Energy 84 (2015) 121–130

Contents lists available at ScienceDirect

Energy

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

Comparison and parameter optimization of a segmented thermoelectric generator by using the high temperature exhaust of a diesel engine

Hua Tian [a], Xiuxiu Sun [a], Qi Jia [b], Xingyu Liang [a, *], Gequn Shu [a, **], Xu Wang [c]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China
[b] AVIC Shenyang Engine Design and Research Institute, Shenyang 110015, China
[c] School of Aerospace, Mechanical and Manufacture Engineering, RMIT University, Bundoora, Victoria 3083, Australia

ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form
31 December 2014
Accepted 19 February 2015
Available online 25 March 2015

Keywords:
Conversion efficiency
Diesel engine
Output power
Performance optimization
Segmented thermoelectric generator
Waste heat recovery

ABSTRACT

This paper proposes a segmented thermoelectric generator (TEG) that can be used to recover exhaust waste heat from a diesel engine (DE). A mathematic model of the segmented TEG was constructed based on the low-temperature thermoelectric material bismuth telluride and the medium-temperature thermoelectric material skutterudite. Performance was compared between segmented and traditional TEGs, and the performance of the segmented TEG was optimized based on the comparison. The model simulates the impact of relevant factors, including the exhaust temperature, cold source temperature, thermocouple length, and the length ratio between the two materials, on the output power and conversion efficiency. The results showed that the segmented TEG is more suitable than the traditional TEG for a high-temperature heat source and for large temperature differences. Moreover, the maximum output power was inversely proportional to the thermocouple length; however, the maximum conversion efficiency was directly proportional. The ratio of the two materials depended on the temperature of the heat and cold source. Finally, a comparison of application potential of the TEGs showed that the segmented TEG had greater potential for waste heat recovery compared with the traditional TEG.

1. Introduction

A diesel engine (DE) is one of the main components of petroleum-consuming motors, as well as the main source of greenhouse gas emissions. Research on energy-saving measures in DEs is critical for energy conservation and emission reduction. More than 30% of the energy generated by the combustion of fuel in DEs is converted to waste heat and discharged from the exhaust, resulting in wastage of fuel and environmental pollution [1]. If the waste heat contained in exhaust gas could be effectively reused, the thermal efficiency of the DE would improve considerably.

A thermoelectric generator (TEG) offers numerous advantages, such as the absence of moving parts, absence of friction, and high stability, in addition to being environmentally friendly. Thus, TEGs have become a research focus in view of their use in recovering the waste heat of DEs [2]. A collaborative project to develop a 300 W TEG to be mounted on a GM Sierra pickup truck was initiated by Clarkson University and Delphi Systems, and it was funded by NYSERDA and the Department of Energy [3]. Experimental results showed that the maximum power produced was only 255.1 W during road testing at 112.65 km h^{-1} [4,5]. The targeted 300 W power could not be achieved. GM Research installed a TEG on the exhaust pipe to recover waste heat. The exhaust waste heat recovery system generated an average of approximately 350 W for the Federal Test Procedure cycles, which corresponds to nearly 3% fuel economy improvement [6]. Volkswagen has claimed to obtain 600 W power generation from a TEG under highway driving conditions. TEG-produced electricity can reportedly result in more than 5% reduction in fuel consumption [7]. The Ford Motor Company developed a detailed one-dimensional model to characterize the performance of TEGs. The model predicted the potential of a 2.5 L gas-electric hybrid vehicle to generate 300–400 W under highway drive cycle conditions [8].

Low conversion efficiency is a crucial factor restricting the development of TEGs. Numerous studies have been conducted on

---

* Corresponding author. Tel.: +86 13512277142.
** Corresponding author. Tel.: +86 02227409558.
E-mail addresses: lxy@tju.edu.cn (X. Liang), sgq@tju.edu.cn (G. Shu).

http://dx.doi.org/10.1016/j.energy.2015.02.063
0360-5442/

improving the conversion efficiency of TEGs, and techniques. Xiao et al. [9] compared the performance of three TEGs: single-stage, two-stage, and multistage TEGs. The results showed that a reasonable thermal design for TEGs can be obtained by exploiting the characteristics of thermoelectric materials so as to the power generation performance. Horst et al. [10] developed a dynamic model of the exhaust gas heat exchanger employing the moving-boundary principle. Kim [11] derived an analytic model describing the internal temperature difference as a function of the load current of a TEG. Anatychuk and Kuz [12] analyzed the materials of TEG. Chen et al. [13] proposed a two-stage TEG structure, which is useful for understanding the design and applications of practical TEGs. Gou et al. [14] established a TEG model based on basic principles of TEG and finite time thermodynamics. Meng et al. [15] developed a complete three-dimensional transient model to investigate the dynamic response characteristics of TEGs. Shu et al. [16] applied a method in which a TEG was combined with the Organic Rankine cycle to recover waste heat on internal combustion engine. Wang et al. [17] worked on two-stage optimization of heat exchanger to improve the performance of a TEG; the TEG output power density increased by 88.70%. Sahin and Yilbas [18] studied thermoelectric generator performance from an irreversible perspective. The output power and conversion efficiency of TEGs have a close relationship with entropy generation. Weng and Huang [19] explored the relationship between quantities of TEMs, revealing that using increasing the number of thermocouples does not necessarily increase the total generated power; TEGs have an optimal structure for improving conversion efficiency. This paper proposes using a segmented TEG to recover the waste heat of DEs and optimizing the TEG structure.

