Journal of ELECTRONIC MATERIALS, Vol. 40, No. 5, 2011
DOI: 10.1007/s11664-011-1580-6


# A Thermoelectric Generator Using Engine Coolant for Light-Duty Internal Combustion Engine-Powered Vehicles

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We proposed and fabricated a thermoelectric generator (TEG) using the engine water coolant of passenger vehicles. The experimental results revealed that the maximum output power from the proposed thermoelectric generator was ~75 W, the calculated thermoelectric module efficiency of the TEG was ~2.1%, and the overall efficiency of electric power generation from the waste heat of the engine coolant was ~0.3% in the driving mode at 80 km/h. The conventional radiator can thus be replaced by the proposed TEG without additional devices or redesign of the engine water cooling system of the existing radiator.

**Key words:** Thermoelectric power generator, vehicle waste heat recovery, engine coolant

## INTRODUCTION

As a green energy technology that improves the fuel economy of internal combustion engine-powered vehicles (ICEVs), there has been great interest in the conversion of waste heat to electricity using thermoelectric generators (TEGs).[1–4] Every major automobile manufacturer is currently working on waste heat recovery systems to reduce the emission of carbon dioxide, and some are attempting to develop thermoelectric hybrid electric vehicles.[3–5] As illustrated in Fig. 1, only 30% of the fuel combustion energy is converted to mechanical energy, whereas ~40% of the fuel combustion energy is wasted through the exhaust gas. Waste heat through the engine coolant also accounts for up to 30% of the fuel consumption energy.[1–4] The temperature of the exhaust gas near the engine manifold is higher than 500°C. Because of the advantages and benefits of high-temperature exhaust gas, most vehicle waste heat recovery systems have been based on electric power generation from the exhaust gas.[1–4] Because engine coolant is an important source of waste energy, the development of thermoelectric generators that use both engine coolant and exhaust gas to improve the overall fuel economy is essential.[4,6,7]

We have proposed and developed a low-temperature thermoelectric generator that uses the engine water coolant of passenger vehicles with an engine size of ~2 L. We attempted to substitute the conventional radiator for the proposed TEG without additional water pumps or mechanical devices except for the basic components of the existing water cooling system based on the radiator. Figure 2 depicts a configuration of the proposed TEG substituted for an existing radiator.

(Received May 28, 2010; accepted February 2, 2011; published online March 26, 2011)

## PROPOSED THERMOELECTRIC GENERATION SYSTEM

The proposed engine coolant TEG has an air-cooling structure composed of heat pipes and heat sinks. The cooling performance of the proposed TEG is considerably higher than that of the radiator, due to the air-cooling structure of the TEG and the additional cooling effects as a result of heat conversion to electricity. The framework of the proposed TEG is composed of a hot-side block and a cold-side block consisting of heat pipes and heat sinks, as depicted in Fig. 3. A total of 128 heat pipes were installed in a prototype of the proposed

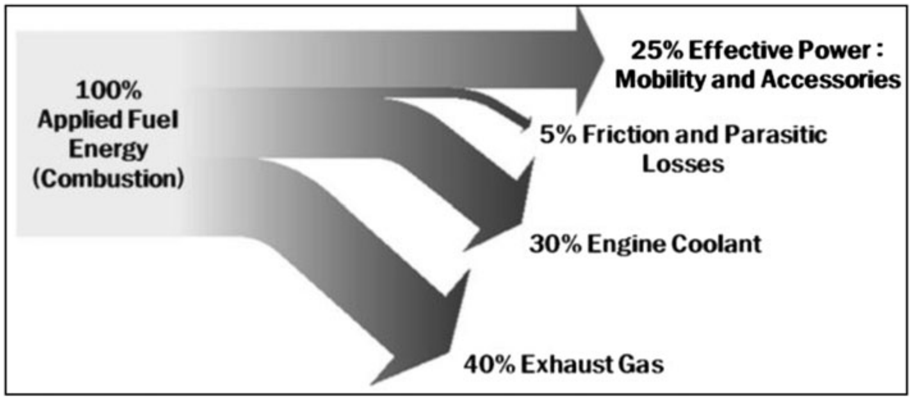


Fig. 1. Typical energy consumption rate for vehicles with gasoline-fueled internal combustion engines.[1–4]

