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Performance analysis of a waste heat recovery thermoelectric generation system for automotive application

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ABSTRACT

Thermoelectric power generators are one of the promising green energy sources. In this case study, an energy-harvesting system which extracts heat from an automotive exhaust pipe and turns the heat into electricity by using thermoelectric power generators (TEGs) has been constructed. The test bench is developed to analysis the performance of TEG system characteristics, which are undertaken to assess the feasibility of automotive applications. Based on the test bench, a new system called “four-TEGs” system is designed and assembled into prototype vehicle called “Warrior”, through the road test and revolving drum test table, characteristics of the system such as hot-side temperature, cold-side temperature, open circuit voltage and power output are studied, and a maximum power of 944 W was obtained, which completely meets the automotive application. The present study shows the promising potential of using this kind of thermoelectric generator for low-temperature waste heat recovery vehicle.

1. Introduction

With the rapid development of semiconductor materials, the heat directly converted into electricity by the thermoelectric generators (TEGs) has begun to enter engineering applications. Due to the merits in energy conversion such as little noise and vibration, high durability, environmental friendliness, and low quality thermal energy directly convert into high quality electrical energy, TEGs are of great interest in military applications and in deep space exploration missions [1–3]. 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 process [4–9]. For example, Li et al. [10] investigated a new type of solar thermoelectric co-generator (STECG) comprising parabolic trough concentrators and thermoelectric modules (TMs). Nikolova et al. [11] proposed a specific system consisted of thermal power plants (TPPs), storage hydro power plants (HPPs), pumped-storage hydro power plant (PSHPP) and wind power plant (WPP) to solve the generation scheduling problem, wind power plants are integrated into the system in order to minimize the total thermal unit fuel costs.

In the case of TEG for waste heat recovery power generation, there have been many conceptual designs of a power conversion system which are potentially capable of obtaining application in this area. Lesage et al. [12] built a Bi_2Te_3-based thermoelectric liquid-to-liquid generator, a correlation between peak thermoelectric power and thermal input conditions is presented as well as an investigation into the validity of electrical load matching. Park et al. [13] investigated a TEG energy harvesting system with a temperature-sensor-based maximum power point tracking (MPPT) method, the proposed MPPT scheme can track the MPP of any TEG system without current measurement, power perturbation or source disconnection, which enables optimal energy harvesting with a much simpler and much less expensive circuitry. Niu et al. [14] constructed an experimental thermoelectric generator unit with the parallel-plate heat exchanger, hot liquid and cold liquid, the two operation parameters such as the hot fluid inlet temperature and flow rate are found to significantly affect the maximum power output.

Waste heat from automotive vehicles is considerable as well. Since the first automobile TEG emerged in 1963, the endeavor to maximize its efficiency never stopped, and the methods were mainly concentrated in changing the structure of heat exchanger and introducing different heat transfer enhancement measures. Likewise, a number of research groups have studied the potential use of TEG systems as a thermal energy recovery method in automobiles, and this system was achieved by installing the thermoelectric devices in automobile exhaust pipes. In 1998 Nissan

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fabricated the first thermoelectric power generator based on Si–Ge elements for automobiles [15]. The Bell Solid State Thermoelectrics (BSST) team that includes BMW, Visteon, and Marlow Industries began the development in 2004 of a highly efficient thermoelectric system to recover waste energy for applications in passenger vehicles [16]. 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 [17]. Yang [18] reports the possibility of generating an average of 350 W on Federal Test Procedure (FTP) cycles with a conventional full size truck. Aleksandr et al. [19] developed a 1 kW TEG for the Heavy Duty Class Eight Diesel Trucks to replace the shaft driven alternator. Most of them used BiTe-based bulk thermoelectric material because it is made commercially available. Hi–Z Technology [20], tried to discover and to improve the efficiency of TMs. HZ-14 modules are based on Bi_2Te_3, of theoretical and experimental efficiency to about 5% [21]; the goal of Hi–Z for a practical device is an efficiency about 20%. Kumar et al. [22] assessed the influence of four different topologies structure of the heat exchanger to the efficiency of TEGs, and the results revealed that a transverse TEG with a single module length is found to be the most favorable design among all the designs studied, with the highest electrical power generation and lower pressure drops. Lu et al. [23] developed a test bench to test the thermal uniformity and pressure drop of muffler-like exhaust heat exchangers with different structures, and the results revealed that the performance of exhaust heat exchanger such as the surface temperature and pressure drop was dependent on exchanger's type and geometry, operating condition, and the temperature field was coupled with flow field. David et al. [24] proposed an optimization method for improving thermoelectric heat pump performance by operating condition management of the TMs and design optimization of the heat exchangers.

