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Energy harvesting performance of hexagonal shaped thermoelectric generator for passenger vehicle applications: An experimental approach

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ABSTRACT

In this study, the waste heat recovery performance of a hexagonal thermoelectric generator (TEG) was investigated experimentally. Based on the system configuration and dimensions, a total of 18 thermoelectric modules (TEMs) were used for thermal energy harvesting. The internal finned structures of the hexagonal TEG were placed on the inner surface of the exhaust gas channel, in consideration of the thermal resistance and friction factor, in order to augment the heat transfer from the exhaust gas to the thermoelectric modules (TEMs), while maintaining the pressure drop across the TEG below ~3.0 kPa, under various operating conditions. The surface of the TEMs was positioned on the hexagonal-shaped exhaust gas channel surface, whereas the other surface of the TEMs was maintained cool by a set of coolers through which the engine coolant flowed. The coolant line was modified in order to induce a total coolant flow of 10 LPM at 353 K from a coolant controller to the hexagonal TEG. In this study, the assembled hexagonal TEG was installed in the middle of the exhaust gas pipe of the internal combustion engine manufactured for hybrid electric vehicles, and was used as the heat source. The waste heat recovery performance of the hexagonal TEG was evaluated by considering eight engine-operating conditions under which the automotive vehicles were most frequently driven. The output power of the hexagonal TEG tended to increase with the increase in engine speed and load, and ranged between 21.2 and 98.8 W, which corresponded to a conversion efficiency of ~1.3–2.6%. An acceptable maximum pressure drop across the hexagonal TEG of ~2.1 kPa was observed for the maximum exhaust gas flow rate condition.

1. Introduction

Thermoelectric energy conversion has drawn considerable attention as a promising candidate of waste heat recovery technology for the improvement of fuel efficiency for energy conversion systems. The application areas of the thermoelectric generators (TEGs) have widened based on advantages such as the solid-state energy conversion mechanism, absence of moving parts in the systems, silent operation, and compact system size [1–4].

The development of high-efficiency TEGs has been accelerated owing to recent advances in thermoelectric material properties and design methods. El-Genk and Saber [5] reported a thermoelectric energy conversion efficiency of ~12% by using a segmented thermoelectric unicouple. The n- and p-type legs were segmented with different types of materials in consideration of the temperature gradient formed along the direction of the leg height. Moreover, they quantified the effect of contact resistance and heat loss and revealed the noticeable effects of unexpected thermal resistance and leakage on the conversion efficiency of thermoelectric modules (TEMs). Zhang et al. [6] investigated a design method of segmenting the thermoelectric generator, with regard to the length of the thermoelectric legs as a primary design parameter. The authors observed that the optimal length ratios of the thermoelectric legs for maximum power output and conversion efficiency were different to each other. In recent years, abundant research has been aggressively conducted on the improvement of TEG performance through enhanced system-level design. Remeli et al. [7] developed a heat pipe assisted TEG in which the hot side of the TEMs was attached to a heat pipe inserted in an exhaust gas channel, whereas the cold side was connected to the second heat pipe, which transferred the heat from the TEMs into the ambient environment. The combination of TEGs with other types of energy systems has been suggested for the purpose of improving the waste heat recovery efficiency. Qui and Hayden [8] investigated a TEG-organic Rankine cycle (ORC) integrated system for micro-CHP systems, where TEG was used as the topping

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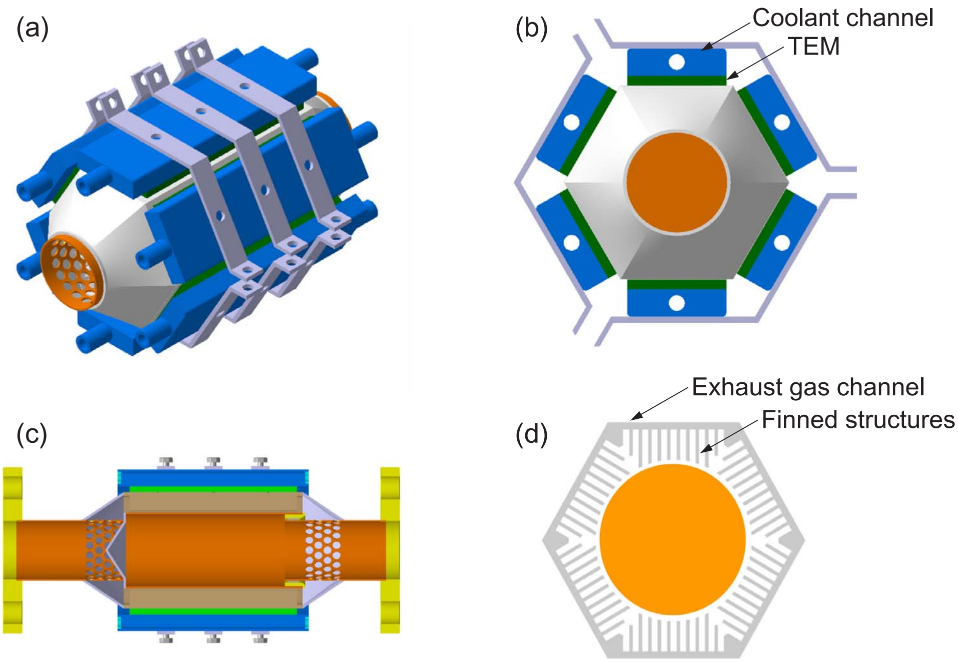

