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Performance analysis of automobile exhaust thermoelectric generator system with media fluid

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ABSTRACT

In the exhaust thermoelectric generator system with media fluid, the media fluid first transfers heat directly from the exhaust. Then, the media fluid is used for thermoelectric generation after heating. Therefore, the exhaust heat exchange process and the thermoelectric generation process are separate processes. A numerical simulation of this system is conducted in this paper. The results show that the output power of the thermoelectric generator system with media fluid first increases and then decreases with an increase in the module area when the exhaust heat exchange area is fixed, i.e., there is an optimal module area to maximize the output power of the system. Compared with the traditional thermoelectric generator system, for a certain condition of the exhaust heat exchange area, although the maximum output power of the novel system decreases slightly, the corresponding module area can be reduced by 74.2%. Consequently, the power generation density can reach 1254 W/m^2, which is 3.39 times higher than that of a traditional exhaust thermoelectric generator system. In addition, the temperature distribution along the module of the thermoelectric generator system with media fluid is more uniform.

1. Introduction

As a solid-state energy conversion device, the thermoelectric generator uses the thermoelectric effect of semiconductor material to convert heat directly into electric energy. Because of advantages such as no moving parts, compact structure, high reliability, and easy maintenance [1–4], it is widely used in the recovery and power generation of waste heat [5–8]. In recent years, with the rapid development of the automobile industry, the problem of automobile energy conservation has captured people's attention. Given that the efficiency of the automobile engine is generally only 30–35%, approximately 40% of the energy is discharged into the external environment as high-temperature exhaust, which not only causes a waste of energy, but also aggravates environmental pollution [9]. The recovery of exhaust waste heat can not only improve driving performance and fuel consumption but also reduce greenhouse emissions and bring about significant social and economic benefits [10,11]. Considerable research and practical applications have shown that the use of thermoelectric generation technology to recover the waste heat of automobile exhaust yields a good performance. Therefore, thermoelectric generation technology is considered to be an effective method of utilizing automobile exhaust [12–16].

At present, the conversion efficiency of a commercial thermoelectric module is still low, which restricts its popularization and application [17]. Research is being conducted on thermoelectric modules with the objective of reducing the heat conduction of the material and improving the Seebeck coefficient and conductivity coefficient by developing new thermoelectric materials, so as to improve the thermoelectric conversion efficiency [18–20]. Zhu [21] investigates hybrid ordered/disordered nanocomposites that consist of crystalline membranes decorated by regularly patterned disordered regions formed by ion beam irradiation. And the results show a reduced thermal conductivity. Chen [22] reveals that dense lattice dislocations are particularly effective at reducing the lattice component to the thermal conductivity. Due to the band convergence of the alloyed 3% mol. EuTe the thermoelectric Fig of merit of 2.2 is achieved. In addition, in view of the current thermoelectric materials, the conversion efficiency of a generator can also be improved by changing the structure of the thermoelectric generator or by employing a combination of different thermoelectric materials [23–26]. In an exhaust thermoelectric generation system, because of the low heat transfer coefficient between exhaust and module, the temperature on the hot side of the module is much lower than that of the exhaust, which makes the conversion efficiency of the module much lower than the theoretical value. Thus, it is also an effective way to

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Nomenclature

Symbols

a	length of module, mm
A	area of control unit, m^2
b	width of module, mm
c_p	specific heat at constant pressure, J/g K
F	superficial area of module, mm^2
h	height of PN couple, mm
k	heat transfer coefficient, $W/m^2 K^1$
l	length of PN couple, mm
m	mass flow rate, g/s
n	number of control unit
p	output power of module, W
P	total output power, W
q	heat transfer amount, W
Q	total heat transfer amount, W
r	electricity resistance, Ωm
S	total area, m^2
T	temperature, K
w	width of PN couple, mm

Greeksymbol

α	seebeck coefficient, V/K
λ	thermal conductivity, W/mK
η	generation efficiency, %

Superscripts

i	line number at module side
k	line number at exhaust side

Subscripts

c	cooling water
cin	inlet cooling water
$cout$	outlet cooling water
f	exhaust
fin	inlet exhaust
$fout$	outlet exhaust
h	hot side of PN couple
l	cold side of PN couple
m	media fluid
max	maximum
mh	high-temperature media fluid
ml	low-temperature media fluid
opt	optimal
per	unit area
pn	PN couple
te	thermoelectric module
w	wall of exhaust channel

improve generation performance by strengthening the convective heat transfer in the exhaust side [27–30].

