction, but also included the fluid heat transfer and the flow resistance characteristics. The interaction relationships between the exchanger scales, heat transfer and flow resistance characteristics, and thermoelectric performance were mainly studied in this study by numerical simulations using the Fortran program. Results show that the high TEG power can be achieved at the small cross section area, and corresponding to a small optimal module area. A small height is required when the cross section area is constant. To obtain the maximum net power with fluid flow resistance, the optimal cross section area should be 0.0056 $m^2$, with the optimal scales at a height of 0.005 m, and length of 0.56 m, when applied in an automotive vehicle. Exchanger scales are available in a wide optimal design range to help achieve a high net power output, if the scale optimization match is met.

## 1. Introduction

It is well known that only 30–40% of the fuel or combustion energy is converted into power energy in vehicle engines, and the rest is wasted. Recently, a technology using the waste heat from exhaust gas has drawn considerable attention. A waste heat recovery system is the technology needed to improve automotive fuel efficiency by recovering the exhaust gas heat and converting it into useable power. The thermoelectric generator (TEG) comprises multiple semiconductor thermocouples (e.g. constructed using bismuth telluride with p- and n-doping), which are capable of generating electrical energy when subjected to a temperature difference across their hot and cold sides [1]. It has many distinct advantages over other technologies, such as being able to operate extremely reliably and silently, simple, compact and safe, requires no maintenance, light in weight and small in size, capable of operating in high temperatures, suitable for small-scale and remote applications, environmentally friendly, position-independent, and available for flexible power sources [2].

Recently, the low conversion efficiency is still the crucial factor restricting the development of TEG and numerous studies have been conducted on making improvements to it. Many aspects of TEG including energy conversion, performance optimization, thermoelectric material characterization, and various applications have been studied extensively in the literature. In the study of the mathematical model, Chen et al. [3,4] analyzed the effects of the finite-rate heat transfer between a thermoelectric device and its external heat-reservoirs on the performance of a single-element thermoelectric generator by applying finite-time thermodynamics. Fankai et al. [5] introduced a complete numerical model of a commercial thermoelectric generator with finned heat exchangers, taking into account inner and external multi-irreversibility. Meng et al. [6] developed a complete three-dimensional transient model to investigate the dynamic response characteristics of TEGs. Gou et al. [7] established a low-temperature waste heat thermoelectric generator system model and indicated that adding TE models in series would enhance system improvement. Meng et al. [8] developed a multi-physics, three-dimensional numerical TEG model to investigate the TEG performance, and then the model is compared with

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the classical thermal resistance model. Results indicate that to improve the heat insulation effect is critically important for high-temperature TEGs, and to use thin ceramic plates can increase the junction temperature difference, and hence enhances the TEG performance. Fan et al. [9] proposed a comprehensive mathematical model to calculate the optimal leg length and cross-section area of TEG unit to maximize the peak output power. Chen et al. [10] introduced a thermoelectric energy harvester composed of two thermoelectric modules, a wicked copper-water heat pipe, and finned heat sinks. Results show that the use of a heat pipe in this design increased the power output by 6 times over conventional designs. In the study of the TEG structure and system optimization, Shi et al. [11] studied the influence of thermal contact on the output performance of thermoelectric generators by designing a three-dimensional thermal extensional structure. Niu et al. [12] considered the detailed geometry of a thermoelectric generator and exhaust channel. Meng et al. [13] implemented a multi-objective and multi-parameter optimization to design the optimal structure of bismuth-telluride-based TEG module. It points out the counter flow cooling pattern is recommended, and the system performance can be improved under the condition of less thermoelectric materials consumption. Various transport phenomena were investigated, and design optimization suggestions have been reported. Jang et al. [14] optimized the thermoelectric generator module spacing and spreader thickness used in a waste heat recovery system. Shu et al. [15] applied a method in which a TEG was combined with the Organic Rankine cycle to recover the waste heat on an internal combustion engine. Rezania et al. [16] studied the geometrical effect of the TEG on the heat transfer characteristics in the micro-heat sink. Kempf et al. [17] provided the strategies to optimize TEG configuration and heat exchanger design for maximum fuel efficiency improvement. It is found that the thermal conductivity of the heat exchanger material is quite important. In the experimental study on the TEG system, Kim [18] proposed an experimental method to study the relationship between the Seebeck coefficient and the temperature difference of the TEG to optimize the TEG mode. Liu et al. [19] developed a test bench to analyze the performance of the TEG system characteristics, which are undertaken to assess the feasibility of automotive applications. It produced a maximum power of 944 W. Favarel et al. [20] presented the experimental validation of this model and showed interesting experimental results on the TEG configurations. Analyses of the influence of the number of thermoelectric modules and influence of electric currents on the produced electrical power were conducted. Kim et al. [21] developed experimental results by examining engine operated under various conditions. A contour map showing the power output of the TEG as a function of the engine load and speed was obtained. Numerous other new ideas have been proposed to improve TEG performance [22–24].

