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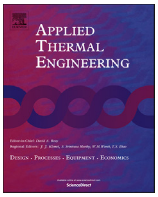

Experiments and simulations on heat exchangers in thermoelectric generator for automotive application

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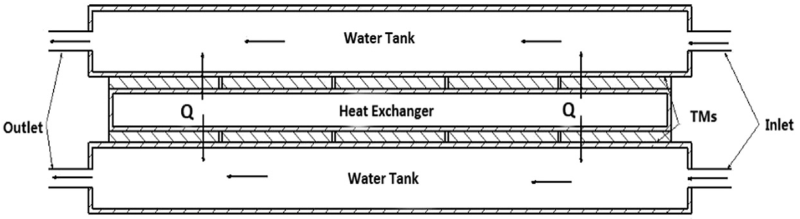
HIGHLIGHTS

- Different internal structures and thickness of heat exchangers were proposed.
- Power output testing system of the two heat exchangers was characterized.
- Chaos-shaped heat exchanger (5 mm thickness) shows better performance.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, an energy-harvesting system which extracts heat from an automotive exhaust pipe and turns the heat into electricity by using thermoelectric power generators (TEGs) was built. Experiments show that the temperature difference in automotive system is not constant, especially the heat exchanger, which cannot provide the thermoelectric modules (TMs) large amount of heat. The thermal performance of different heat exchangers in exhaust-based TEGs is studied in this work, and the thermal characteristics of heat exchangers with different internal structures and thickness are discussed, to obtain higher interface temperature and thermal uniformity. Following computational fluid dynamics simulations, infrared experiments and output power testing system are carried out on a high-performance production engine with a dynamometer. Results show that a plate-shaped heat exchanger with chaos-shaped internal structure and thickness of 5 mm achieves a relatively ideal thermal performance, which is practically useful to enhance the thermal performance of the TEG, and larger total output power can be thus obtained.

1. Introduction

Because of the global energy crisis and the environmental protection issues, energy recovery techniques have become significantly demanding for a long time. Some examples of energy recovery techniques are water heat recycling, heat recovery ventilation, heat recovery steam generators, and so on [1]. Waste heat recovery by using thermoelectric power generators (TEGs) is another attempt. TEGs can directly convert thermal energy to electrical energy and have the advantages of light weight, no noise, and no mechanical vibration. Owing to these merits, TEGs have found its potential in many applications, such as space applications, thermal energy sensors, textiles, etc [2–8].

Waste heat from automotive vehicles is considerable as well. For a typical gasoline-engine vehicle, about 40% of the fuel energy is discharged from the exhaust pipe and about 30% is lost into the coolant. The automotive exhaust is low in specific heat and small in time-averaged mass flow rate, so that an efficient heat exchanger is essential to extract heat energy from exhaust when thermoelectric conversation of conventional materials is 5%–7%

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for TEG [9]. Making good use of these waste heats improves the energy efficiency and saves money [10]. Historically, several types of heat exchanger and different heat transfer enhancement measures such as the ribbing, grooving and protrusions have been investigated since the first automobile TEG was built in 1963. Serksnis [11] initially reported a stainless heat exchanger just like the exhaust pipe, no heat transfer enhancements were set in gas side. Birkholz et al. [12] designed a Hastelloy X rectangular heat exchanger with internal fins in exhaust side and an aluminum cold-side heat exchanger. Bass et al. [13] proposed a hexagonal cylinder and a center hollow displacement conic heat-diffuser for Cummins 14L NTC 350 diesel engine, discontinuous swirl fins were installed on surface of the center body to break laminar boundary layer and enhance gas turbulence. Yang [14] indicated that the consumer fuel savings over a three-year period is about $400 for a 23.5 mpg vehicle, under the assumption of $2/gallon, 15,000 miles/yr, and a desired 10% fuel-economy improvement (the overall objective raised by the US Department of Energy in 2004). The commonly utilized components in a vehicle for implementing the TEGs are the radiators and the exhaust system. Hsiao et al. [15] attached the TEGs to the waste recovery system than to the radiators which obtains a better performance based on the simulation models and experiments. Chung et al. [16] investigated a thermoelectric energy generation system which used a TEG. The main feature of their study was the use of high temperatures (up to 200 °C) to ensure TEG reliability, especially for diesel engines, whose exhaust gases are as hot as 200 °C–300 °C at the outlet of the catalyst filter. Thacher et al. [17] employed a rectangular, 1018 carbon steel compact heat exchanger with offset strip fins for a 5.3 L V8 gasoline engine. With the same requirements for exhaust heat exchanger in vehicle waste heat recovery by Rankine cycle, a shell and tube counter flow heat exchanger was used with exhaust gases in tubes and working fluids in shell [18]. Hsu et al. [19] [20] constructed a heat exchanger mounted with eight Bi_2Te_3-TEG systems with eight heat sinks, the heat sinks need electricity to drive the air. This system obtains a total 44 W excluding the heat sinks. In 2012, they enlarged the heat exchanger with 24 Bi_2Te_3-TEG systems and added a slopping block in the inlet. A maximum power of 12 W was just obtained. The experimental results surprisingly show that a small-size heat exchanger with less TEGs has a good performance and gets a large output power.

