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Experiments and Simulations on a Heat Exchanger of an Automotive Exhaust Thermoelectric Generation System Under Coupling Conditions

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The present experimental and computational study investigates an exhaust gas waste heat recovery system for vehicles, using thermoelectric modules and a heat exchanger to produce electric power. It proposes a new plane heat exchanger of a thermoelectric generation (TEG) system, producing electricity from a limited hot surface area. To investigate the new plane heat exchanger, we make a coupling condition of heat-flow and flow-solid coupling analysis on it to obtain the temperature, heat, and pressure field of the heat exchanger, and compared it with the old heat exchanger. These fields couple together to solve the multi-field coupling of the flow, solid, and heat, and then the simulation result is compared with the test bench experiment of TEG, providing a theoretical and experimental basis for the present exhaust gas waste heat recovery system.

Key words: Automotive exhaust heat, heat exchanger, multi-physics field coupling, bench test

INTRODUCTION

Because of the increasing emphasis on environmental protection, applications of thermoelectric technology are being extensively studied. Thermoelectric generators (TEG) may offer thermoelectric energy conversion in a simple and reliable way.[1] In addition, a thermoelectric module (TEM) has many advantages such as no moving parts, quiet operation, and being environmentally friendly. Due to these merits, the use of TEG to recover waste heat has been comprehensively discussed in many industrial fields.[2] Over the last 30 years, there has been growing interest in applying this thermoelectric technology to improve the efficiency of waste heat recovery, using the various heat sources such as geothermal energy, power plants, automobiles, and other industrial heat-generating processes.[3]

As in most research the internal structure of the heat exchanger used in the TEG is a cavity, this study proposes a new plane heat exchanger of a thermoelectric generation (TEG) system. TEMs made of semiconductor materials are sandwiched between the hot-side plane heat exchanger, which are connected with the exhaust pipe and the cooling water tanks (the cooler) in an exhaust-based TEG, and electricity is generated by the temperature gap of the heat exchanger and the cooler. The new plane heat exchanger is designed to provide a large heated surface area to install at least 60 TEMs. As the new plane heat exchanger is a very efficient heat-conducting device, it is possible to transfer a large amount of heat through the TEMs to generate electric power. This study presents experimental and computational investigations conducted to improve such a system's electric power.

An automobile exhaust thermoelectric power generation system uses the TEMS to achieve the energy conversion; however, at this stage, the conversion efficiency is not high and so does not meet the application requirements.[4] Vehicle exhaust thermal energy converters endure high temperatures, thermal loads, and high-intensity mechanical

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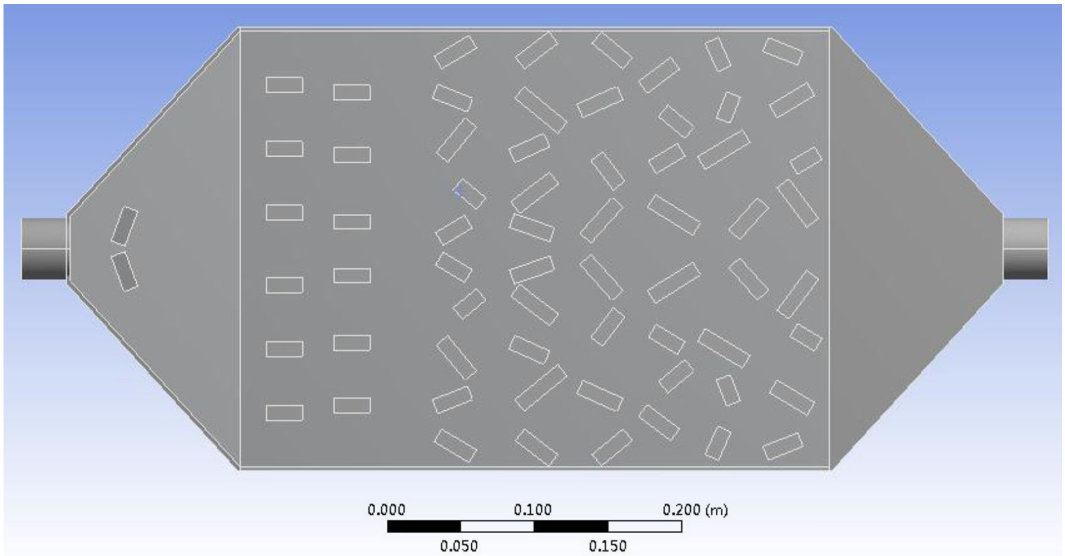

Fig. 1. Three-dimensional model of the new heat exchanger.

loadd, at the same time as the existence of many physical fields including the flow field, temperature field, and pressure field of a high-temperature exhaust.

