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Effect of cooling design on the characteristics and performance of thermoelectric generator used for internal combustion engine

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ABSTRACT

By developing a thermoelectric generator (TEG) model coupled with exhaust and cooling channels for an exhaust-based TEG (ETEG) system, the influence of the cooling type, coolant flow rate, length, number and location of bafflers, and flow arrangement are investigated. It is found that the net output power is generally higher with liquid cooling than air cooling. Since a very low velocity of liquid coolant is sufficient for cooling the TEG modules, the flow resistance is negligible, and inserting a baffler, increasing the baffler length or the flow velocity generally improves the performance. However, both the baffler length and flow velocity of air cooling need to be moderate. Placing one baffler in front of a TEG module is sufficient to guide the cooling flow. The performance is generally unaffected by the change of baffler location. By maintaining sufficient temperature difference for all the TEG modules, the counter-flow arrangement leads to higher output power than the co-flow arrangement. Although liquid cooling is more complicated, and extra cooling power may be needed to cool down the circulating coolant, the temperature increment of liquid coolant through cooling channel is insignificant for cooling 20 TEG modules producing about 250 W of power.

1. Introduction

Although environmental and energy issues have attracted considerable attentions in recent years, most of the energy being utilized is still from the combustion of fossil fuels, which simultaneously releases significant amount of waste heat. As the major power source of automobiles, and machineries for construction, agriculture and many other applications, internal combustion engines (ICEs) can only utilize about 40% of the energy in fuels, and significant part of the energy available is released as waste heat through exhaust channels and coolant circulations [1,2]. Therefore, significant energy saving can be achieved by proper recovery of ICE waste heat [3]. Among different waste heat recovery technologies, thermoelectric generator (TEG) has received many attentions, because it is highly reliable and compact without any moving part, and can directly convert heat into electricity.

Many studies have been conducted for the waste heat recovery of ICEs by using TEGs. Karri et al. [4] analyzed the potential benefits of the application of TEG modules in a SUV in steady-state operation, and 100–450 W of electricity could be generated, which saves about 2–2.3% of fuel. Yu et al. [5,6] developed a numerical model and found that the performance of TEG modules is improved with the increment of the vehicle (a pickup truck) speed: from 18 W to 220 W when the speed increases from 20 km h^{-1} to 120 km h^{-1}, and the transient behaviors of the TEG modules in different driving conditions were also investigated. Weng and Huang [7] found that increasing the number of TEG units may not necessarily generate more power, and proper coverage of the TEG units on heat exchangers is important.

Although some previous studies showed the feasibility of TEGs in the waste heat recovery of ICEs (e.g. vehicles), further design optimization of such exhaust-based thermoelectric generator (ETEG) system is needed. Generally, there are two approaches to the optimization of TEG systems: one is to optimize the TEG module, for example, development of new thermoelectric materials [8–10] and structure design optimization (e.g. segmented structure) [11–15]; and the other is to enhance the heat transfer from heat source (e.g. exhaust gas) to TEG module and from TEG module to heat sink (e.g. air or coolant) [16–19]. To gain in-depth understanding of the transport phenomena in the ETEG systems, some mathematical models have been developed by researchers coupling the heat source/sink flow and TEG modules. Yu and Zhao [20] developed a numerical model for TEG modules with a parallel-plate heat exchanger. This model was used to predict the fluid temperatures and the temperatures in the TEG modules.

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Nomenclature

A	cross section area of inlet and outlet (m^2)
J	current density ($A\,m^{-2}$)
L	length of baffler (mm)
N	number of bafflers above one TEG modules
p	pressure (Pa)
P	power (W)
q	heat transfer rate (W)
Q	flow rate ($kg\,s^{-1}$)
S	source term
T	temperature (K)
v	velocity ($m\,s^{-1}$)
V	potential (V)

Greeks symbols

α	Seebeck coefficient ($V\,K^{-1}$)
β	baffler angle (°)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
σ	electrical conductivity ($S\,m^{-1}$)

Subscripts/superscripts

c,s	ceramic, stainless steel
copper	copper unit
in	inlet
l	loss
n	n unit, net
o	output
ohm	Ohmic
p	p unit
sbk	Seebeck
T	temperature

Heat exchangers were also coupled with TEG modules in the models of Chen et al. [21] and Astrain et al. [22]. Different TEG models were also comprehensively discussed by Fraisse et al. [23].