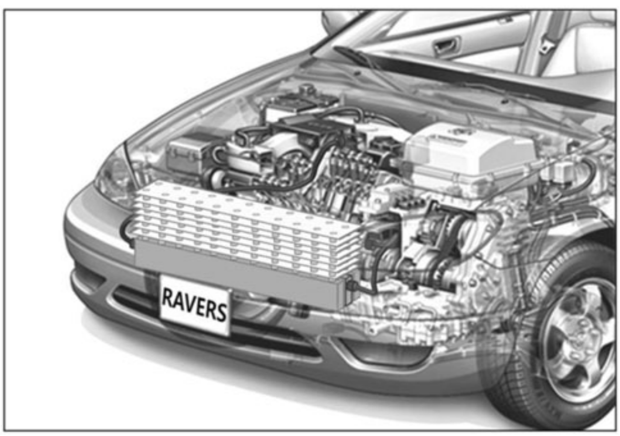


Fig. 2. Conceptual diagram of the proposed thermoelectric generator substituted for an existing radiator.

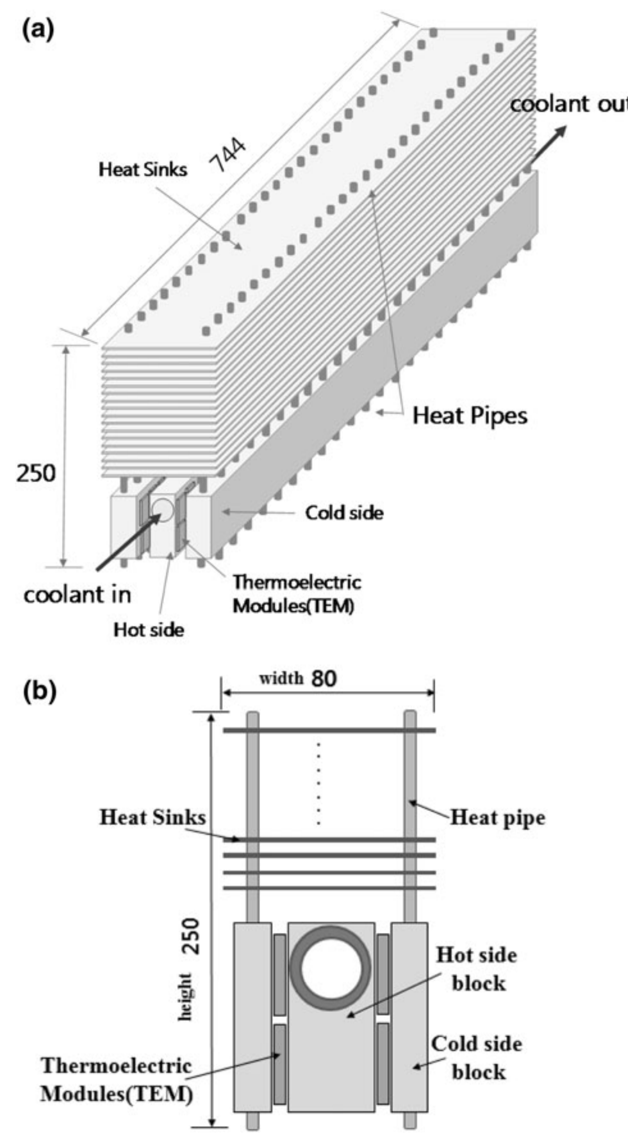


Fig. 3. Perspective (a) and side view (b) of the proposed thermoelectric generator. Dimensions are in millimeters.

thermoelectric generator. The feature size and number of heat pipes shown in Fig. 3 are not to scale. The hot-side block of the TEG has inlet and outlet ports for the engine coolant to link to the water cooling system of the vehicle. The cooling plates and hot-side block have a sandwich structure. Thermoelectric modules can be attached on both sides of the hot-side block. To increase the effective surface area of the hot-side block, there are a number of partitions, as illustrated in Fig. 4. The interior structure of the hot-side block with partition walls enables proper transfer of the coolant heat to the hot side of the thermoelectric modules and uniform distribution of the hot-side temperature of the TEG.