In a previous study, we constructed a new plane heat exchanger instead of the old heat exchanger with no internal fins for vehicles to analyze the heat exchanger's flow and heat transfer process of the high-temperature exhaust gas. When the TEG is in the stable state, physical and mathematical models of the exhaust gas as well as heat transfer numerical simulation can be obtained. With the thermal boundary conditions and flow boundary conditions determined, the coupled system of the heat exchanger could be analyzed so as to get the temperature field and flow field, which solves the multi-field coupling of the flow, solid, and heat.

SIMULATION ON THE HEAT-FLOW FIELD OF THE TWO HEAT EXCHANGERS

Simulation Model of the New and Old Heat Exchangers

We propose a new plate-shaped heat exchanger of the TEG, which is connected with the exhaust pipe. Exhaust gas flows into the new plate-shaped thermoelectric generation heat exchangers through the intake manifold and then flows out into the exhaust manifold.

The diameters of the intake and exhaust manifolds of the heat exchanger are both 36 mm. The three-dimensional model of the heat exchanger is shown in Fig. 1. There are two small fins set at the entrance for diverting the flow, so that the high-temperature exhaust gas is diffused into the entire lateral area rather than concentrated in the central region; Many small fins are set in a disordered fashion in the internal structure for disturbing the flow, so that the exhaust gas can be more fully in contact with the metal walls of the heat exchanger, and stays in the cavity of the heat exchanger longer, which can increase the heat that the airflow transfers to the fins, whereby the energy of the high-temperature exhaust gas can be effectively absorbed.

Compared with the new heat exchanger, the old one has the same external dimensions, but with no internal fins.

Boundary Conditions of the Simulation Model

Boundary Conditions of the Inlet and Outlet of the Two Heat Exchangers

For a incompressible fluid, either velocity or mass flow rate can be used as the inlet boundary condition of the TEG. The TEG inlet is set as the velocity entrance, and the temperature of the exhaust gas is 673 K; The TEG outlet is set as a pressure export, and the outlet pressure is the ambient static pressure, so that the back pressure at the exit can be set to 0.

Boundary Conditions of Solid Domain and Gas Domain

Fluid coupling simulation is mainly the coupling of a solid domain and a gas domain about heat transfer. In the heat transfer, the transfer conditions of heat–fluid coupling include the same temperature and the same heat flux in the coupled boundary. So the temperature and heat flow of the coinciding surfaces of the two domains are set as the same. Additionally, the coefficient of convective heat transfer between the outer surface of the exchanger and the air is set to 20 W/(m^2 K). The boundary conditions of the two heat exchangers are set as the same.