In previous studies, the design optimization of ETEG systems mainly focused on conductive systems [24–26], convective systems [27–29] and radiative systems [30]. In this study, the effects of cooling design (convective system), such as the channel dimension and baffler placement, are investigated. For the ETEG systems of ICEs, the effect of exhaust channel design on the performance of TEG modules was investigated by Niu et al. [31], showing that the TEG output power can be significantly improved by the design optimization of exhaust channel (i.e. hot side heat transfer enhancement). However, the detailed coolant channel design effect was largely ignored in previous studies, which may also have significant impact on the performance. In this study, a numerical TEG model coupled with both ICE exhaust channels and coolant channels is developed. The air cooling and liquid coolant cooling conditions are compared, and the different designs of cooling channels are investigated in details.

2. Numerical model

2.1. Computational domain

Fig. 1 shows a schematic of the ETEG system (TEG modules, and heat source and heat sink channels are all included). 20 TEG modules are installed on both sides of the ICE exhaust channel (10 on each side). The exhaust channel serves as the heat source, and the air or ICE liquid coolant flows through the cooling channels (on top and bottom of the exhaust channel) acting as the heat sink. A TEG module consists of 160 TEG units, which are connected in series electrically and in parallel thermally. A single TEG unit includes a p-type semiconductor and an n-type semiconductor, which are connected by a conductor (e.g. copper), and substrates (e.g. ceramic) are placed on the top and bottom for electrical insulation.

2.2. Formulation

The air flow in the cooling channels and the flow in ICE exhaust channels have high Reynolds numbers up to 80,000. This Reynolds number is calculated based on the hydraulic diameter of cooling channel and an air velocity of 27.8 $m\,s^{-1}$ (corresponding to a vehicle speed of 100 $km\,h^{-1}$). Thus the renormalization group (RNG) $k-\varepsilon$ turbulence model with heat transfer is used. For the liquid coolant flow in cooling channels, the Reynolds number is generally lower than 2000, which is considered to be laminar flow with heat transfer.

For the TEG modules, the steady-state conservation equation of energy is written as

$$\nabla\cdot[k_{p,n,copper}\nabla T_{p,n,copper}]+S_T=0 \tag{1}$$

where $k_{p,n,copper}$ ($W\,m^{-1}\,K^{-1}$) is the thermal conductivity of p-type, n-type or copper unit. $T_{p,n,copper}$ (K) is the temperature of p-type, n-type or copper unit. S_T ($W\,m^{-3}$) represents the energy source (Joule heat and Thomson heat generations):

$$S_T=\begin{cases}\frac{1}{\sigma_p}\|\vec{J}_p\|^2+T_p(\nabla\alpha_p)\cdot\vec{J}_p; & \text{p-type unit}\\ \frac{1}{\sigma_n}\|\vec{J}_n\|^2+T_n(\nabla\alpha_n)\cdot\vec{J}_n; & \text{n-type unit}\\ \frac{1}{\sigma_{copper}}\|\vec{J}_{copper}\|^2; & \text{copper units}\end{cases} \tag{2}$$

where $\vec{J}_{p,n,copper}$ ($A\,m^{-2}$) is the electrical current density vector, and $\sigma_{p,n,copper}$ ($S\,m^{-1}$) is the electrical conductivity. A detailed description of the heat generations can also be found in [15].

The energy conservation equation in ceramic (substrates of TEG modules) and stainless steel 310 (shells of cooling and exhaust channels) in steady state only accounts for heat conduction:

$$\nabla\cdot(\lambda_{c,s}\nabla T_{c,s})=0 \tag{3}$$

where $\lambda_{c,s}$ ($W\,m^{-1}\,K^{-1}$) is the thermal conductivity of ceramic or stainless steel 310.

The balance of electrical motive force due to Seebeck effect in p/n units is written as

$$\nabla V_{sbk}=-\alpha_{p,n}\nabla T \tag{4}$$

where V_{sbk} (V) is the Seebeck potential, and $\alpha_{p,n}$ ($V\,K^{-1}$) is the Seebeck coefficient of p/n units. Taking the divergence of V_{sbk}, Eq. (4) yields:

$$\nabla\cdot(-\nabla V_{sbk})+V_{sbk}=0 \tag{5}$$

$$V_{sbk}=\begin{cases}\nabla\cdot[-\alpha_p\nabla T_p]; & \text{p-type unit}\\ \nabla\cdot[-\alpha_n\nabla T_n]; & \text{n-type unit}\end{cases} \tag{6}$$

The Ohmic voltage conservation equation is

$$\nabla\cdot[-\sigma_{p,n,copper}\nabla V_{ohm}]=0 \tag{7}$$