However, according the studies above, the majority of them have focused mainly on the optimization of the heat exchanger geometry or the temperature difference of TM, and the maximum power of all various TEGs is less than 200 W expect for the one used in heavy diesel trucks, which cannot meet the requirement for general automotive application. Also, external dimensions of those TEGs are another problem, the distance between chassis and ground is short, and nearly all TEGs cannot be used to automobiles. In a previous study, we constructed various heat exchangers, including maze-shaped, fishbone-shaped [25] and chaos-shaped [26] heat exchangers, to analyze their thermal performance. The height of those heat exchangers was also short, which was suitable for automotive application. The results showed that fishbone- and chaos-shaped heat exchangers resulted in a higher and more uniform interface temperature. At the cold side, a TEG water-cooling unit was inserted to the engine cooling system (called an " integrated cooling system" herein), which can avoid problems such as lack of space when TEG systems are used in vehicles [27]. In this study, the test bench are developed to analysis the performance of TEG system characteristics, especially the temperature difference, open circuit voltage and maximum power output. A complete TEG system to recover waste heat has been designed, simulated and fabricated to achieve the objective of recovered energy, as explained in the following sections. Based on the test bench, a new system called "four-TEGs" system is designed and assembled into the prototype vehicle called "Warrior", transforming the energy of waste heat into electricity, which is the specific issue of this research. Based on the road test and revolving drum test table, the new system in "Warrior" to recover waste heat has been designed, simulated, fabricated and tested to achieve the objective of recovered energy, and large output power of 944 W is obtained, as explained in the following sections.

2. Experimental procedures

2.1. TEG system architecture

Fig. 1 shows the schematic diagram of the experimental automotive waste heat recovery system, including automobile engine, catalytic converter, muffler, TEG and so on. A completed TEG system to recover waste heat has been designed, simulated and fabricated to achieve the objective of recovered energy. The waste heat recovery system shown in Fig. 2 was designed for use with the exhaust pipe of automobiles. The TMs are clamped with sufficient compressive force between a heat exchanger connected to the exhaust pipe and cooling water tanks in the exhaust-based TEG. Four concave type steel is used as the clamping devices while the torque wrench used to provide an applied pressure at a pressure load of 2.50 kg/cm^2 on the TMs. Exhaust gas flows into the heat exchanger through a bypass to provide a heat source. The cooling water is pumped into the water tanks to form the cold side. Then, electric power is generated due to the temperature difference between the two sides of the modules and stored in batteries. TMs (Shanghai Institute of Ceramics of the Chinese Academy of Sciences) were arranged on both surfaces of the brass heat exchanger where the exhaust gas passes. The geometric features and transport properties of the PN materials used in this work are listed in Table 1. Various measuring instruments were applied to construct this experimental setup. A 2.0-L naturally aspirated engine was used as study object. A dynamometer (maximum power input 160 kW, maximum speed 6000 rpm) was also used. Several transducers were used: 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 was connected to the system and used to measure the voltage and power output.

The principal components of the experimental apparatus and manufactured TEG system, as illustrated in Fig. 2, are the main heat exchanger, TMs, the water tank (cooling system), the clamping device, and the charging system, with engine coolant as the working fluid. The size is 620 mm in length and 310 mm in width. There are 60 TMs in total, arranged in six rows, with five modules in each row on the upper and lower surfaces of the heat exchanger. Table 2 lists the boundary conditions and dimensions of each element used in this work. In subsequent analysis without special description, values are taken from Tables 1 and 2. The system efficiency can be calculated using Eq. (1) from the measured values maximum output power (P_{max}) and engine power (Q_{engine}).

$$\eta = \frac{P_{max}}{Q_{engine}}, \tag{1}$$

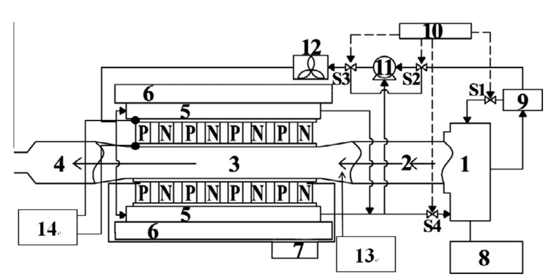

Fig. 1. Schematic diagram of the experimental thermoelectric generator system 1: Automobiles engine. 2: Catalytic converter. 3: Heat exchanger for passing exhaust gas. 4: Muffler. 5: Water tank. 6: Clamping device. 7: Electronic load. 8: Dynamometer. 9: Cooling system. 10: Controller. 11: Water pump. 12: Heat sinks. 13: Tachometer and K-type thermocouples. 14: K-type thermocouples.