The dimensions of the fabricated TEG are ~80 mm (width) × 250 mm (height) × 740 mm (length), which is almost the same length and is half the height of the original radiator of the vehicle. Seventy-two thermoelectric modules with area of 4 mm × 4 mm can be attached to the proposed TEG. The cold side of the TEG has an efficient heat-spreading structure

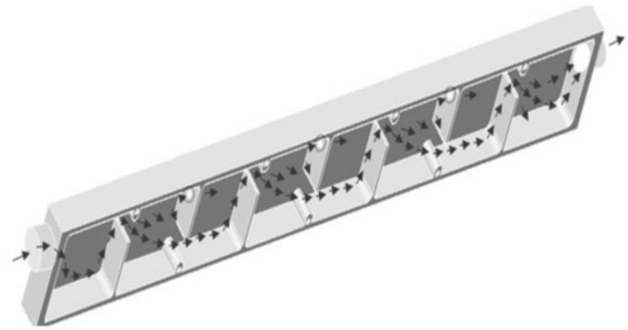

Fig. 4. Interior structure of the hot-side block. Arrows indicate the direction of coolant flow.

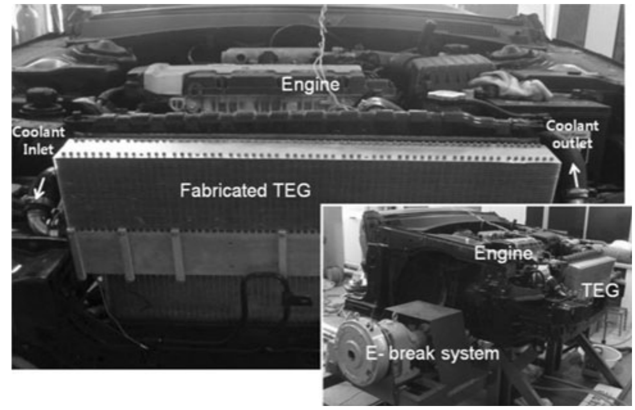


Fig. 5. Fabricated TEG mounted on the test vehicle with engine size of ~2 L. The radiator was replaced by the fabricated TEG.

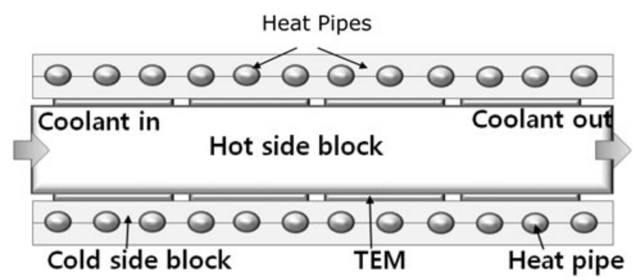


Fig. 6. Bottom-side view of the proposed TEG. Infrared images shown in Fig. 7 correspond to this bottom-side view.

consisting of heat pipes and heat sinks. The heat energy is transferred from the cold-side block to the heat sink by the internal processes of the heat pipes. A heat pipe is a heat transfer device that combines the principles of both thermal conductivity and phase transition to achieve efficient heat transfer between two solid interfaces.[8] At the hot interface within a heat pipe, which is typically at a very low pressure, a pressurized fluid that is in contact with a thermally conductive solid surface turns into a vapor by absorbing the latent heat from the surface. The vapor naturally flows through the system at atomic speeds because of the low pressure, and then condenses back into a liquid at the cold interface, releasing this latent heat. The liquid subsequently returns to the hot interface through either capillary action or gravity action, where it evaporates once more and repeats the cycle. We use an air-cooling mechanism for the heat sink, which is the same method used in conventional engine radiators. We can thus replace the conventional radiator with the proposed TEG without additional devices or redesign of the engine water cooling system.

