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Performance investigation and design optimization of a thermoelectric generator applied in automobile exhaust waste heat recovery

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ABSTRACT

This work develops a multiphysics thermoelectric generator model for automobile exhaust waste heat recovery, in which the exhaust heat source and water-cooling heat sink are actually modeled. Special emphasis is put on the non-uniformity of temperature difference across thermoelectric units along the streamwise direction, which may affect the performance of exhaust thermoelectric generator systems significantly. The main findings are: (1) The counter flow cooling pattern is recommended, although it cannot elevate the overall output power as compared with the parallel flow counterpart, it reduces the temperature non-uniformity effectively, and hence ensures the system reliability. (2) The temperature non-uniformity strikingly deteriorates the output power of thermoelectric unit along the streamwise direction; meanwhile, an additional lateral heat conduction effect exists within the exhaust channel wall, the both mechanisms leads to that the maximum output power of the system is not enhanced but is actually reduced when too many thermoelectric units are adopted. (3) When the exhaust channel length is fixed, the maximum output power of the system can be elevated by increasing the thermoelectric unit number but keeping thermoelectric unit spacing unchanged. This means that the system performance can be improved under the condition of less thermoelectric materials consumption.

1. Introduction

In recent years, research on waste heat recovery techniques is a very active field because of the global energy crisis [1]. Among various waste heat recovery techniques, thermoelectric generators (TEGs), which can directly convert heat into electricity utilizing Seebeck effect of semiconductor materials, are regarded as one of the most promising ways in the future, mainly because they have the advantages of simplicity, ruggedness, silent operation, as well as absence of compression-expansion moving parts and working fluid [2]. Different sources of waste heats can be supplied to TEGs. Li et al. [3] proposed that combining the solar concentrating thermoelectric generation with micro-channel heat pipe can save the quantity of thermoelectric generation and reduce the cost significantly. Barma et al. [4] estimated the amount of electrical power produced by a TEG placed between flue gas duct and fresh air duct of an industrial thermal oil heater. Xie et al. [5] presented a technical solution to the power resource problem of sensors placed on seafloors by recycling the thermal energy of hydrothermal fluids using TEGs.

Automobiles are the most important means of transportation nowadays, which are quite convenient but also generate a lot of waste heat. According to the statistics, two thirds of the automobiles fuel combustion energy is lost and diffused as heat, and 40% of the heat is discharged to the atmosphere in the form of automobile exhaust [6]. Effective re-using of the waste heat from automobiles will not only improve the use efficiency of existing energy sources, but also can reduce emissions and improve the environmental quality. Research suggests that for an engine with 50 kW mechanical power, harvesting less than 2% of the power wasted in exhaust alone could provide electric supply of 1 kW, sufficient for the devices in the vehicle supplied by alternator [7].

For a long period of time, relatively low thermoelectric conversion efficiency limited the development and application of TEGs. Although the conversion efficiency of TEGs is much lower than conventional power generation devices, the thermoelectric power generation technology still receives many attentions worldwide, and the reason of which is that the acquisition of automobile exhaust virtually has no cost. For applications of TEGs on automobile waste heat recovery, Royale and Simic [8] pointed out that a

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comprehensive investigation of the TEG technology limitations, new TEG design and development, together with the simulations and testing are the current and future research objectives. In the late 1980s, Birkholz et al. [9] for the first time applied a single $FeSi_2$-based TEG module on a vehicle and successfully produced 1 W electric power. Only a few years later (1995), Bass et al. [10] obtained 1 kW of output power with TEG designed for exhaust of 14 L diesel engine. Subsequently, Ikoma et al. [11] applied an array with 72 pieces of TEG module to gasoline engine vehicles. By maintaining 563 K temperature difference between hot and cold sides of the module, 35.6 W electric power was generated. Thacher et al. [12] found that insulating the exhaust and lowering the coolant temperature had dramatic effects on the power production through testing on a light truck. Ibrahim et al. [13] recommended that packing of the exhaust duct by inserting aluminum wool material can enhance heat transfer and hence improve the TEG performance. Aranguren et al. [14] built a TEG prototype, which can roughly obtain 100 W m^{-2} of usable energy from the exhaust of a combustion chamber with an efficiency of 2.2%. Through experiments on a micro-combustor, Yadav et al. [15] found that the overall conversion efficiency increased with the number of TEG modules, which was 1.2% for one module, 2.56% for two modules and 4.6% for four modules. Adopting a two-stage TEG design, the system conversion efficiency can reach 5.35% [16]. With the average exhaust temperature of 823 K and the mass flow rate of 480 g s^{-1}, the TEG system constructed by Zhang et al. [17] generated 1002.6 W electricity with a 2.1% heat-to-electricity efficiency. The maximum output power of 944 W for the TEG application on automobiles was reported by Liu et al. [18] Subsequently, Liu et al. [19] designed a new system called the "four-TEGs" system and assembled the system into a prototype vehicle called "Warrior". Their testing showed great potential for application of this technology in future vehicles. Moreover, some famous auto manufacturers worldwide, e.g., Hi-Z Technology in USA [20] and Nissan in Japan [21], had been attempting to improve the conversion efficiency of thermoelectric modules. Based on Bi_2Te_3 materials, Hi-Z Technology's goal for a practical device was an conversion efficiency of about 11%, which could save 5–12% fuel consumption if the 1 kW TEG module was used; however, the experimental conversion efficiency of the Hz-14 modules was only 5% [22].

