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Waste heat recovery of a diesel engine using a thermoelectric generator equipped with customized thermoelectric modules

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ABSTRACT

The waste heat recovery performance of a thermoelectric generator (TEG) was experimentally investigated. Forty customized thermoelectric modules (TEMs) were installed on the upper and lower sides of a rectangular exhaust gas channel in a 4 × 5 arrangement. Water at an ambient temperature of ∼293 K was supplied from a cooling tower and was used to create a temperature difference across each TEM. The water flow rate was fixed at 8 SLPM. A turbocharged six-cylinder diesel engine was used as the heat source; the engine was operated under various conditions. Three engine rotation speeds—1000, 1500, and 2000 rpm—were employed to determine the effect of the exhaust gas flow rate on the TEG power output. The temperature of the exhaust gas was varied by changing the engine load, i.e., the brake mean effective pressure (BMEP), at an interval of 0.2 MPa. From the experimental results, a contour map showing the power output of the TEG as a function of the engine load and speed was obtained. From the contour map, we observed that the power output of the TEG increases with the engine load or speed. The maximum power output was ∼119 W at 2000 rpm with a BMEP of 0.6 MPa; the maximum energy conversion efficiency was ∼2.8%. The pressure drop across the TEG was experimentally found to be 0.45–1.46 kPa under all engine operation conditions.

1. Introduction

The use of petroleum-based fuels causes environmental problems, such as air pollution and global warming, and raises the global concern about energy security [1–3]. Thermoelectric (TE) energy conversion is considered as a possible approach to alleviate the abovementioned problems by converting waste thermal energy into valuable electrical energy. Thermoelectric generators (TEGs) are easy to implement because they have no moving parts, are compact, and have relatively low pressure drop [4–9]. Owing to the efforts of a number of research groups worldwide, the energy conversion efficiency of thermoelectric materials and modules has been improving [10,11]. As a result, the applications of thermoelectricity have been expanded from medical, military, remote, and space applications [12] to automotive [13–15], geothermal [16], stove [17–19], power sensors and stations [20–23].

Several efforts have been made to investigate the system-wise performance of TEGs. Kumar et al. [24] numerically studied the effect of the shape of the exhaust gas channel where thermoelectric modules (TEMs) are attached. They reported that a rectangular exhaust gas channel yields a lower surface temperature, which helps meet the maximum temperature requirement (∼493 K) of the TEM, while exhibiting a uniformly distributed exhaust gas flow inside. Ibrahim et al. [25] studied the automotive exhaust heat recovery characteristics of thermoelectric modules using a rectangular exhaust gas channel. They found that the packing of a porous material inside the exhaust gas channel improves the thermoelectric energy conversion performance by boosting the heat transfer from the gas stream flowing in the hot-side duct to the surfaces of TEMs.

Despite all these efforts, however, there is still a lack of information on the performance of TEGs and their power output characteristics as functions of the variation in the temperature and flow rate of the heat source. Therefore, in this study, a TEG was fabricated according to the optimum internal fin design guidelines suggested in a companion paper [26]. The middle of the TEG is a rectangular exhaust gas channel, the top and bottom surfaces of which are used for the TEM attachment. Forty custom-fabricated TEMs [26] were used to recover the waste heat of exhaust gases emitted from an internal combustion engine. The test engine was an inline six-cylinder turbocharged diesel engine. The waste heat recovery performance of the TEG was examined for three engine rotation speeds—1000, 1500, and 2000 rpm—and for engine loads in the

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range of 0.2–1.0 MPa. The surfaces of the TEMs were kept cool by coolers in which water at 293 K flows at a flow rate of 8 SLPM. The power output of the TEG increases with engine rotation speed and/or engine load. The maximum power output of ~119 W was measured at 2000 rpm and at a brake mean effective pressure (BMEP) of 0.6 MPa; the maximum energy conversion efficiency was ~2.8%. In addition, the pressure drop across the TEG was also obtained under all engine operation conditions. The pressure drop measurement results show that the rise in the back pressure in the exhaust gas channel owing to the installation of the TEG is in the range 0.45–1.46 kPa, which is relatively lower than that caused by the installation of conventional after-treatment systems.

2. Experimental setup and procedure

2.1. TEG preparation

Fig. 1 shows photos of the fabricated TEG. The rectangular exhaust channel in the middle of the TEG was made of stainless steel. The exterior dimensions of the channel were $253.5 \times 372 \times 60$ mm. Finned structures were installed on the inner surface of the exhaust gas channel to augment the heat transfer from the exhaust gas to the surface of the TEMs. Considering the heat transfer rate as well as the operating range of the engine and pressure characteristics, we set the fin thickness and channel width formed between two adjacent fins to 2 and 4.57 mm, respectively, as suggested by Kim et al. [26]. In order to connect the TEG to a conventional exhaust gas pipe, 50-mm-long diverging and converging cones were located at the front and rear ends of the exhaust gas channel. A 2-mm-thick perforated stainless steel plate was placed in the upstream extension channel to straighten the exhaust gas flow. The diameter of the perforated holes was 5.1 mm. The custom-fabricated TEMs [26] were used for waste heat recovery. The electrical resistance of the TEMs, measured with an LCR meter (IM3533, HIOKI E.E. Corp.), was in the range of 2.0–2.15 Ω. Forty TEMs were installed on the top and bottom sides of the exhaust gas channel in a 4×5 arrangement with 13-mm gaps between adjacent TEMs. In the gaps, an array of nuts was welded on the exhaust channel for achieving mechanical clamping between the exhaust gas channel and two coolers, sandwiching the TEMs between them. The side surfaces of the exhaust gas channel were shrouded with an insulation material (Interam™ Mat 1500HT, 3M™) to reduce heat loss to the environment. A thermal grease (SC102, Dow Corning Toray Co., Ltd.) was applied between the TEMs and the exhaust gas channel.

