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Prediction of the fuel economy potential for a skutterudite thermoelectric generator in light-duty vehicle applications

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HIGHLIGHTS

- Developed and validated a semi-empirical model for fuel saving estimation.
- Fuel saving of a thermoelectric generator used in light-duty vehicle was investigated.
- Thermoelectric generator integration effects has been identified and analysed.
- Installation position has a significant influence on the fuel saving potential.
- DC-DC convector and added weight are the main effects to fuel saving reduction.

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ABSTRACT

Thermoelectric generators (TEGs) have the characteristics of low maintenance, silent operation, stability, and compactness, which make them outstanding devices for waste heat recovery in light-duty vehicles. Significant strides have been made in the high temperature (300–800 °C) thermoelectric materials and recent work is beginning to translate those material improvements into TEG performance. Recently developed modules that incorporate new, competitive formulations of skutterudite form the basis for this study. Vehicular TEGs have not had real commercial applications yet and faced commercialization challenges. Simply estimating the fuel saving potential from the TEG output is not sufficient and due consideration must also be given to the system integration effects. Thus, a new approach for predicting the fuel saving potential of a vehicular TEG while also considering integration effects is developed in this paper. The prediction is based on a recently developed high temperature skutterudite thermoelectric modules [1]. Based on this method, the benefit of a skutterudite TEG is investigated by balancing the benefits with the added complexity of a TEG and improvement measures are explored.

Based on two scenarios of the TEG integrated in different positions of a conventional light-duty vehicle, a semi-empirical model is developed, which includes a quasi-static vehicle model, a dynamic exhaust model, a dynamic coolant model, and a dynamic TEG model. Four integration effects: the additional mass, the power consumption of an electric circulation pump, the effect of exhaust back-pressure and the energy loss in the DC-DC converter, are studied in the semi-empirical model. The evaluation results show the TEG installation position has a significant influence on the fuel saving potential due to the higher quality of the exhaust gas. Placing the TEG closer to the exhaust manifold can increase fuel saving potential by 50%. The four integration effects taken together cause a 25% reduction of fuel saving potential. The energy loss in DC-DC convector and added weight are the main contributors to this reduction. An optimised design for the TEG installation operating under an optimised control strategy delivers a fuel consumption reduction of 4% over the constant-speed 120 km/h driving cycle.

1. Introduction

Based on the typical energy flow path of an internal combustion engine (ICE), approximately one third of the energy is discharged through the exhaust flow [2–4]. A thermoelectric generator (TEG) can convert a proportion of the otherwise wasted thermal energy of the exhaust gas to electricity directly for use in the vehicle systems. Higher degree of electrification is being driven by conventional ICE vehicles for

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enhanced driving experience, safety and efficiency, making electric recovery more useful [5]. Besides, compared with other waste heat recovery (WHR) technologies such as organic Rankine cycle and turbocompounding, TEG has the advantages of low maintenance, silent operation, stability, and compactness. All of these advantages in addition to the increasingly demanding CO_2 emissions requirements for passenger cars [6] make the TEG an attractive option for conventional light-duty vehicles. Nevertheless, considerable technical challenges for TEG integration remain. The two main challenges include:

- Low conversion efficiency and low maximum operating temperature dictated by the properties of the chosen thermoelectric materials
- Integration effects arising from increased mass, increased exhaust backpressure, and installation complexity

Many efforts have been made in the development of improved thermoelectric materials during the last few years. Bismuth telluride (Bi_2Te_3) is the well-known thermoelectric material and has already been proposed for WHR. Car manufacturers and their suppliers have successfully demonstrated the use of Bi_2Te_3 in TEG systems [7]. However due to the limit that the use of Bi_2Te_3 places on the hot side temperature, an exhaust by-pass proved necessary. Since a lot of thermal energy at high temperature escaped without recovery, the efficiency of the Bi_2Te_3 TEGs were less than 5% [7–9]. Thus, the most promising and practical materials for a vehicular TEG in WHR would be materials designed to withstand high temperatures. This means larger temperature gradients can be achieved with this material and thus more power and higher efficiency could be potentially achieved. Skutterudite thermoelectric materials have shown good potential for higher efficiency at higher temperature (500 °C) based on a number of recent material and module test results. Garcia et al. [10] fabricated skutterudite module, which provides more than $1.5\ W\ cm^{-3}$ volume power density at a temperature difference of 365 K. Nie et al. [11] demonstrated excellent stability of their skutterudite module with 7.2% conversion efficiency. Yang et al. developed skutterudite module with $1.4\ W\ cm^{-3}$ volume power density at a temperature difference of 365 K [1]. The operating temperature range of skutterudite is better matched to automotive applications, especially for gasoline engines. Consequently, an increased TEG efficiency can be expected. Recent work is beginning to translate those material improvements into TEG performance. Compared with the strides in thermoelectric materials development, the integration challenges have also been studied. Since the TEG represents another component in the exhaust system, its integration presents challenges. The fuel economy benefit could be compromised through a number of integration effects:

- Added mass
- Power consumption of an electric circulation pump
- Increased exhaust backpressure
- Energy loss in DC-DC converter

All of the listed effects above may lead to a significant reduction in the fuel saving potential of a TEG in vehicle application. Rowe et al. [12] identified the added weight penalty for a TEG applied in a 1.5L family car. For a 13 kg mass TEG, at least 156 W electrical power had to be generated in order to compensate for its added weight penalty. Li et al. [13] proposed a novel design for a concentric cylindrical TEG system for use in the automotive exhaust system with a compact and lightweight heat sink. Instead of using a bulky and heavy heat exchanger, this innovative design combined the heat pipes with heat exchanger, which reduced the weight of the TEG system and the whole vehicle as well, consequently improving the fuel economy. Deng et al. [14] investigated the compatibility of engine-cooling system when a TEG cooling unit was integrated. Based on both simulation and experimental data, it was found out that the temperature of the integrated cooling system is 5 °C more than that of the primary engine cooling system. More powerful water pump and cooling fans were recommended to reduce the effect of the TEG cooling unit. He et al. [15] optimized the heat exchanger of TEG by considering engine power loss caused by exhaust backpressure. It was found out that the engine power loss increased linearly with exhaust backpressure and the influence of backpressure could be reduced by optimizing the dimensions of the hot side heat exchanger. Cao and Peng [16] proposed a multiphase multilevel DC-DC conversion networks based on a 630 W TEG prototype for automotive applications. The proposed DC-DC conversion networks could effectively reduce the power loss in DC-DC converter from 5% of total TEG power output to about 3%.

This view of the literature strongly suggests that integration effects are sufficiently significant that they must be taken into account in evaluating the potential fuel economy improvement. However, the integration effects are usually neglected in the TEG performance prediction [17–19]. Therefore, the goal of the paper is to investigate, for the first time, the integration effects on the fuel saving potential of a skutterudite TEG applied in a light-duty conventional ICE vehicle. In contrast to the previous TEG performance prediction methods [17–19], which only predicts the electric power output, this proposed approach can further estimate the fuel saving percentage of TEG. Another novelty of this paper is that relatively complete experimental validations are conducted with experiments on both engine and recent developed skutterudite TEG prototype.

2. TEG integration into a light-duty vehicle

2.1. TEG integration scenario

New technology is usually firstly adopted in high-end cars and then gradually being used in standard cars. Consequently, for the purposes of this study, the TEG is assumed to be integrated in a 2 l-gasoline and D-segment passenger car whose specification is shown in Appendix A. The TEG integrated into the exhaust system converts part of the exhaust energy into electricity and through the DC-DC converter the regenerated electrical power is converted to fit the electric system of the car (Fig. 1(b)). Therefore, the load on the alternator is relieved and engine torque dragging the alternator is reduced, so is the fuel consumption. The method of calculation to quantify this fuel consumption reduction will be detailed later in this paper.

There are a few possible installation positions for the TEG in the exhaust line, such as upstream of the three-way catalytic (TWC), downstream of the TWC, and downstream of the muffler. Considering the optimal efficiency of the skutterudite materials in its temperature range, positioning the skutterudite TEG downstream the muffler significantly reduces the available exhaust gas temperature and conversion efficiency. Thus, with a typical gasoline engine exhaust system featuring a close-coupled catalyst (CCC) and a main TWC, there are two conceivable TEG installation positions: between CCC and main TWC (scenario 1) and downstream of main TWC (scenario 2). Fig. 1(a) shows the integration scenarios of TEG in the exhaust line.

Apart from the integration of TEG in the exhaust line, the TEG also needs to be integrated with the vehicular cooling circuit, which absorbs the heat drawn from the exhaust gas. The lower the coolant intake temperature of TEG, the higher the electric power output of the TEG. Thus, maintaining the cold side temperature of TEG with cold coolant from the radiator outlet is set as the integration scenario for both scenario 1 and scenario 2. The operation of thermostat valve can prevent coolant from flowing to the TEG. Thus, an electrical water pump is added to form an independent coolant circuit. As can be seen from Fig. 1(b) that the added electrical water pump circulates the coolant through the cold side of TEG and the radiator. The heat from the engine and the TEG are both rejected to the ambient air through the radiator.