Overall, previous studies were mostly based on experiments [6–22], only a few works [23–29] simulated the performance of automobile exhaust TEG systems. It is well known that the numerical simulation technique, as one of the most important research methods, can directly evaluate the device performance and suggest the direction of design optimization in a short research cycle. Weng and Huang [23] numerically investigated effects of the heat exchanger length and the thermoelectric module coverage on the automobile exhaust TEG system performance. In their study, the TEG module was simplified to a block with a thickness of 2.8 mm and an equivalent thermal conductivity of 3.26 W m^{-1} K^{-1}, the real TEG structure however was not modeled. Hsiao et al. [24] established a mathematical model of TEG modules applied on an automobile, and they concluded that the output power and conversion efficiency could be improved by increasing engine speed or coolant temperature. However in Ref. [24], they simplified the automobile exhaust TEG system as a thermal resistance network, so that the heat source, the cold source, and the TEG module were treated as three blocks with certain thermal resistances. Deng et al. [25] focused on the structure design of the heat exchange attached on the TEG module. He et al. [26] presented that a thin-plate exchanger should be used in the TEG system owing to its high power output. They expected to improve the performance of automobile TEG systems by further increasing the heat amount transferred into the TEG module. However, the TEG module were not modeled and investigated in their works.

Moreover, some previous studies [24,27] assumed that the performance of per TE unit in automobile exhaust TEG systems was the same; thus, only one TE unit was modeled, and then the overall performance of TEG systems was obtained by multiplying the number of TE units. However, for a TEG module applied on an automobile, the flow of the exhaust in the automobile pipe, as well as the coolant in the heat sink, is unidirectional. As the TEG module absorbs heat from the exhaust and dissipates heat into the heat sink, the temperature of exhaust will decrease while the temperature of coolant will increase along their respective streamwise direction, leading to a significant drop of the temperature difference supplied to each TE unit. As a result, the output powers of TE units are deteriorated along the exhaust flow direction, and hence the overall output power of TEG module cannot be characterized by one TE unit. In order to reflect the temperature non-uniformity, Wang et al. [28] divided the entire automobile exhaust TEG system into N subsystems along the streamwise direction and assumed that the outlet temperature of exhaust for $(i-1)$th subsystem was equal to the inlet temperature of exhaust for ith subsystem. Tatarinov et al. [29] adopted the similar approach. In these studies [28,29], the convective heat transfer between exhaust and TE units was actually not solved. Instead, constant convective heat transfer coefficients were introduced into the exhaust and coolant channels and a set of algebraic equations was used to iteratively solve the inlet/outlet temperatures of exhaust in each subsystem based on the energy conservation between exhaust and TE units. Furthermore, the output powers of TE units were evaluated by the thermal resistance model. However, because the convective heat transfer in the channels as well as the heat conduction and electrical conduction in TE units are inherently coupled, the inlet/outlet temperatures determined by the above method must be inaccurate, which inevitably will lead to a significant deviation of the predicted output powers of TEC units from the their practical values. To avoid this issue, the temperature variation of exhaust along its streamwise direction can be determined through experimental measurements. An alternative approach is to develop a coupled multiphysics model, in which the convective heat transfer of exhaust and coolant in channels, as well as the heat conduction and electrical conduction in thermoelectric materials are coupled solved. Unfortunately, up to now such coupled model for automobile exhaust TEG systems has not been built in the open literature.

Based on the above analysis, a practical TEG system for the automobile exhaust waste heat recovery is first modeled numerically, wherein the exhaust is considered as the actual heat source and a water-cooling heat sink is used as the cold source. Using the established model, the overall performance of the automobile exhaust TEG system is then investigated for various cooling patterns and TE unit numbers to highlight the effect of temperature non-uniformity in TE units. Finally, at the condition of constant exhaust channel length, the arrangement of TE units in the system is optimized under two constraints, i.e. fixed volume of TE materials and fixed spacing between TE units.

2. Model

The TEG devices can be installed on two potential positions, i.e. exhaust pipe and radiator. Hsiao et al. [24] demonstrated that the TEG module presents better performance on the exhaust pipe than on the radiator. Therefore, the automobile exhaust TEG system is investigated in this work, which consists of three parts: an automobile exhaust channel, a TEG module and a water cooling heat sink. One TEG module generally has r rows and each row has m TE units. Due to the structure periodicity of automobile TEG system, the performance of each row along the streamwise direction