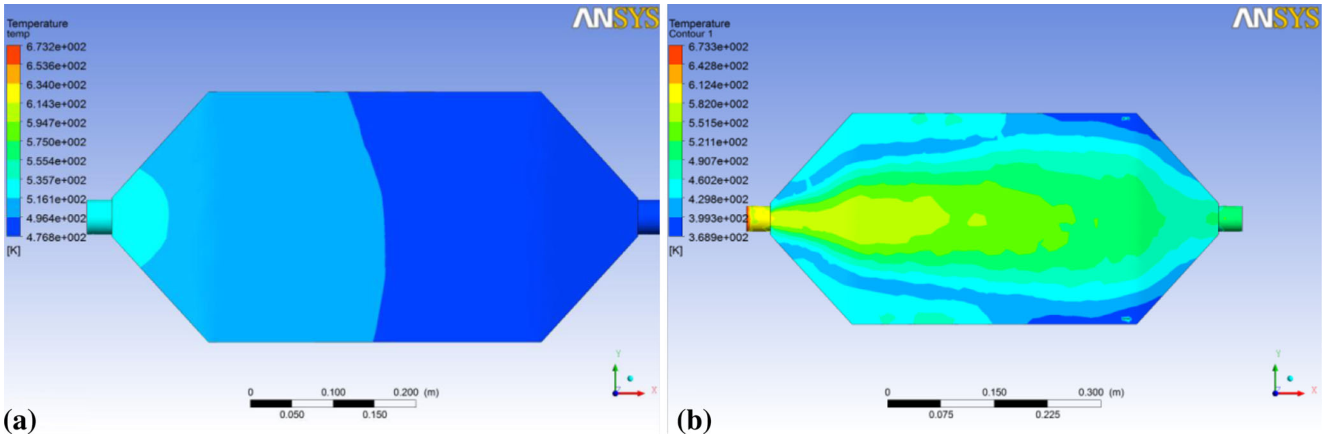

Fig. 2. Simulation results for temperature distribution of (a) the new heat exchanger and (b) the old heat exchanger.

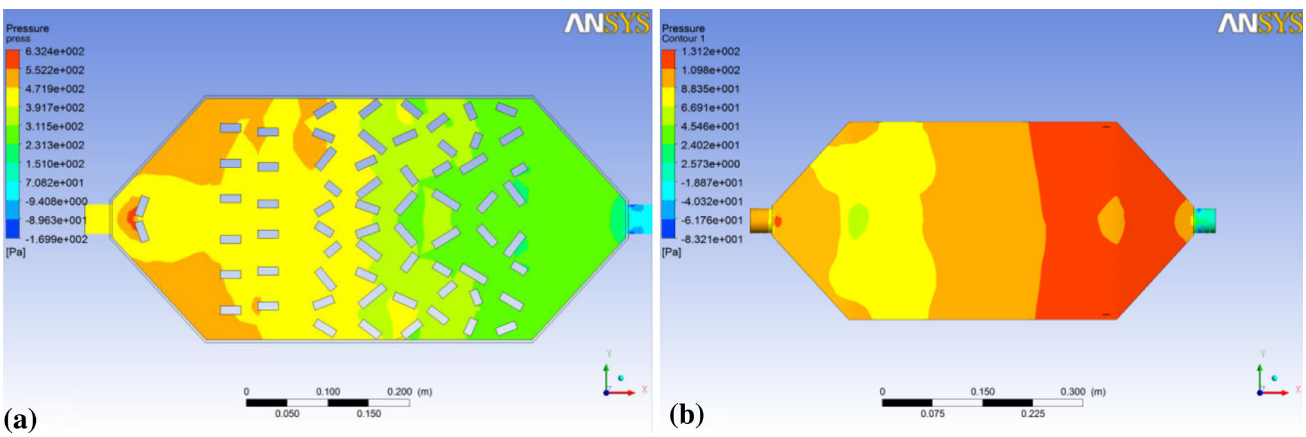

Fig. 3. Simulation results for pressure distribution of (a) the new heat exchanger and (b) the old heat exchanger.

