Applied Energy 218 (2018) 391–401

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance evaluation of an automotive thermoelectric generator with inserted fins or dimpled-surface hot heat exchanger

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HIGHLIGHTS

- A virtual platform to assess the performance of an on board TEG is constructed.
- The backpressure could be reduced by 20.57% in the ATEG with dimpled surface.
- The net power output of the ATEG with dimpled surface could be improved by 173.60%.
- The efficiency of the ATEG with dimpled surface is 0.68%.

ARTICLE INFO

Keywords:
TEG
Hot heat exchanger
CFD
Inserted fins
Dimpled surface

ABSTRACT

A virtual evaluation method that computational fluid dynamics combines with a mathematical model was proposed to compute the temperature distribution and final power output of an onboard automotive thermoelectric generator (ATEG), which was configured for an off-road vehicle called Mengshi. A road test was conducted to validate the accuracy and reliability of the virtual evaluation method. The output power and voltage of the ATEG in the road test showed that the virtual evaluation method exhibited satisfactory accuracy in predicting the performance of the ATEG and could provide effective guidance for the design of the ATEG. Furthermore, dimpled surfaces were introduced to replace the inserted fins in the conventional hot heat exchanger to reduce the pressure drop but maintain the temperature difference between the hot and cold end of the ATEG. Computational results showed that, compared with the ATEG with inserted fins, the pressure drop in the ATEG with dimpled surface was reduced by 20.57%, and the net power output was increased by 173.60%.

1. Introduction

Warm climate and serious environmental pollution are the most significant challenges for human beings in the 21st century. In the fossil fuel consumption structure, a large proportion of fossil fuel is consumed by vehicles. Vehicle emissions are one of the main reasons for global warming and pollution, and internal combustion engines operate only at approximately 25–35% efficiency with approximately 30–40% of energy loss through the exhaust. Therefore, recovering the waste heat in the exhaust is an effective approach to conserve energy and reduce the emission of vehicles. In recent developments in waste heat recovery, the thermoelectric technique has demonstrated many advantages in generating clean electricity through the thermoelectric generator (TEG). The TEG can convert heat into electricity in an eco-friendly manner, with temperature difference between hot and cold ends without any pollution. Moreover, the compact structure of the TEG without moving parts could reduce maintenance cost, vibration, and noise. For practical applications in vehicles, approximately several hundred watts of power can be generated in different experimental conditions to increase the fuel efficiency of vehicles. Many experiments involving bench and road tests exhibited a high performance [1–6]. Although the TEG offers many benefits, the low conversion efficiencies limit their applications. Recently, the rapid development of thermoelectric materials can significantly promote the performance and application forms of TEG. However, thermoelectric materials with high ZT that have been developed in the laboratory still need a long time to introduce into the large-scale commercial application [7]. Furthermore, when the thermoelectric modules are embedded into a thermoelectric system, the hydraulic-thermal-electric multi-physics interaction of the entire system was more important than the intrinsic thermoelectric

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https://doi.org/10.1016/j.apenergy.2018.02.176
Received 7 December 2017; Received in revised form 27 February 2018; Accepted 28 February 2018

material to the conversion efficiency of the thermoelectric system [8]. Thus, the system-level design and optimization of the TEG are important to offset the margin between conversion performances of the thermoelectric material and the thermoelectric system [9]. Early conceptual design, theoretical analysis and performance evaluation are very important to obtain a reasonable design of a TEG.

To obtain a reasonable design of a TEG and improve the efficiency of the TEG in the early stage, Computational fluid dynamic (CFD) was often used to evaluate the thermal and hydrodynamic performance of a TEG, such as temperature difference, pressure drop and temperature uniformity. For instance, Hsu et al. [10] introduced the CFD to discuss the influence of the slopping block on the thermal field distribution. Wang et al. [11] discussed the thermal performance of TEGs with different heat pipes by CFD. Musial et al. [12] revealed the influence of a dispersion cone on the temperature distribution in the hot heat exchanger of a TEG. Furthermore, to get more uniform temperature distribution, CFD also can be used for optimizing the design of TEG heat exchanger [13–15].

Otherwise, based on the given heat source or temperature difference, several mathematical models have been constructed to evaluate the output power and conversion efficiency of TEGs. For instance, Wang et al. [16] presented a mathematical model of a TEG using the exhaust gas of vehicles as heat source, and analyzed the influence of heat transfer coefficient, the height of the PN couple, the ratio of external resistance to internal resistance on the output power and efficiency of TEGs. Ali et al. [17] proposed a mathematical model to analyse the thermoelectric performance of a TEG with extended and segmented pins configuration. Lan et al. [18] developed a dynamic model of TEG system designed for vehicle waste heat recovery, and carried out experiment to validate the model by thermoelectric module test rig and TEG engine test bench. Kwan et al. [19] constructed a hybrid mathematical model for a hybrid photovoltaic cell and TEG system. Based on the hybrid model, the dynamics performance was revealed. Moreover, the mathematical model coupled with transient inputs could estimate the dynamic response of vehicle exhaust heat recovery [20,21]. Further validation showed that the mathematical model could provide an accurate prediction of the electrical performance of thermoelectric devices. To simulate the onboard environment, mathematical models coupled with vehicle or engine simulation software, such as ADVISOR, AMESim, and GT-POWER, were used to evaluate the performance of thermoelectric devices [22–24]. Undeniable, the theoretical model constructed on the basis of thermoelectric and thermodynamic theory was quite helpful to improve the conversion efficiency of TEG and significant to improve the design of thermoelectric module. However, almost without exception, the aforementioned mathematical models were often used in 1D simulation and a TEG with one thermoelectric module, also the heat source was often a hypothetical.