The most common way to strengthen the heat transfer of the exhaust channel is to add a strengthening element to it, such as a fin [31], a vortex generator [32], a heat pipe [33], or foam metal [34]. Byung et al. [35] arranges a square pillar, a forward-facing triangular prism, and a reverse-facing triangular prism in the fluid channel of the thermoelectric generator and observes that the best power generation performance is obtained from the square pillar. Ma et al. [36] applies a longitudinal vortex generator to the exhaust heat transfer channel. The net output power is increased by 59–150% and the maximum generation efficiency is up to 1.5%. Bai et al. [37] attaches foam metal to the inner and outer surfaces of the thermoelectric generator, which not only increases the output power by 170%, but also reduces the average noise by 16.6 dB. However, the addition of foam metal results in a larger pressure drop. Therefore, Li et al. [38] states that the foam metal should only partially fill the exhaust channel for better comprehensive performance. Their experimental results show that the output power more than doubled under a pore density of 20 PPI and a filling rate of 75%. Orr et al. [39] combines a heat pipe with thermoelectric generation to recover the waste heat of the exhaust. The experiment demonstrates that the placement mode of the heat pipe has a significant influence on power generation performance. The bottom heat mode is found to be the best option, and the maximum generation efficiency reaches 2.46%. In addition, in order to reduce the contact resistance, Kim et al. [40,41] focuses on a design of thermoelectric generators fabricated with an exhaust channel and coolant channel having openings on the surface. In this manner, the thermoelectric module can be directly exposed to hot and cold fluids. They examine the effect of engine load, engine rotation speed, and cooling water temperature on generation performance, and find that the generation efficiency of the system is between 1% and 2%, with a maximum pressure drop of less than 700 Pa.

Additionally, in the exhaust thermoelectric generator, because of the larger reduction in the exhaust temperature along the flow direction, the uneven temperature distributions at the hot and cold sides of the module (especially the hot side) restrict the increase in the output power [42,43]. Improving the uneven distribution of the module temperature can not only increase the output power [44] but also reduce the thermal stress of the generator, which is more beneficial to the long life and safe operation of the system [45].

In the current thermoelectric generator, the generation efficiency of the system is relatively low due to the lower heat transfer coefficient in the exhaust channel. Various enhanced heat transfer technologies can improve the output power of the system, but cause a large increase of pressure drop that not only affects the normal operation of the internal-combustion engine, but also limits the increase of heat transfer coefficient. Meanwhile, it also has no effect on the inhomogeneous distribution of the module temperature caused by a reduction of the exhaust temperature. Considering the above problems, this paper suggests that media fluid with high convection heat transfer coefficient be used instead of the exhaust to complete the heat transfer process with the hot side of the module, thereby increasing the hot side temperature of the module to improve the generation performance of the exhaust thermoelectric generator system.

On this basis, this paper proposes an exhaust thermoelectric generator system with media fluid. The novel thermoelectric generator system uses high thermal conductivity fluid as media fluid. The fluid first exchanges heat with a high-temperature exhaust, then it is used as the heat source of the thermoelectric module to complete the power generation process. This system makes a separation between the exhaust heat exchange process and the module generation process. Because there is no need to enhance the convective heat transfer on the exhaust side, the large pressure drop in the exhaust channel is avoided. Meanwhile, considering the high convective heat transfer coefficient of the media fluid, the generation performance of the system can also be improved. In addition, the temperature distribution of the module in the novel system is more uniform, and the module area corresponding to the maximum output power can be greatly reduced, which means a significant decrease in the cost of an exhaust thermoelectric generator system.