It is necessary to optimize the structure of the segmented TEG because of the characteristics of the exhaust and thermoelectric material. The ratio of the thermoelectric material, the number and the length of the thermocouples can be obtained by optimizing the structure of segmented TEG. The exhaust temperature of DEs is shown in Fig. 1, which is approximately 523 K at low engine loads and exceeds 813 K at high engine loads. Some studies have shown that the value can exceed 500 K [20,21]. The main engine specifications are shown in Table 1. The exhaust temperature is measured after the turbine. The ZT value is the thermoelectric figure of merit, which can represent the capability of thermoelectric material of directly converting thermal energy into electrical energy. The ZT value is closely linked with the temperature (Fig. 2). A temperature difference can be introduced between the two sides of a TEG for recovering the exhaust heat. The ZT value changes considerably for one material in such conditions. Therefore, the segmented thermoelectric generator has been proposed under conditions of a high-temperature heat source and a large temperature difference between the two sides of a TEG.

Table 1
Diesel engine specifications.

Diesel engine	
Model	YC6L330-30
Type	Turbocharged intercooled
Cylinder number	6
Bore	113 mm
Stroke	140 mm
Displacement	8.424 L
Compression ratio	17.5:1

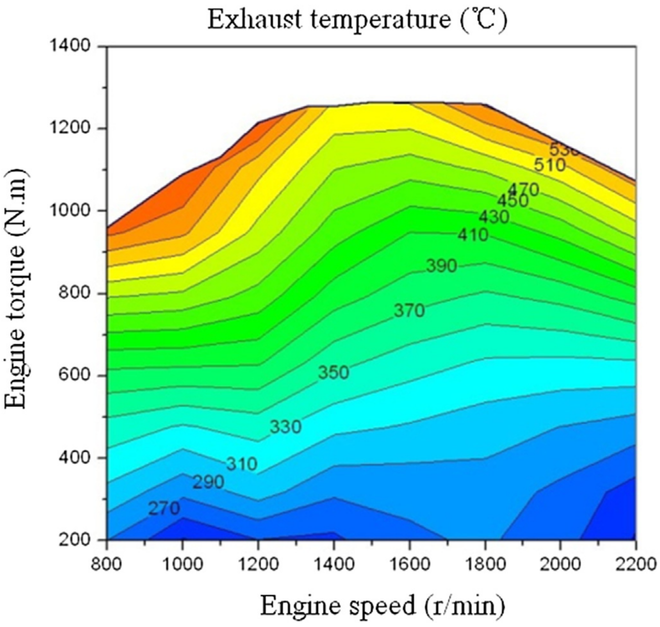

Fig. 1. Exhaust gas temperature.

Numerous studies have focused on the physical properties of segmented TEG [22–24]; however, it is extremely crucial to optimize the structure of segmented TEGs. In the present study, a segmented TEG model was constructed compared with a traditional TEG and the performance characteristics of the segmented TEG under various boundary conditions have also been discussed, which include temperatures of the heat and cold sources and various lengths of the thermocouple leg. The optimized structure and application potential of the segmented TEG were studied in detail. Based on these analyses, the best performance of the segmented TEG is determined, which may provide guidance in the design and application of segmented TEG in DE.

2. Mathematical model of segmented thermocouple

2.1. Governing equations

A typical one-thermoelectric-module TEG consists of numerous thermocouples. For simplifying calculations, only one segmented thermocouple was analyzed in the present study. The preliminary discussion on performance of segmented TEG has been researched in the steady state of DE. The structures of the segmented and traditional thermocouples are shown in Fig. 3(a) and (b). The P or

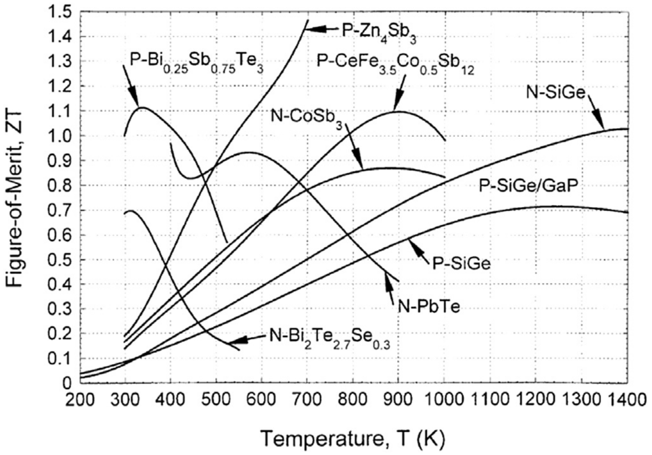

Fig. 2. Comparison of ZT values versus temperature for various materials up to 1400 K [25].