The cold surfaces of the TEMs were cooled by coolers in which water at an ambient temperature of ~293 K flowed at a rate of 8 LPM. The width and length of each cooler were 253.5 and 372 mm, respectively, to cover the entire surface of the attached TEMs. The total height of each cooler was 29 mm, including a 5-mm-thick bottom plate, a 20-mm-thick coolant passage, and a 4-mm-thick top cover. The coolers also had finned structures inside to facilitate uniform distribution of coolant flow. The thickness and height of the fins were 2 and 10 mm, respectively. The channel width between adjacent fins was 4.57 mm. An array of holes, aligned with the nuts welded onto the exhaust gas channel, was drilled through the bottom plate of each cooler. The exhaust gas channel and the coolers were connected tightly by screws. Teflon washers were placed beneath the heads of the screws to prevent leakage of water through the holes. Thermal pads (TGX, t-Global Technology) with a thermal conductivity of 12 W/m K were placed between the TEMs and the cooler to reduce the contact resistance and tighten the contact between the modules and the cooler/exhaust gas channel by compensating for the mechanical tolerance and the height difference between the TEMs. K-type thermocouples were inserted into the middle of the cones placed upstream and downstream of the TEM array to measure the inlet and outlet exhaust gas temperatures of the system. There were also pressure taps in the cones to measure the pressure drop across the TEG using a pressure transducer with a measurement range 0–2 kPa and 0.5% full-scale accuracy (DPLH02.00R, Sensor system technology Co., Ltd.). A 0.8-mm-thick k-type thermocouple was used to measure the surface temperature of the TEM located in the first row and the second column on the top surface of the TEG, referred to the reference module hereinafter. For this purpose, a straight groove 1 mm wide was made on the top surface of the exhaust gas channel, from the side to where the center of the

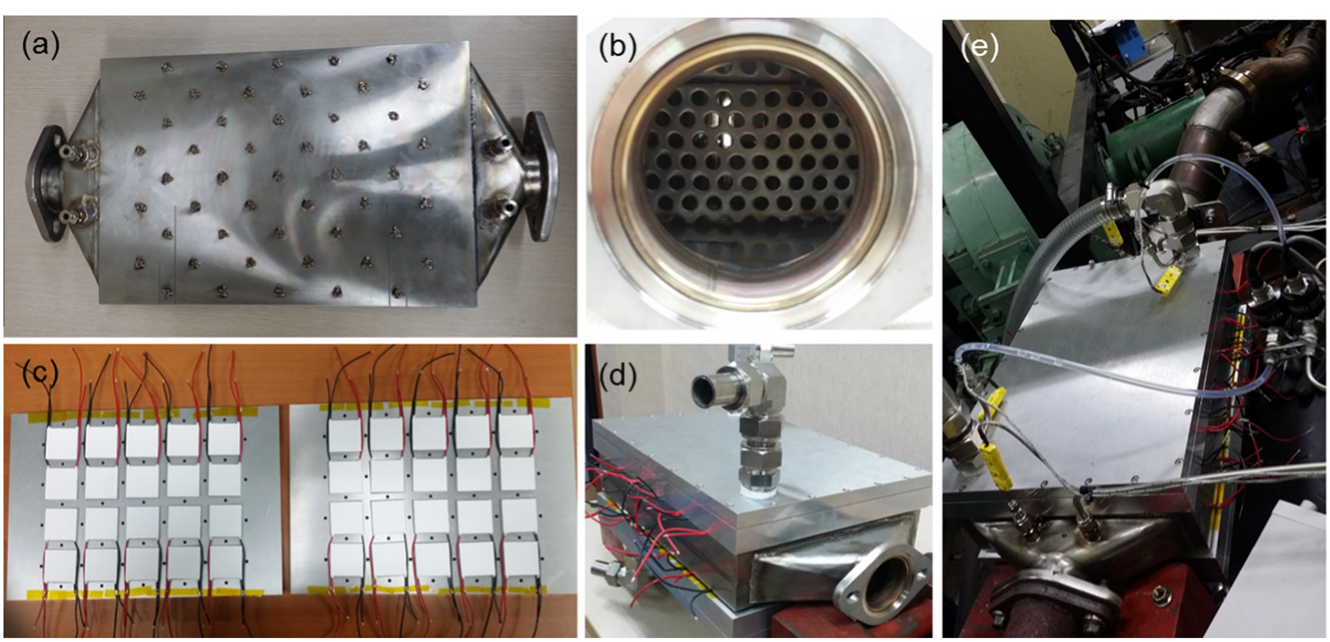

Fig. 1. Photos of the fabricated TEG in the present study: (a) rectangular exhaust gas channel and cone structures, (b) perforated plate placed inside the rectangular exhaust gas channel, (c) TEM arrays attached to the surfaces of the coolers, (d) assembled TEG, and (e) TEG installed in the middle of the tail pipe of the diesel engine.