Fig. 1. Schematic diagrams of present hexagonal TEG: (a) isometric view, (b) front view, (c) cross-sectional side view of TEG, and (d) cross-sectional front view of exhaust gas channel.

cycle and ORC was used as the bottoming cycle. The concept of the direct contact–type TEG (DCTEG) was proposed in our previous study [9,10] in order to improve the practicality of TEGs. With this configuration, the TEGs could be beneficial to system fabrication, long-term reliability, maintenance, and maximization of system efficiency, in cooperation with other energy systems, owing to their simple system configuration and lack of an interface between the TEMs and heat sources.

Even with the above-mentioned advantages and the tremendous effort made within the materials science and systems engineering fields, technical challenges still remain, and particularly with regard to the automotive applications of TEGs. Additionally, a wide body of previous TEG research has focused on power output values rather than on the design restrictions specified for real vehicle applications. One of the challenges and restrictions is space availability, which restricts system dimensions and configurations. For conventional passenger vehicles, the energy conversion systems utilizing the thermal energy of the exhaust gas can be installed in the middle of the exhaust gas pipe in the underbody of the vehicles. However, the underbody space should be shared with other post-treatment systems, such as catalysts and particulate filters; thereby, the size and configuration of the automotive thermoelectric generators are limited according to their target applications. Birkholz et al. [10], in collaboration with Porsche, proposed a TEG with dimensions of 300 (H) × 300 (W) × 500 (L) mm^3. The Nissan research center developed TEGs by using various types of thermoelectric materials in accordance with system size criteria [11–13]. A TEG with cartridge-type power generation components was developed under the consideration of a passenger vehicle platform [14]. By comparison to the vast number of investigations into large size truck applications, investigation into applications for passenger vehicles is currently lacking.

Additional concerns regarding the automotive applications of TEGs include the evaluation of performance under experimental conditions and in accordance with actual vehicle driving conditions. Risseh et al. [15] carried out simulations and experiments under nine steady-state drivable conditions for evaluating TEG performance in the actual diesel truck application of a TEG designed based on space availability.

In this study, the waste heat recovery performance of a hexagonal TEG was investigated experimentally for passenger vehicle applications. Under the specified space restrictions for passenger vehicles manufactured by Hyundai Motor Co., the TEG was fabricated with dimensions of 136 (H) mm × 141 (W) mm × 214 (L) mm. Because three TEMs were positioned on each surface of the hexagonal exhaust gas channel, a total of 18 TEMs were installed for waste heat recovery. The TEMs were sandwiched by the exhaust gas channel and rectangular coolers through which the engine coolant flowed. For improved waste heat recovery performance, the finned structures were fabricated on the inner surface of the exhaust gas channel in order to increase the heat transfer rate from the exhaust gas flow to the surface of the TEMs. The power generation performance of the hexagonal TEG was evaluated by using an internal combustion engine that was manufactured for a hybrid electric vehicle as the heat source. The assembled hexagonal TEG was installed in the middle of the exhaust gas pipe and was derived from the engine's exhaust gas manifold. Based on the analysis of the driving cycles and patterns, the eight most frequently operated driving points of the passenger vehicle's engine were chosen as the experimental conditions under which the performance of the hexagonal TEG was observed. In addition to the power generation characteristics, the change in the exhaust gas temperature, variation in coolant temperature, hot side surface temperature of the TEMs, and pressure drop across the TEG, were measured by using an electric load, thermocouples, and manometers. The output power and conversion efficiency of the hexagonal TEG were shown to both increase as the engine speed and load increased. A maximum output power of 98.8 W was observed for the engine operating conditions of 0.6 MPa under the brake mean effective pressure (BMEP), and an engine speed of 3000 rpm, which provided the highest exhaust gas temperature and flow rate. Additionally, a maximum heat recovery efficiency of 32.9% and energy conversion efficiency of 2.6% were obtained. As designed, the maximum pressure drop across the hexagonal TEG was maintained below ~2.1 kPa under all experimental conditions.

2. Experimental setup and procedure

2.1. TEG design

Fig. 1 shows, the current hexagonal TEG designed under the space restrictions specified for passenger vehicles. With the current TEG design, the exhaust gas flow was guided by a cone structure and induced into the internal finned structures that facilitated heat transfer from the