ARTICLE IN PRESS

Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Experimental study on the influence of porous foam metal filled in the core flow region on the performance of thermoelectric generators

Yanzhe Li, Shixue Wang *, Yulong Zhao, Chi Lu

School of Mechanical Engineering, Tianjin University, PR China
Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Ministry of Education, Tianjin University, PR China

HIGHLIGHTS

- Experiment using TEG to recover the exhaust heat of automobile is performed.
- Foam metal is applied to improve the efficiency of TEG.
- Core flow heat transfer enhancement is used to improve the efficiency of TEG.
- The effect of different PPI foam metal on the TEG has been analyzed.

ARTICLE INFO

Article history:
Received 2 February 2017
Received in revised form 19 June 2017
Accepted 28 June 2017
Available online xxxx

Keywords:
Thermoelectricity
Metal foam
Waste heat recovery
Heat-transfer enhancement
Core flow

ABSTRACT

Semiconductor thermoelectric generator technology is a new type of power generation technology. The use of semiconductor thermoelectric power generation technology for automobile exhaust heat recovery and utilization can effectively improve energy efficiency. In this study, a test system is set up to simulate the automobile exhaust, and the effect of core flow heat-transfer enhancement on the performance of the thermoelectric generator is investigated using thermoelectric module Bi_2Te_3 to recover the waste heat from automobile exhaust and convert it into electrical energy. The results show that filling foam metal can significantly improve the performance of the generator. The convective heat-transfer coefficient of the channel increases by four times, and the output power of the thermoelectric generator is doubled when the intake flow rate is 120 m^3/h, the inlet temperature is 300 °C, the pore density of the foam metal is 20 pores per inch, and the filling rate of the foam metal is 75%. In addition, the improvement in the performance of the generator is different under different intake air flows, different foam-metal filling rates, and different pore densities.

1. Introduction

With the development in the automobile industry, energy consumption of vehicles has increasingly become serious. Recovery and utilization of waste heat of the automotive exhaust gas have attracted increasing attention from all walks of life. Semiconductor thermoelectric generator technology is a new type of power generation technology. The use of semiconductor thermoelectric power generation technology for automobile exhaust heat recovery and utilization can primarily effectively improve energy efficiency. The working principle of a semiconductor thermoelectric generator is based on three basic concepts [1]: Seebeck, Peltier, and Thomson effects. Compared with other power generation methods, the power generation process is noiseless and has no wear and medium leakage. In addition, the module enjoys the advantages of small volume, light weight, convenient movement, and long service life. Thus, it is very suitable for waste heat recovery and utilization system, especially in low-grade energy utilization. The low-grade heat energy can be directly converted into high-grade electrical energy. This technology is very attractive for the recovery and utilization of waste heat from automobile exhaust. As early as 1988, Birkholz et al. [2] proposed a method that used the waste heat from a car exhaust to generate electricity and tested it on a Porsche car. Dozens of watts was generated in this experiment. In 1998, Nissan Co. of Japan developed a thermoelectric generator consisting of 72 thermoelectric modules for the recovery of waste heat from vehicle exhaust. When the car was climbing at a speed of 60 km/h, the temperature difference between the cold and hot sides of the thermoelectric module was approximately 386 K, and the output power of the thermoelectric generator was

* Corresponding author at: School of Mechanical Engineering, Tianjin University, PR China.
E-mail address: wangshixue_64@tju.edu.cn (S. Wang).

http://dx.doi.org/10.1016/j.apenergy.2017.06.089
0306-2619/

approximately 950 W [3]. In 2001, HI-z Co. of the U.S. arranged 72 pieces of thermoelectric modules along the circumference of a Cummins 250-kW diesel truck exhaust pipe and found that under a temperature difference of 250–270 K, 30-V/1-kW power could be generated using the device [4]. Gou [5] made a number of recommendations to improve the performance of thermoelectric generators, such as increasing the exhaust gas temperature, connecting thermoelectric modules in series, expanding the heat dissipation area in an appropriate range, and improving the cold-side heat-transfer capability, among others. Hsu [6] developed a thermoelectric generator consisting of 24 thermoelectric modules and carried out experiments. The results showed that the increase in the open-circuit voltage with the temperature difference was linear, and the open-circuit voltage increased with the increase in the temperature difference. Lee [7] optimized the design of a thermoelectric generator whose cold side was cooled by a heat sink and found that the dimensionless power generation achieved a maximum value when the load resistance ratio of the thermoelectric generator was 1.7. Kim [8] calculated the effective Seebeck coefficient of the thermoelectric generator. Chen [9] designed a two-layer thermoelectric generator model, and the results showed that the best way to optimize the performance of thermoelectric generator is to explore the appropriate heat-transfer area of the hot and cold sides and to find the best thermoelectric module layout. Using numerical calculations, He et al. [10] found that choosing an optimal module area in the thermoelectric generator system design is important.