The above literature review revealed that the thermal and electrical investigation was often separated and disconnected. Obviously, this separation is deficient to design and evaluate the performance of TEG. Therefore, Borcuch et al. [25] proposed a method that the CFD coupled with some simplified mathematic formulas to analyse the fins geometry of a hot-side heat exchanger on the performance parameters of a TEG. Weng [26] conducted a CFD simulation for a TEG consisting of a heat exchanger and several thermoelectric modules. The power generated was calculated using the temperature distribution on the two sides of the thermoelectric modules. Wang [27] also used a similar approach to investigate the thermal and electrical performances of a TEG system composed of a heat exchanger, a coolant, and thermoelectric modules. However, these approaches were not validated by experiments. Li [28] proposed a numerical simulation method that the CFD coupled with a finite element (FE) model of the thermoelectric module to evaluate the thermal performance and electrical performance of a TEG with one thermoelectric module. The further experiments also validate the reliability of this method. However, for the simulation of a large scale TEG system with hundreds thermoelectric modules, the construction of FE models was quite difficult and the expenditure of computational resources was also quite huge. Moreover, the CFD coupled with a mathematical model had been used to investigate the thermal and electrical performance of some simple TEGs. However, for an onboard complex automotive thermoelectric generator (ATEG) which composed of multiple sub-TEGs and integrated with the engine cooling system, there are hundreds of thermoelectric modules and the flow inside the exhaust pipe is dynamically changed, the use of the approach that the CFD coupled with a mathematical model to analyse its performance has not yet been reported to date. Therefore, in current research, in view of the effectiveness in providing a precise prediction of flow field and heat transfer, the CFD was used to determine the flow state, temperature distribution and heat transfer in a vehicle-mounted complex ATEG. In view of the feasibility in theory, a proven mathematical model was used to calculate the output power and voltage of an ATEG. Furthermore, a road test was carried out to validate the reliable accuracy of the approach that CFD coupled with a mathematical model in the prediction of thermal and electrical performances in a vehicle-mounted complex ATEG.

In general, the installment of an ATEG on the exhaust system increases backpressure, which adversely affects the efficiency of the internal combustion engine. For instance, for a 7.79 L IVECO engine, once the backpressure exceeds the point where engine performance starts to deteriorate, the fuel consumption would increase by approximately 3.1% when backpressure is increased to 10 kPa [29]. Moreover, the installation of several fins [30], inserts [31], protrusions [32] or longitudinal vortex generators [33,34] inside the heat exchanger to enhance the heat transfer and ensure a uniform temperature distribution on the surface of the hot heat exchanger also will result in a further increase in backpressure. Hussain [24] revealed that, when an ATEG is installed on a hybrid vehicle with an Atkinson cycle engine, approximately 330 W time-averaged cycle power can be obtained by the EPA highway test, but the backpressure of the exhaust system increases from 2.57 kPa to 5.59 kPa. The research carried out by Massaguer [35] further revealed that the pressure drop played a key role in designing an automotive TEG for real applications. Therefore, for the design of a TEG, less pressure loss and more efficient heat transfer in the hot heat exchanger are vital to the performance of a TEG. To improve the performance of the TEG, the geometry optimization design for the geometry of the TEG was the most common approach [36,37]. In current research, to reduce the backpressure of the exhaust system induced by the introduction of the ATEG, a hot heat exchanger with non-smooth dimpled surfaces [14] was introduced as hot end of the ATEG. Finally, the effect of the hot heat exchanger with dimpled surface on the performance of the ATEG was revealed by comparing the temperature difference, pressure drop, net power output and thermo-electric conversion efficiency with a traditional ATEG whose hot end was a heat exchanger with inserted fins.

2. Computational method and procedure

2.1. Geometry and meshing

The onboard complex ATEG used in this study was configured for an off-road vehicle called Mengshi manufactured by Dongfeng Motor Corporation, which was equipped with a 3.9L Commins four-cylinder inter-cooled turbocharged diesel engine. The physical model of the vehicle and ATEG and the installation of the ATEG are illustrated in Fig. 1. The temperature difference of the ATEG was maintained by the heat supplied by the exhaust gas and the coolant shared with the engine cooling system. Four sub-TEGs were used in the current study to recover waste heat as much as possible. A total of 240 thermoelectric modules were arranged on the exterior surface of the hot heat exchanger. The entire system was encapsulated inside a metallic cuboid for waterproofing. Finally, the overall size of the ATEG was 1420 mm in length, 670 mm in width, and 185 mm in height, and the overall weight