Journal of the Energy Institute 89 (2016) 271–281

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

An experimental study of a novel prototype for two-stage thermoelectric generator from vehicle exhaust

Changxin Liu [a, b, d], Xinxiang Pan [a], Xiaofeng Zheng [b], Yuying Yan [b], Weizhong. Li [c, *]

[a] Marine Engineering College, Dalian Maritime University, Dalian 116026, PR China
[b] Energy and Sustainability Research Division, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[c] School of Energy and Power Engineering, Dalian University of Technology, Dalian 116023, PR China
[d] School of Mechanical and Power Engineering, Dalian Ocean University, Dalian 116023, PR China

ARTICLE INFO

Article history:
Received 18 March 2013
Accepted 8 September 2014
Available online 29 January 2015

Keywords:
Thermoelectric power generation
Thermoelectric module
Exhaust heat recovery
System modeling
Thermal efficiency

ABSTRACT

For the vehicle engine, about 30% of the primary energy is discharged as waste heat in the exhaust gases. The recovering of heat from that is a noticeable promising application of thermoelectric power generation (TEG). In this paper, a novel prototype for two-stage TEG from vehicle exhaust has been proposed. After system modeling, an experiment structure has also been built and tested for further study. Results of both theoretic analysis and experiment show the reasonability for exhaust heat recovery. The prototype can generate a maximum power output of about 250 W when operating at hot side temperature 473 K. The system thermal efficiency can reach 5.35%, it is improved by 32% compared to 4.04% of single stage TEG in the same operating conditions. System optimization and future improvement of the prototype is also discussed. Finally, based on a vehicle made by our research funder, economic value for commercialization in diesel vehicles has been analyzed.

1. Introduction

According to the current assessment of vehicle engine, about 60% of the fuel energy is not used effectively [1]. If approximately 6% of the exhaust heat could be converted into electrical power, it would be possible to reduce the fuel consumption around 10% [2,3]. Increased concerns over vehicle fuel economy and exhaust emissions lead thermoelectric technology to be profitable in the automobile industry. Thermoelectric power generators (TEG) have many distinct advantages over other technologies [4–8]:① operate extremely reliably and silently; ② simple, compact and safe; ③ require less maintenance; ④light in weight and small in size; ⑤ capable of elevated temperatures operation; ⑥ suitable for small-scale and remote applications; ⑦ environmentally friendly; ⑧ position-independent; ⑨available for flexible power sources.

Xu et al. [1] build a test rig to study the performance and economic analysis of TEG based on Dongfeng EQ14021 truck. Yodovard et al. [9] assess the waste recovery potential of TEG for gas turbine and diesel cycle cogeneration. It is shown that gas turbine and diesel cycle cogeneration systems can generate electricity at 33% and 40% of fuel input, respectively. The useful waste heat from stack exhaust of the system was estimated at 20% for a gas turbine and 10% for the diesel cycle. The Nissan Research Centre [10–12] has developed TEGs for different temperature ranges with a shape similar to Birkholz, U [13].

But only one stage TE module is employed in those TEGs. Due to the performance limits of thermoelectric materials, TEG of two stages or more should be applied to improve the performance. There are few studies for the performance analysis and optimization of two-stage TEG except for Zhou [14]and Chen [15]. They built a model of two-stage TEG and analyzed the performance of it. Yan and his team [16–19] also make some achievements in the field of TEG with both single-stage and multi-stage for heat recovery.

In previous studies, the TE module is mainly attached directly to the external of exhaust pipe. There are some disadvantages:

A. The different engine operating conditions cause the exhaust temperature to vary, even at the same point of the exhaust pipe. This affects the performance of the TE modules, and hence the electrical power generated.

* Corresponding author. Tel.: +86 (0) 411 84708774.
E-mail address: wzhongli@dlut.edu.cn (Weizhong. Li).

http://dx.doi.org/10.1016/j.joei.2015.01.019
1743-9671/

B. Temperature range of the vehicle exhaust varies greatly from 500 K to 1200 K. But the normal TE module such as Bi_2Te_3 has a limited operating temperature range. Attaching TE module directly to the external exhaust pipe may increase the risk of burning TE modules.
C. The exhaust pipe section used for TEG has uneven temperature distribution. The closer to the muffler, the lower the exhausts temperature is. That means it is usually need to purchase TE modules with a maximum operating temperature of 600 K, but make some of them work at a temperature of 400 K. And most TE materials exhibit peak performance at or near their maximum temperature limits. Thus, it is desirable to operate them near this limit and keep a steady hot side temperature.