## EXPERIMENTAL RESULTS AND DISCUSSION

The fabricated TEG was mounted on a test vehicle with an engine size of ~2 L, as depicted in Fig. 5. The fabricated thermoelectric generator has almost the same length and height as the conventional radiator of the ICE vehicle. The test vehicle is a remodeled ICE vehicle simulator with an engine, front-wheel drive train, and electric power brake system. We simulated actual driving conditions on the road using the test vehicle in an indoor experimental laboratory. To monitor the performance of both electricity generation and cooling, the fabricated TEG was mounted on the test vehicle after the radiator was removed. Figure 5 illustrates the experimental setup using the fabricated TEG. During the experiment, we attached 72 bismuth telluride ($Bi_2Te_3$) thermoelectric modules with an area of 4 mm × 4 mm to the TEG. The experiment was performed under both vehicle idle and driving conditions. The temperature profile of the TEG during operation was measured using a thermal imager. Infrared images were obtained from the bottom side of the TEG. Figure 6 depicts the bottom-side view of the proposed TEG. The temperature was measured after the test vehicle was in the steady state. Figure 7 shows an infrared image of the bottom side of the TEG when the vehicle was operating at a driving condition of 80 km/h. Figure 8 shows the temperature profile across the hot-side and cold-side blocks along the straight line in Fig. 7. The temperature distribution of the hot-side block ranged from 90°C to 95°C. The cold-side temperature was ~70°C in idle mode. The temperature difference between the thermoelectric modules was ~25°C. The radiator air-cooling fan of the test vehicle was switched off during the experiment in the idle condition, so there was no cooling air flow assistance.

Figure 9 depicts the measured voltage versus current characteristics of the TEG in the idle condition. The maximum power point is the midpoint of the short-circuit current ($I_{sc}$) and the open-circuit voltage (OCV).[9] In the idle condition, the measured OCV, $I_{sc}$, and power at the maximum point were 30 V, 3.8 A, and 28.5 W, respectively. We installed 72 thermoelectric modules during the experiments, so the maximum output power was ~0.40 W per module at the idle condition.

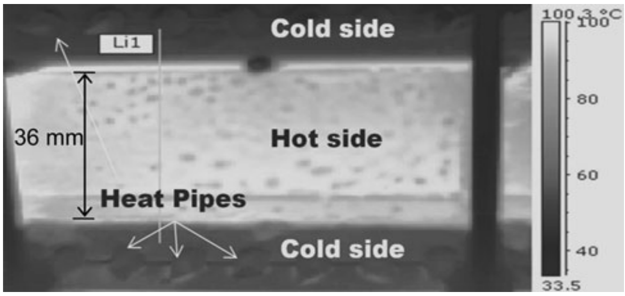


Fig. 7. Infrared image of the bottom side of the TEG when the vehicle was operating in the driving condition at 80 km/h.

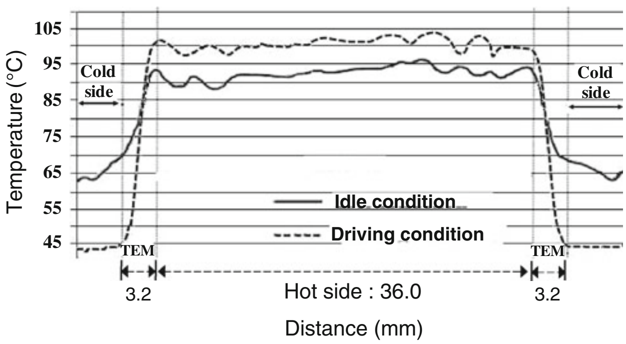


Fig. 8. Temperature profile across the hot-side and cold-side blocks along the straight line in Fig. 7.

