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Simulation and experimental study on thermal optimization of the heat exchanger for automotive exhaust-based thermoelectric generators

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A B S T R A C T

Thermoelectric technology has revealed the potential for automotive exhaust-based thermoelectric generator (TEG), which contributes to the improvement of the fuel economy of the engine-powered vehicle. As a major factor, thermal capacity and heat transfer of the heat exchanger affect the performance of TEG effectively. With the thermal energy of exhaust gas harvested by thermoelectric modules, a temperature gradient appears on the heat exchanger surface, so as the interior flow distribution of the heat exchanger. In order to achieve uniform temperature distribution and higher interface temperature, the thermal characteristics of heat exchangers with various heat transfer enhancement features are studied, such as internal structure, material and surface area. Combining the computational fluid dynamics simulations and infrared test on a high-performance engine with a dynamometer, the thermal performance of the heat exchanger is evaluated. Simulation and experiment results show that a plate-shaped heat exchanger made of brass with accordion-shaped internal structure achieves a relatively ideal performance, which can practically improve overall thermal performance of the TEG.

1. Introduction

Approximately 40% of the fuel energy is lost in exhaust gas according to energy balance of a combustion engine, which intense the energy crisis and environment pollution [1]. As one way to recover waste heat,Thermoelectric generation (TEG) technology can recover waste heat from the exhaust and convert thermal energy into electrical energy with the advantages of being highly reliable, zero emission,low noise and involving no moving parts. Thermoelectric modules (TEMs) made of semiconductor materials are sandwiched between the heat exchanger and the cooling unit in an exhaust-based thermoelectric generation. This sandwich structure is kept by the clamping devices. Exhaust gas flows into the hot-side heat exchanger through a bypass to form the hot source. Cooling water pumps into the cooling water tanks to form the cooler. The electric power is generated as a result of the temperature difference based on the Seebeck effect [2]. The schematic diagram of TEGs system is shown in Fig. 1.

In order to get higher thermoelectric efficiency and generation capacity, the heat exchanger's geometry, mounted location, contact area with thermoelectric modules, operating conditions and so on were optimized by numerical analyses and experiments. Astrain et al. [3] optimized the influence of heat exchangers' thermal resistances (in both the hot and cold

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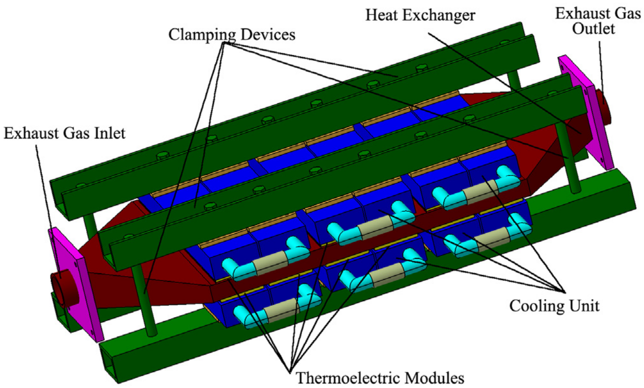

Fig. 1. Schematic diagram of TEGs system.

side) and pressure drops by CFD [4] to maximize the electric power generated. The geometrical effect of TEG on heat transfer characteristics was investigated in a parallel micro channel heat sink [5].Optimization of the heat exchanger aims to increase the overall efficiency of TEG, which involves two major tasks: maintaining a sufficient temperature difference across the thermoelectric models (TEMs) and reducing thermal losses of the system. In the same irrelevant conditions, such as exhaust condition, cooling condition, raising the interface temperature by improving the thermal performance of the heat exchanger can obviously increase the overall efficiency of the TEG. Due to the constraints of a single module's size and performance, a certain number of TEMs are usually tiled between the heat exchanger and the cooler with a series–parallel connection [6]. As the thermal energy of exhaust gas harvested, the temperature gradient will appear on the heat exchanger surface, which reduces the electricity generation of TEMs in return. In order to utilize the performance of each TEM, it is essential to optimize the heat exchanger to get uniform temperature distribution.

2. Thermal simulation of the heat exchanger

Computational fluid dynamics (CFD) software is used to simulate the exhaust gas flow within the heat exchanger, presenting the temperature distribution [7]. Internal structure, material and thickness of the heat exchanger are changed to obtain the ideal thermal field simulation results.

2.1. Boundary condition of simulation model

Simulation model is assured that the exhaust flow in the heat exchanger is fully turbulent and molecular viscosity can be neglected, so the standard κ–ε model is adopted in the CFD simulation. As Near wall area processing with standard wall function, the natural convection heat transfer coefficient and the environment temperature are set.

The automobile exhaust was approximately 300–500 kPa in pressure and 500–700 °C in temperature when just discharged from the engine cylinder [8], the gas inlet temperature is set to 400 °C, which can take advantage of the performance of TEMs applied in the TEG. Base on the working operating characteristics of the engine, the inlet flow velocity can reach 20 m/s. Considering the acoustic attenuation performance of the TEG, the traditional muffler is replaced on the test bench [9]. The outlet of the mixing flow use the pressure boundary condition, the gauge pressure at the outlet is set to 0 Pa. In addition, the heat transfer coefficient between the external surface of the heat exchanger and the air is set to 20 W/(m^2 K) with the environmental temperature is set to 25 °C.

As for the heat exchanger presenting an approximately axial symmetry in geometry, so the flow, pressure and temperature fields also show axisymmetric characteristics in the absence of ambient winds.

3. Simulation results and analysis

By applying fundamental formula of heat transfer $\Phi = hA\triangle T$, heat convection can be greatly strengthened by the increase of the heat transfer area *A*. This target can be approached by changing the structure of the conduction surface by fitting baffles. Another approach is to increase the heat transfer coefficient h.

According to the fluid dynamics theories, under the condition of Reynolds number Re > 104, macro turbulent fluid flow is a significant impact factor on improving the heat transfer. Moreover, the greater the heat transfer coefficient *h*, the better the heat transfer quantity. The thermal resistance of turbulent flow convection mostly exist in the boundary layer.

The field synergy principle was proposed as another indication of the synergy degree between velocity and temperature field for the entire flow and heat transfer domain, the better the synergy was between the temperature field and velocity field, the better the heat transfer [10]. According to both theories above, the strengthening of the heat transfer can be approached by adding turbulence devices to enhance the fluid disturbance and damage the boundary layer [11].