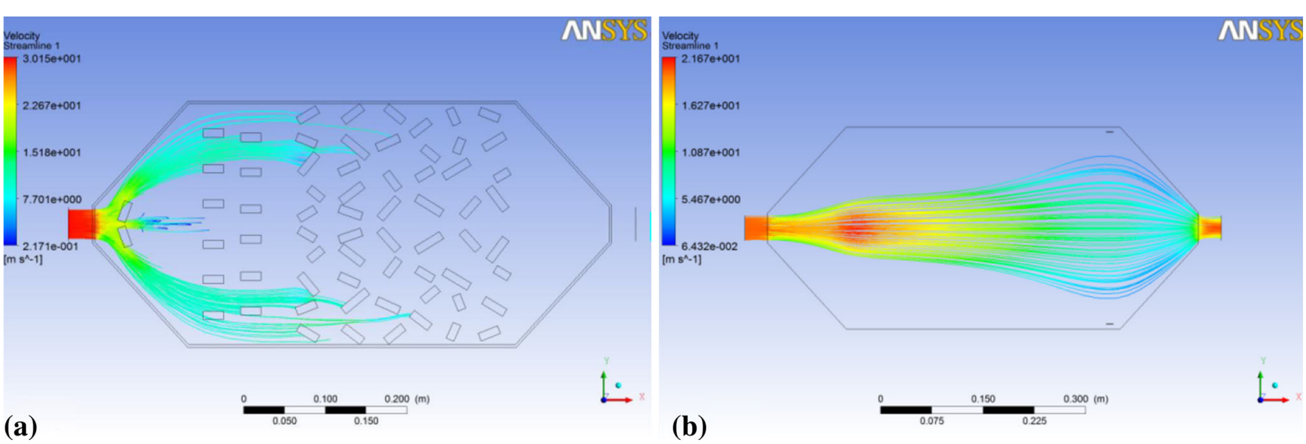

Fig. 4. Simulation results for flow distribution of (a) the new heat exchanger and (b) the old heat exchanger.

Simulation Results and Discussion

Temperature Distribution of the Coupling System

According to the simulation results shown in Fig. 2a, the interface temperature of the new heat exchanger is an average 520 K. The highest temperature is at the inlet and the minimum temperature is proximately at the outlet. The overall temperature appears as a cascade distribution, the transverse temperature distribution is uniform, and the longitudinal temperature gradually reduces. The heat of the high-temperature exhaust gas is insufficient to maintain the high-temperature state in the second half of the heat exchanger after the gas has been in full contact with the covers and the fins.

As illustrated in Fig. 2b, the high-temperature region is mainly in the middle of the heat exchanger. The general temperature distribution is not even, with low temperature at the two sides. Moreover, the temperature of part of the heat exchanger is only 373 K. It is obvious that the heat exchanger cannot meet the requirement.

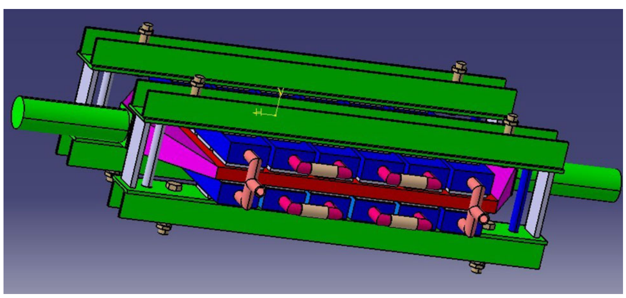

Fig. 5. TEG system.

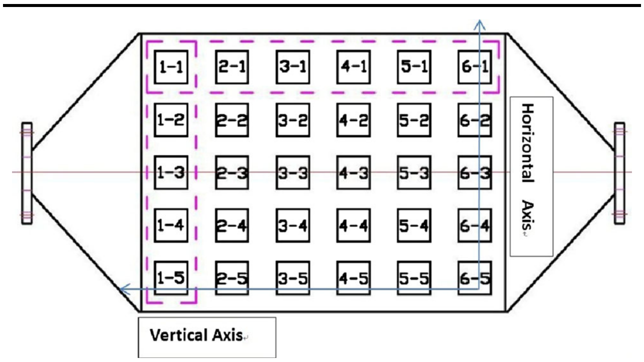

Fig. 6. Arrangement of TEMs on the heat exchanger.

Pressure Distribution of the Coupling System

High-temperature exhaust gas flow rate depends on the engine exhaust system. The pressure drop directly affects the back pressure of the engine exhaust gas, and then the intake and exhaust system of the engine is also affected, which may reduce the engine power. Thus, a lower pressure drop is better under the premise of the appropriate surface temperature, uniform temperature distribution, and full contact between the exhaust gas and the heat exchanger.

Indicated by the simulation result shown in Fig. 3a, b, in the new heat exchanger, the relative pressure at the fin closest to the gas inlet is highest, with a value of 632.4 Pa; the relative pressure at the outlet is smallest, with a value of -109.9 Pa. From the above data, the pressure difference between the inlet and the outlet of the heat exchanger can be calculated as 742.3 Pa. As for the old heat exchanger, the pressure differential of the import and export is 210 Pa, which is less than that of the new heat exchanger. While considering that the back pressure of the automobile exhaust gas is usually 30–40 kPa, on the whole, the high-temperature exhaust gas pressure distribution is relatively uniform and the pressure loss is very small.

