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Peak power evaluation and optimal dimension design of exhaust heat exchanger for different gas parameters in automobile thermoelectric generator

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ABSTRACT

When a thermoelectric generation (TEG) system is used to recover waste heat from gasoline engine exhaust, the thermal parameters of the exhaust gas vary greatly; this has an influence on the optimal performance of the TEG system. To improve the recovery of exhaust waste heat and its conversion to electric power effectively, the peak power evaluation and optimal performance analysis are conducted on a TEG system with different exhaust thermal parameters. A sandwich plate-type exhaust heat exchanger is modeled using finite element analysis. The maximum net power is the parameter chosen for optimization, which is achieved by identifying the optimal length, width, and height. The results show that the flow velocity and TEG module area are two key parameters for optimization of the TEG system. Furthermore, all the optimal performance parameters are derived by deducing correlation equations. Using these correlations, the optimal performance and ideal peak net power of the TEG system can be conveniently obtained for any given exhaust thermal parameters. This is an effective method to determine the optimal design dimensions and evaluate the net power recovery ability of the designed TEG system.

1. Introduction

The amount of waste heat generated from automotive vehicles is considerably large [1,2]. For a typical gasoline-fueled vehicle, approximately 40% of the fuel energy is discharged from the exhaust pipe, and approximately 30% is lost into the coolant. Making good use of the waste heat improves the energy efficiency and saves money. In recent years, thermoelectric generator (TEG) has emerged as a promising technology for waste heat recovery in the automotive industry. However, this technology is not currently used in cars, and is still in the conception stage because of its low efficiency [3,4]. As such, two common approaches have been taken by researchers to improve the conversion efficiency form heat to electricity. One approach involves the search for better materials to be used as the thermocouple of the device. The other approach is to improve the geometric design of the TEG [5].

In terms of structural optimization research, many studies have been carried out. Weng [6] introduced a hexagonal pipe-type exhaust heat exchanger, and the thermoelectric couple number and coverage rate on the heat-exchanger of the TEG were optimized via simulations. Liang [7] optimized a two-stage TEG by analyzing the effects of the thermocouple ratio, heat source temperature, cold source temperature, and heat transfer coefficient. Baker [8] used a downhill simplex method to optimize the parameters that affect the electrical power output. Su [9] optimized the thermal characteristics of heat exchangers with various heat transfer enhancement features to achieve a uniform temperature distribution and higher interface temperature. Meng [10] implemented single-objective and multi-objective optimizations to identify the optimal TEG performance. Tian [11] optimized a segmented TEG based on the low-temperature TE material bismuth telluride and the medium-temperature TE material skutterudite. Moreover, Favarel [12], Jang [13], Kempf [14] and Liu [15] optimized the TEG configuration parameters by taking the total power density for a thermoelectric module as the objective function to be maximized, for a plate-shaped heat exchanger. However, the optimization results obtained above mainly used total maximal power output as the optimization object. In practical, achieving maximal net power with minimal pressure drop is critical to a highly effective design regarding TEG system geometrics. Therefore, Lu [16] and Niu [17] investigated the effects of the exhaust channel size on the TEG characteristics. It was found that the exhaust channel size needed to be of a moderate value in order to balance the heat transferred to the TEG modules and pressure

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Nomenclature

c	specific heat capacity of fluid (J g^{-1} K^{-1})
D	hydraulic diameter (m)
dev_h	percentage deviation (%)
f_z	pressure drop (Pa)
F	darcy resistance coefficient
h	total exchanger height (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
I	electric current (A)
i	the line number
j	the row number
K	semiconductor thermal conductivity (W K^{-1})
k	total heat transfer coefficient (W m^{-2} K^{-1})
k_m	constant value
k_T	constant value
k_{Tm}	constant value
L	total exchanger length (m)
m	fluid mass flow rate (g s^{-1})
n_x	total P-N couple number in line
n_y	total P-N couple number in row
Nu	Nusselt number
P	power (W)
Pr	Prandtl number
q	quantity of heat (W)
R	resistance (Ω)
Re	Reynolds number
s	exchanger plate areas (m^2)
T	temperature (°C)
u	flow velocity (m s^{-1})
w	total exchanger width (m)

