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An energy-harvesting system using thermoelectric power generation for automotive application

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ABSTRACT

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. Two test benches have been developed to analyze the thermoelectric module (TM) performance and TEG system characteristics. The experiments are carried out to examine the influences of the main operating conditions, the hot and cold side temperatures, flow rates and the load resistance, on the power output and voltage. As the performance of a TM is most influenced by the applied pressure and the temperature difference, a thermostatic heater, thermostatic water tank, and clamping devices are used in our experimental apparatus, the three operation parameters such as the applied pressure, cold-side flow rate and cold-side temperature are found to significantly affect the maximum power output. Based on the single TM measurement, the whole TEG system has also been designed and tested on the bench test. Through these experiments, maximum power output of the system is characterized. The results establish the fundamental development of automotive exhaust thermoelectric generator system that enhances the TEG efficiency for vehicles.

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 [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 process [3–9].

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. Making good use of these waste heats improves the energy efficiency and saves money [10]. In 1998 Nissan fabricated the first thermoelectric power generator based on Si–Ge elements for automobiles [11]. 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 [12]. Yang [13] 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. In the case of waste heat recovery power generation, there are many conceptual designs in automobiles. Most of them used BiTe-based bulk thermoelectric material because it is made commercially available. Hi-Z Technology [14], tried to discover and to improve the efficiency of thermoelectric modules (TMs). HZ-14 modules are based on Bi_2Te_3, of theoretical and experimental efficiency to about 5% [15]; the goal of Hi-Z for a practical device is an efficiency about 20%. Hsiao et al. [16] established mathematic models and performed experiments; they found a better performance can be obtained by attaching TEGs to the exhaust system than to the radiators. Chung et al. [17] 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,

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whose exhaust gases are as hot as 200–300 °C at the outlet of the catalyst filter. Thacher et al. [18] 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 [19]. Hsu et al. [20] proposed a heat exchanger mounted with eight Bi_2Te_3-TEG chips and employed eight air-cooled-heat-sink assembles. A maximum power of 44 W was obtained. In 2012, they enlarged the heat exchanger with a similar interior structure and added a slopping block in the inlet [21]. A maximum power of 12 W was obtained instead when twenty-four TEG chips and twenty-four air-cooled-heat-sink assembles were implemented. Their experimental results surprisingly suggest that a small-size heat exchanger with less TEGs can generate more power. Niu [22] connected 56 BiTe-based TEG modules in series to show the promising potential of using TEG for low-temperature waste heat recovery, which also shows good conversion efficiency. Gou [23] proposed many suggestions to obtain better performance, such as increasing the waste heat temperature and TEG modules in series, expanding heat sink surface area in a proper range and enhancing cold-side heat transfer capacity. Kim et al. [24] proposed a new heat pipe TEG system called “HPTEG”, to provide a large heated surface area on which to install numerous TMs.

However, according the studies above, none of the previous work discussed here used a specific clamping device that applies a proper pressure. Considering the thermal contact resistance, the temperature difference of TM is higher than its true value, a comprehensive study regarding the applied pressure of TMs that includes such analysis is lacking. Moreover, the maximum power of all various TEGs is less than one hundred watts, which cannot meet the requirement for automotive application. In this study, a test bench including thermostatic controller and spring balance is developed to analyze the performance of TM characteristics, especially the temperature difference, open circuit voltage and maximum power output. Based on the TM characteristics, a complete TEG system to recover waste heat has been designed, simulated and fabricated to achieve the objective of recovered energy, and another test bench is built to analyze the performance of whole TEG system. Transforming the energy of waste heat into electricity, which is the specific aim of this research, as presented below.

Experimental procedures

TM System architecture and testing

As shown in Fig. 1, a single TM measurement system was used to measure the performance of a single TM. A single TM (Shanghai Institute of Ceramics of the Chinese Academy of Sciences) was clamped between a cooling water tank (upper side) and a heater (lower side). A thermostatic heater (30–600 °C) and water tank (−10–120 °C) were used to control the temperature difference between the hot and cold sides of the module, the temperature controllers were used to control the temperatures of the cold fluids and the hot iron plate within 0.1 °C. The cold fluids volume flow rates were measured by volumetric flow meters located at the inlets of the cold fluid passages, respectively. The total capacity of the fluid flow meter was 0.2–1.0 $m^3\,h^{-1}$. A clamping device was used to provide an applied pressure of 0–2000 N. A high-power electrical load was connected to the system to measure the voltage and power output. The geometric features and transport properties of the PN materials used in this work are listed in Table 1. The waste heat $Q_{exhaust}$ in the exhaust pipe was transferred upward through the TM, through the heat sink, and then to the environment. Part of the waste energy was converted into electrical energy Q_{power}. According to an analysis of the thermal resistors in Fig. 2, the exact temperature difference across the TE element (ΔT_{TM}) can be calculated with Eq. (1) from the measured values T_h and T_c.

Table 1
Parameters of PN materials.

Parameter	P type	N type
Seebeck coefficient (μV/K)	215	−215
Electrical resistivity (Ωm)	1.04×10^{-5}	1.04×10^{-5}
Thermal conductivity (W/(m K))	1.5	2.5
Height (m)	0.005	0.005
Sectional area (m^2)	$0.01 * 0.01$	$0.01 * 0.01$

$$\Delta T_{TM} = \frac{(R_N + 2R_{SOL})//(R_P + 2R_{SOL}) \times (T_h - T_c)}{2(R_{CER} + R_{CU}) + (R_N + 2R_{SOL})//(R_P + 2R_{SOL})}, \qquad (1)$$

where T_h and T_c are the temperatures measured at the hot and cold sides of a single TM.

For a temperature difference ΔT applied to a TM element, an external load is connected in series. The power generated by the TM is estimated from the voltage across the external load and the current in the circuit. In such single TM testing, temperature, pressure, volume flow rate and power output are the main parameters measured during experimentation.

The performance of a TM is also influenced by the applied pressure through the effect of the thermal contact resistance such that, the larger the applied proper pressure, the better the performance. The results of these measurements are shown in Figs. 3 and 4. Fig. 3 shows typical measured power output curves with varying the external load resistance at a fixed hot temperature and cold fluid temperature as well as cold fluid flow rates. As can be seen in

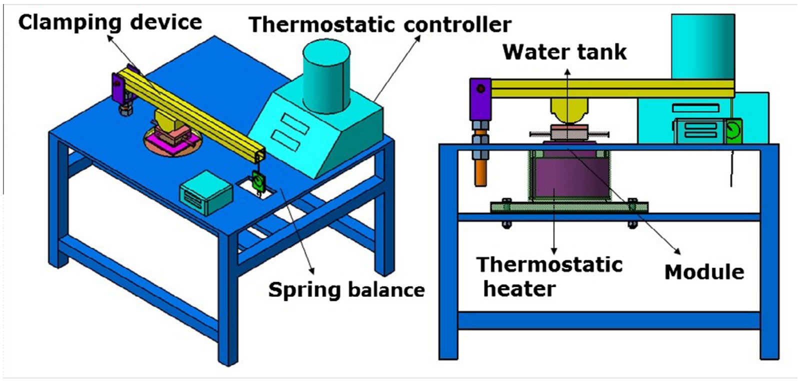

Fig. 1. Single TM testing system.