Flow Distribution of the Coupling System

The flow speed of the exhaust gas in the internal cavity of the heat exchanger cannot be too slow or too fast, because the exhaust heat cannot be transferred fully by the heat exchanger if the speed is too fast, and the pressure drop would be increased to affect the engine power if the speed is too slow. Meanwhile, the uniformity of the exhaust gas in the heat exchanger must be considered to avoid the temperature of the partial region in the heat

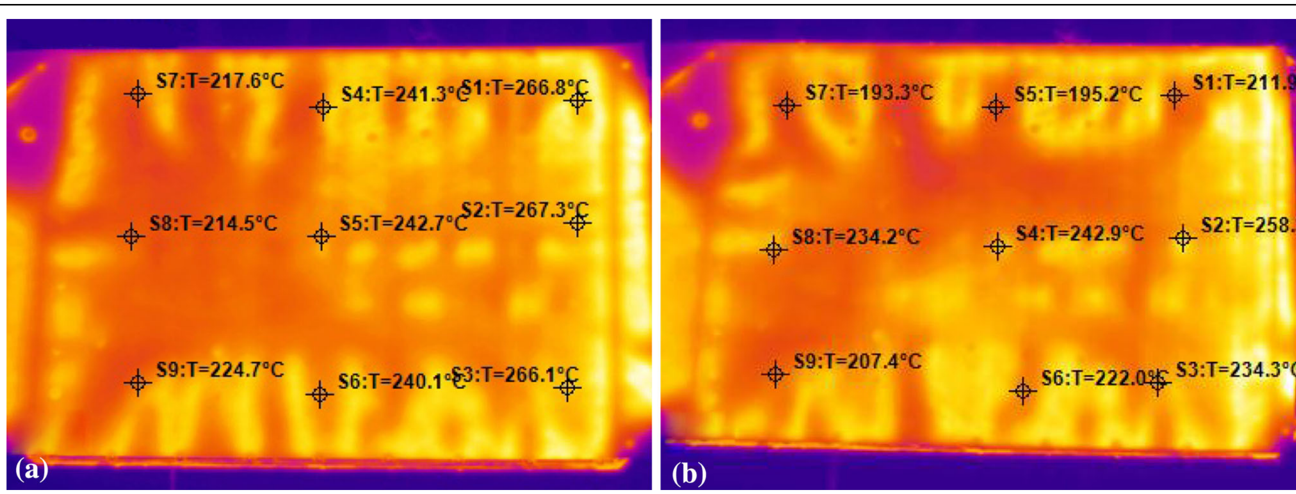

Fig. 7. Thermal images of (a) the new heat exchanger and (b) the old heat exchanger.

exchanger being too low to affect the generation power of the rear TEM.

We can conclude from the simulation result shown in Fig. 4a that the high temperature gas flowing quickly into the inlet is diffused in three directions due to the two fins near the inlet. Then, the airflow can be sufficiently distributed within the heat exchanger and the gas flow rate in the internal cavity is relatively high, which meets the requirement. However, in Fig. 4b, the high-temperature gas gathers in the middle region, while there is less high-temperature gas flowing to the two sides. In other words, the airflow cannot transfer enough heat to the two sides of the heat exchanger, which cannot meet the requirement.

EXPERIMENTAL SYSTEM

The priuncipal components of the experimental apparatus and manufactured TEG system, illustrated in Fig. 5, are the main heat exchanger, TEMs, the cooling system, the clamping device, and the charging system, with engine coolant as the working fluid. As shown in Fig. 6, there are 60 modules in total arranged in six rows, with 5 modules in each row on the upper and lower surfaces of the heat exchanger.

The experimental system is composed of a four-cylinder inline internal combustion engine (displacement 2 L at maximum power output of 108 kW) and a dynamometer (maximum power input 160 kW, maximum speed 6,000 rpm).