In order to overcome disadvantages of the above, this paper proposes a novel two-stage TEG prototype based on some performance tests of the TE module. This novel method has the following advantages:

A. The conducting oil can play a role of heat storage;
B. Heat storage layer can minimize the impact of a sudden significantly exhaust temperature variation to the TE module and play a role of protection;
C. This approach allows the pipe section used for TEG has a more even temperature distribution and all the mounted TE modules can work near their optimum performance for the most common working point of the engine.
D. Two stage TE modules can significantly improve the efficiency and power output.

2. Two-stage TEG system modeling

Fig. 1 is the schematic diagram of a two-stage TEG consisted of a top stage with m pairs of thermoelectric elements and a bottom stage with n pairs of thermoelectric elements. The total number of pairs is M, i.e. M = m + n [14,15].

Assuming that the heat-transfers between the hot and cold junctions of the TEG and their respective reservoirs obey Newton's law, the following equations apply at the three junctions:

$$Q_H = k_1F_1(T_H - T_1) = m\alpha IT_1 - mI^2R/2 + mK(T_1 - T_m) \quad (1)$$

$$Q_m = m\alpha IT_m - mI^2R/2 + mK(T_1 - T_m) = n\alpha IT_m - nI^2R/2 + nK(T_m - T_2) \quad (2)$$

$$Q_C = k_2F_2(T_2 - T_C) = n\alpha IT_2 - nI^2R/2 + nK(T_m - T_2) \quad (3)$$

where $\alpha = \alpha_p - \alpha_n$, α_p and α_n are the Seebeck coefficients of the p-and n-type semiconductor legs for each TE modules, Q_m is the rate of heat flow between the two stages in the system. T_1 is the hot-junction temperature, T_2 is the cold-junction temperature, and T_m is the temperature of the junction between the two stages. T_H and T_L is the temperature of the heat source and cold source, respectively. For the generator, the rate of heat transfer at the hot junction is Q_H, and the rate of heat transfer at the cold junction is Q_C. The power output is P. The electrical resistance of the external load is R. Assume that the two heat exchangers between the hot and cold junctions of the TEG and their respective reservoirs are for counter flows, and the heat conductance of the heat exchangers are k_1F_1 and k_2F_2, respectively, where k_1, k_2 (W/m^2 K), F_1, and F_2 are heat transfer coefficients and heat-transfer surface-areas of the two heat-exchangers, respectively. K is thermal conductance of the semiconductor couple (W/K). m, n presents the number of $P\&N$ junctions for the first and the second stage, respectively.

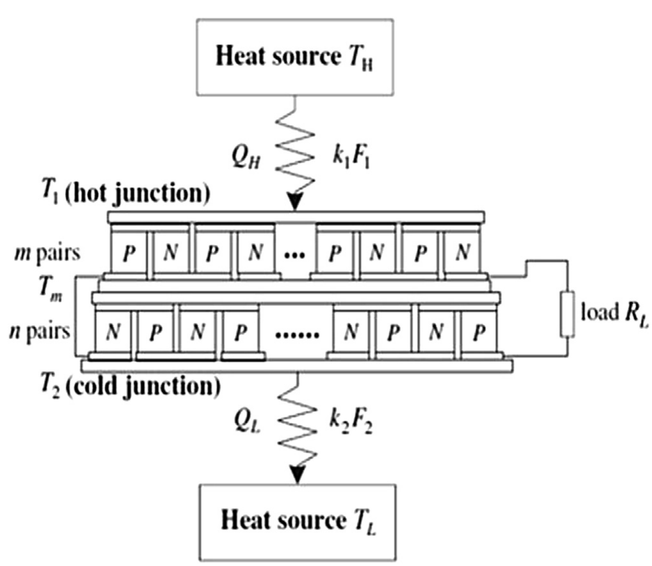

Fig. 1. A schematic diagram of a two-stage semiconductor thermoelectric-generator.