Greek

α	Seebeck coefficient (V K^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})

Subscript

c	cold fluid
cin	inlet cold fluid
$design$	design value
det	account step
f	hot fluid
fin	inlet hot fluid
$fout$	outlet hot fluid
fav	averaged value of hot fluid
h	TE module hot-side surface; fixed height
$high$	upper limit value
L	TEG cold-side surface; external load
low	lower limit value
max	maximum value
opt	optimal value
pn	P-N semiconductor couple
wav	average value on exchanger hot-side wall
teg	TEG module value
$pump$	consumed pump value
net	net value
$peak$	ideal peak value
$perm$	per unit exhaust mass value

Superscript

i	the line number

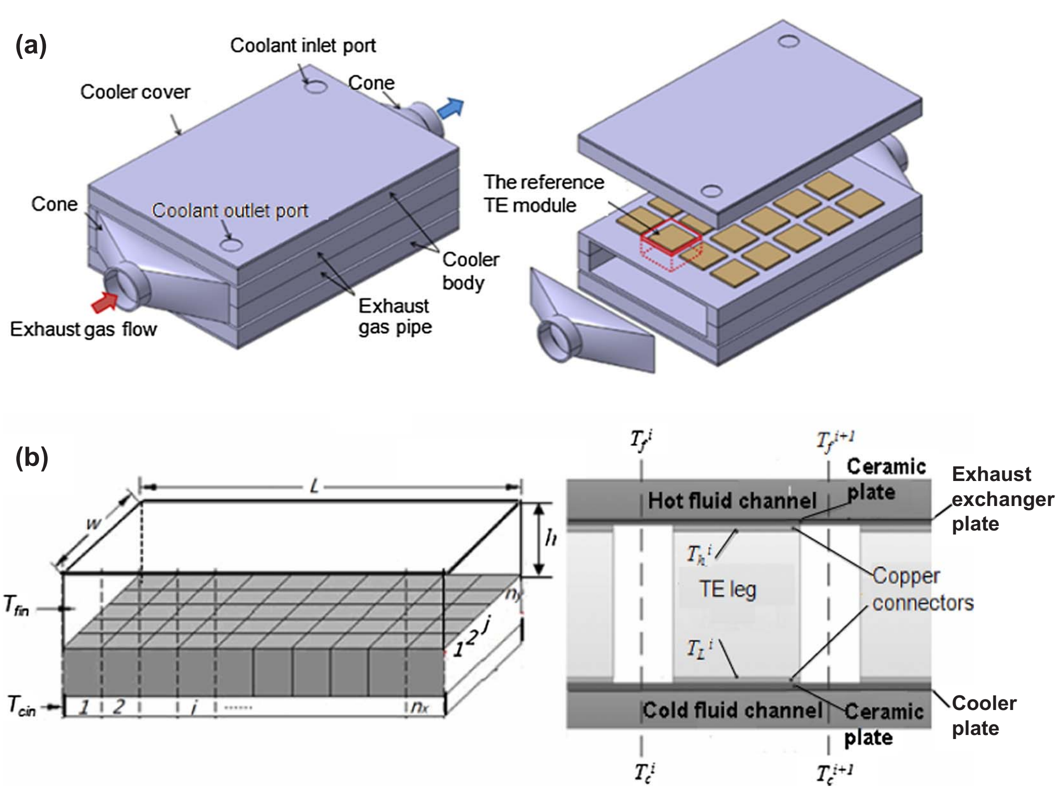

Fig. 1. Schematic of TEG system: (a) sandwich plate-type structure, (b) finite element model.