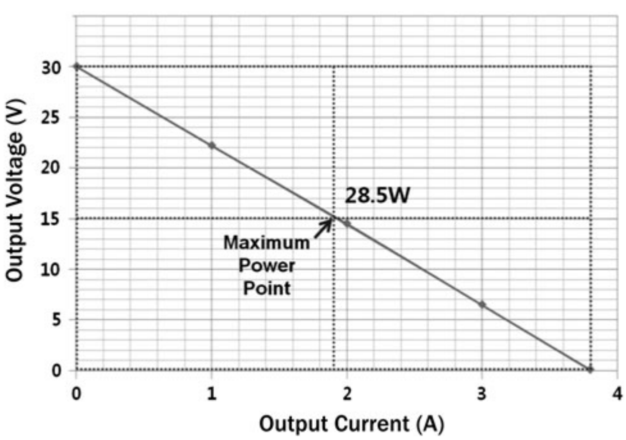


Fig. 9. Voltage versus current characteristics of the proposed TEG when the vehicle was in the idle condition.

When the vehicle was operated in the driving condition at 80 km/h, the temperature distribution of the hot-side block ranged from 95°C to 100°C, and the cold-side temperature was ~45°C. The temperature difference between the hot and cold side of the thermoelectric modules was ~55°C. The cold-side temperature in the driving condition was lower than that in the idle condition, thanks to the assistance of the incoming cooling air flow while the vehicle was running. The radiator air-cooling fan embedded in the test vehicle was switched off during the experiment in the driving mode test. We applied an external fan to supply air flow to simulate the driving mode condition. Figure 10 presents the measured voltage versus current characteristics of the TEG in the driving mode at 80 km/h. The measured OCV, $I_{sc}$, and power at the maximum point were 50 V, 6.0 A, and 75.0 W, respectively. The maximum output power was ~1.04 W per module in the driving condition. In the driving mode, the increment of the hot-side temperature compared with the idle mode was ~5°C. On the other hand, reduction of the cold-side temperature by incoming air-cooling was ~25°C.

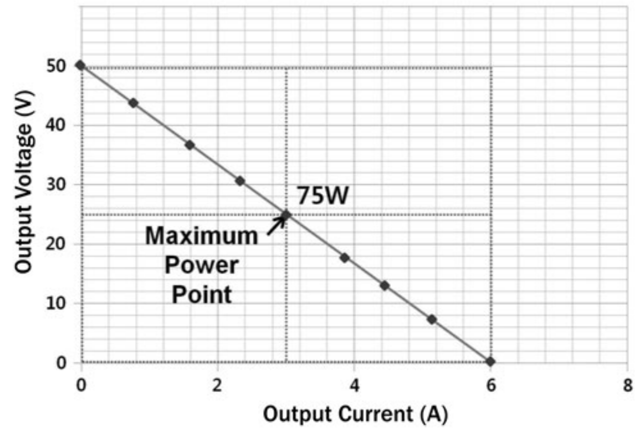


Fig. 10. Voltage versus current characteristics of the proposed TEG when the vehicle was in the driving condition at 80 km/h.

The efficiency of the TEG module in automotive applications can be estimated as[3,4]

$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}},$$

where $ZT$ is the figure of merit, and $T_H$ and $T_C$ are the hot-side and cold-side temperatures of the thermoelectric materials, respectively. We used $Bi_2Te_3$ TE modules with $ZT \approx 0.7$. The calculated module efficiency of the TEG is ~0.9% and 2.1% in the experimental conditions of idle and driving mode, respectively. Because the maximum obtainable output power at the driving condition is 75 W, the overall efficiency of electric power generation from the waste heat of the engine coolant is only ~0.3%. For calculation of the overall efficiency, we assume that the waste heat through the engine coolant is ~22 kW during the driving condition with a 100 HP engine.[4]

## CONCLUSIONS

We proposed and developed a low-temperature thermoelectric generator that uses the engine water coolant of passenger vehicles with an engine size of ~2 L. The experimental results revealed that the maximum estimated output power from the proposed TEG is ~75 W and the calculated module efficiency of the TEG is ~2.1%. The overall efficiency of electric power generation from the waste heat of engine coolant is ~0.3% in the driving mode at 80 km/h. The proposed TEG can replace conventional radiators without additional water pumps or mechanical components of the existing water cooling system of radiators.

## ACKNOWLEDGEMENT

This work was supported by the IT R&D program of MKE (2009-F-007-01). EDA tools were supported by IDEC.

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