In the bench test, the experiment conditions such as the room temperature, wind speed, etc., remained unchanged and the engine revolutions were maintained at around 2,500 rpm. The experiments were carried out to test and compare the output power of the 60 modules of the two exchangers under the same conditions. Several transducers were used: a pressure sensor, *K*-type thermocouples, and an infrared camera to record the temperature distribution of the exhaust heat exchanger.

EXPERIMENTAL RESULTS AND DISCUSSION

The temperature distribution of the heat exchanger is crucial for the TEG in three aspects: firstly, it determines the available thermoelectric material by the maximum continuous operating temperature; secondly, it seriously affects the energy conversion efficiency of heat to electricity; thirdly, it dominates the uniformity of the thermal stress of the device and TEMs, because a nonuniform thermal stress makes poor contact between TEMs and the heat exchanger, or even worse, produces permanent damage to the TEMs.[5]

From Fig. 7a, b, the averaged surface temperature of the new exhaust heat exchanger is nearly 240 °C, while the averaged temperature of the old one is about 220 °C. The temperature of the two sides of the old exchanger is obviously lower than that of the middle area because the high-temperature gas flow does not spread to the two sides. However, the temperature distribution of the new exchanger is relatively even in the horizontal axis. The conclusions are compatible with the simulation results.

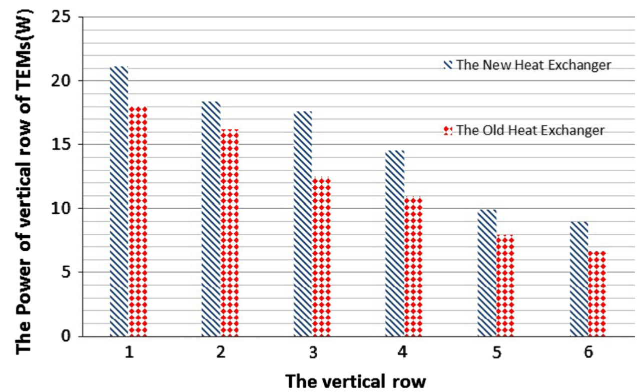

Fig. 8. Power output of vertical row of TEMs of the two heat exchangers.

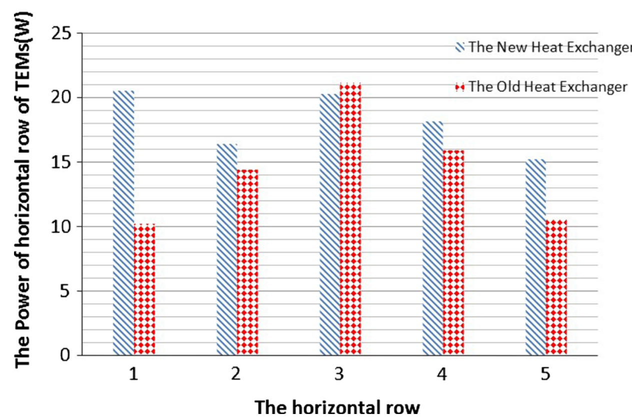

Fig. 9. Power output of the horizontal rows of TEMs of the two heat exchangers.

Only 30 upper modules of each exchanger have been taken to compare output power due to the symmetry of upper and lower faces. As for the total power of every horizontal row, the power of the new exchanger is 15–20 % more than that of the old one, shown in Fig. 8. The overall power of the new one is improved because of its hotter surface.

Figure 9 shows that the total power of the middle vertical row of the old exchanger is much more than other rows due to the gas flow gathering in the middle area. In comparison, the power of five vertical rows of the new heat exchanger has a smaller difference, which verifies the simulation result that the temperature and flow distribution of the new exchanger is very even.

CONCLUSION

Considering the agreement between the infrared experimental results and the heat-flow and flow-solid coupling simulation, especially the coupling analysis of the temperature, heat, and pressure fields of the heat exchanger, the present heat exchanger can reduce the resistance to exhaust heat conductions and obtain a relatively high surface temperature and ideal temperature uniformity to improve the efficiency of the TEG.

In future studies, the method of simulation modeling with infrared experimental verification introduced here needs to be combined with heat transfer theory and materialogy to serve for further structural design and optimization of TEM and TEGs, so as to improve the overall exhaust heat utilization and enhance the power generation.[6]

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