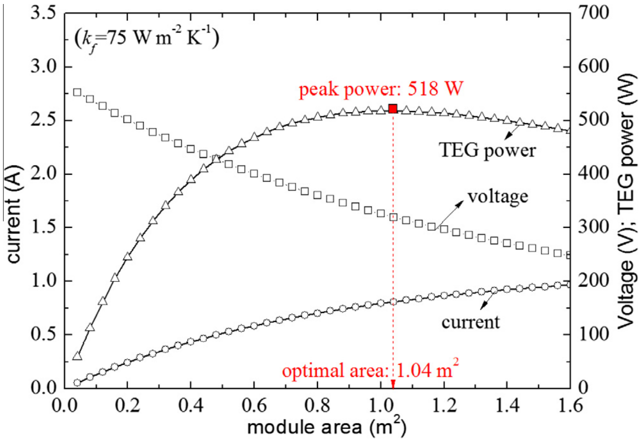

**Fig. 1.** Thermoelectric characteristics based on temperature gradient.

However, despite the numerous promising results obtained, the previous models usually neglected the existing large temperature gradient along the fluid flow direction. In practice, the temperature on TEG hot surfaces has a large decrease along the exhaust flow direction when heat energy is continually recovered, owing to the exhaust mass flow rate being limited. Therefore, our previous studies mainly focused on the TEG performance optimization with consideration on the characteristics of large temperature gradient along the fluid flow direction, as well as exploring some new features [25]. The previous results showed that an optimal module area exists corresponding to a peak TEG power output when the total heat transfer coefficient $K_f$ when heat is transferred from a hot fluid to the hot-side surface of a TEG module is given a constant value, as shown in Fig. 1. The basic parameters in Fig. 1 follow Table 1 listed in this paper later. The feature has been explained by the internal temperature variation of the small TE units in the fluid flow direction in the literature [25].

However, previous studies take a constant value of the convective heat transfer coefficient when exhaust gas flows through an exhaust exchanger [25]. The specific heat-transfer characteristics and scales of exchangers are not discussed in the literature. In fact, the convective heat transfer coefficients are functions of the fluid nature, temperature, and velocity. All these parameters may vary moving from the inlet to outlet of the exchanger channel, and have a direct relationship with the exchanger scale. Therefore, the scale optimization has a close relationship with the practical convective heat transfer coefficient. It will be more scientific if the convective heat transfer coefficient is calculated corresponding to the specific exchanger scale. Moreover, our previous work neglected the flow resistance characteristics and their effect on the net power output of the TEG system. Therefore, it takes the maximum TEG system power output as the optimal object, and doesn't consider the effect of the flow resistance characteristics on the net power output of the TEG system. In fact, to be effective for exhaust waste heat recovery, a heat exchanger must exhibit high heat transfer performance and a reasonable pressure drop to achieve a high net power output.

In order to obtain a more accurate optimal thermoelectric performance on an exhaust TEG system, we formulated a complete numerical TEG model. The temperature gradient along the fluid flow direction was considered as well as the specific fluid heat

**Table 1**
Basic calculation parameters of the TEG system.

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $c_1$, $c_2$, $c_3$ | 5 mm | $m_f$ | 80 g s$^{-1}$ | $m_c$ | 500 g s$^{-1}$ |
| $T_{fin}$ | 550 °C | $T_{cin}$ | 80 °C | $k_c$ | 1000 W m$^{-2}$ K$^{-1}$ |
| $\alpha_p$ | $2.037 \times 10^{-4}$ V K$^{-1}$ | $\alpha_N$ | $-1.721 \times 10^{-4}$ V K$^{-1}$ | $\rho_p$ | $1.314 \times 10^{-5}$ Ω m |
| $\rho_N$ | $1.119 \times 10^{-5}$ Ω m | $\lambda_p$ | 1.265 W m$^{-1}$ K$^{-1}$ | $\lambda_N$ | 1.011 W m$^{-1}$ K$^{-1}$ |
| $\delta_{exc}$ | 0.3 mm | $\delta_{cop}$ | 0.2 mm | $\delta_{cer}$ | 0.05 mm |
| $\lambda_{exc}$ | 398 W m$^{-1}$ K$^{-1}$ | $\lambda_{cop}$ | 398 W m$^{-1}$ K$^{-1}$ | $\lambda_{cer}$ | 35 W m$^{-1}$ K$^{-1}$ |