However, according to Hsu's study, the thermal performance of heat exchanger is not good. The heat exchanger needs to be optimized, especially internal structure, adding a slopping block in the inlet is not enough. This paper presents analysis of a large heat exchanger. Regardless of other conditions, such as exhaust condition, cooling condition, and clamping force, raising the interface temperature by improving the heat exchanger will significantly enhance the overall efficiency of the TEG. To take advantage of the electricity generation performance of each thermoelectric module (TM), optimization of the thermal uniformity of the heat exchanger is also vital [21], and a large total power can be thus obtained.

2. Experimental setup

There are three ways of heat transfer: heat convection, heat conduction and heat radiation. Exhaust heat passes to the heat exchanger walls by thermal convection, and then passes to the TMs and water tank walls by heat conduction. Finally, water flow takes the heat away. Every water tank has three surfaces in direct contact with air, so part of heat is dissipated by thermal convection into the atmosphere. This waste heat recovery system is designed for exhaust pipe of automobiles. TMs are clamped with sufficient compressive force between a heat exchanger connected to the exhaust pipe and cooling water tanks in an exhaust-based TEG. Exhaust gas flows into the heat exchanger through a bypass to provide a heat source. The cooling water (engine cooling water) is pumped into the water tanks to form the cold side [22]. Then, electric power is generated due to the temperature difference between the two sides of the modules and to be stored in batteries. The design and simulation of the heat exchanger are mainly described in this article. TMs (Shanghai Institute of Ceramics of the Chinese Academy of Sciences) are arranged on both surfaces of the heat exchanger when the exhaust gas passes by. The schematic diagram of the experimental exhaust waste heat recovery system is illustrated by Fig. 1. Some measuring instruments are equipped to construct this experimental setup. A 2.0-L naturally aspirated engine is used as study object. Its performance data are listed in Table 1. A dynamometer (maximum power input 160 kW, maximum speed 6000 rpm) is also used. Several transducers are used: pressure sensor, K-type thermocouples and infrared camera to record the temperature distribution of the exhaust heat exchanger, TMs and water tanks. A high power electrical load is connected to the system which is used to measure the voltage and power output.

Considering the square-shaped TMs, plate-shaped and hexagonal-prism-shaped heat exchangers meet the requirement. However, the distance between chassis and ground is short and the height of plated-shaped heat exchanger is also short, which is benefit for the arrangement of TMs, so the plate-shaped heat exchanger is more suitable for TEG application. Fig. 2 shows a plate-shaped heat exchanger, its TEG system and bench test. The plate-shaped heat exchanger of TEG is connected to the exhaust pipe of diameter 36 mm on both sides. The section of the plate-shaped exchanger is a 400-mm-long by 290-mm-wide rectangle, its height is just 18 mm. There are 60 TMs placing on front and back surface of heat exchanger.

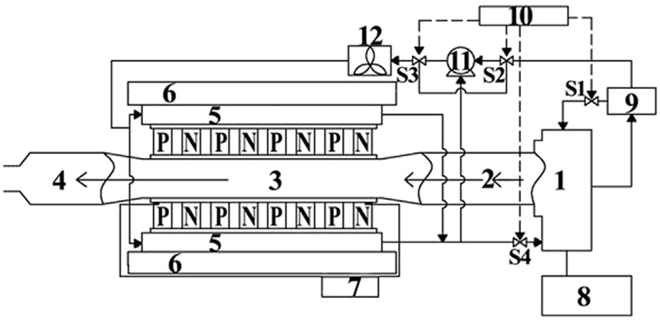

Fig. 1. Schematic diagram of the experimental thermoelectric generator system 1: Automobiles engine. 2: Catalytic converter. 3: Heat exchanger for passing exhaust gas. 4: Muffler. 5: Water tank. 6: Clamping device. 7: Electronic load. 8: Dynamometer. 9: Cooling system. 10: Controller. 11: Water pump. 12: Heat sinks.

Table 1
The engine performance parameters.

Parameter	Value	Parameter	Value
Cylinder number	4	Governed Power（kW）	108
Valves per cylinder	4	Governed speed（rpm）	6000
Displacement	1997 ml	Peak torque/speed	200 N m/4000 rpm
Bore/stroke (mm)	85/88 mm	Power of pump	0.18kw
Firing order	1-3-4-2	Cooling mode	Water Cooling
Radiator size	547 × 415 × 50 mm	Number of fan shift	1