Although the thermoelectric conversion of waste heat of an automobile exhaust has been studied for many years, the relevant basic research is not perfect, which restricts the promotion and application of the waste heat recovery method. Making a breakthrough in the relevant basic research and providing support for the development of a high-efficiency thermoelectric generator are thus necessary.

The theoretical thermoelectric conversion efficiency of the thermoelectric generator is generally expressed as follows:

$$\eta_{\max} = \frac{T_h - T_c}{T_h}\left[\frac{(1+Z\overline{T})^{1/2} - 1}{(1+Z\overline{T})^{1/2} + \frac{T_c}{T_h}}\right] \tag{1}$$

Here, T_h – the hot side temperature of the module, T_c – the cold side temperature of the module, $\overline{T}$ – the average temperature of the hot and the cold side of the module, Z – the thermoelectric figure of merit, $\overline{T}$ and Z are calculated using Eqs. (2) and (3) respectively.

$$\overline{T} = (T_h + T_c)/2 \tag{2}$$

$$Z = \frac{\alpha^2\sigma}{\kappa} \tag{3}$$

In the formula, α – Seebeck coefficient, σ – Electrical conductivity, κ – Thermal conductivity.

Two methods are available to improve the efficiency of thermoelectric conversion of the module: one is to increase the thermoelectric figure of merit of the thermoelectric materials, and the other is to increase the temperature difference between the hot and cold sides of the thermoelectric module. Therefore, this paper, presents a method on how to improve the thermoelectric conversion efficiency of thermoelectric generators from the perspective of heat-transfer enhancement.

For an exhaust heat recovery thermoelectric generator, its cold side is usually cooled with engine cooling water whose heat-transfer coefficient is relatively large. Thus, the main reason for increasing the temperature difference at the hot and cold sides of a thermoelectric generator is to enhance its hot-side heat transfer [11]. For example, Espinosa et al. [12] designed a five-layer fin-type heat-transfer structure whose area was 50 cm × 31 cm. When the exhaust gas temperature was approximately 300 °C and the exhaust gas flow rate was 0.4 kg/s, the total heat transfer of the heat exchanger was 23 kW, and the pressure drop was 4500 Pa. However, the relationship between the thermoelectric generator performance and pressure drop was not discussed. Liang [13] designed a test system with multiple thermoelectric generators in parallel. The results showed that the open-circuit voltage was as large as that of a single thermoelectric generator, but the internal resistance is n times smaller than a single thermoelectric generator. To improve the compactness of the thermoelectric generator, Suzuki et al. [14–17] designed a roll-cake-type heat-exchanger structure whose size was significantly reduced under the same thermal conditions and output power requirements. Esarte et al. [18] compared the heat-transfer effect of heat exchangers with three different shapes, namely, spiral, zigzag, and straight-fin types, by experiments. The results showed that the temperature difference values at both sides of the thermoelectric module in the thermoelectric generator were 60, 72, and 72.9 K, respectively, and the pressure drop values of the generator were 0.1, 1.3, and 0.003 bars, respectively, when the gas passed through these three structure types. Although the temperature difference in the heat-exchanger-type structure was the largest, the pressure drop was also the largest. Baker et al. [19] compared the heat-transfer effect of five types of heat-exchange structures: (1) without an enhanced heat-transfer structure with monolayer plate-type heat-exchange structure, (2) single-plate-type with a straight fin, (3) monolayer plate-type with full filling of 92% porosity and 10 pores per inch (PPI) porous foam metal, (4) three-layer plate-type with parallel flow structure, and (5) three-layer plate-type with serpentine flow field in a series-connected structure. The results show that the heat-transfer effect of the serpentine flow field and the porous foam-metal-filled structure was better than those of the other structures. However, the pump power caused by the pressure drop reached up to the kilowatt level when the exhaust gas flowed through the channel, which seriously affected the net output power. In fact, many studies on heat-transfer enhancement in a channel have been conducted. For example, Megerlin et al. [20] carried out an experimental study using stainless steel woven wire mesh and brush as fillings. The porosity of these two porous bodies was approximately 80%. The experimental results showed that all the fillings exerted a positive effect on the heat transfer in the channel, and the effect of the mesh filling was more favorable. The experiments of Pavel [21] using porous fillings made of wire mesh showed that the high porosity of the porous medium could effectively improve the heat transfer in the channel. When the porosity was 98.1%, the channel pressure drop was 64.8 Pa, and when the porosity was 99.3%, the channel pressure drop was 19.1 Pa. Therefore, the high porosity of the porous media caused a small pressure drop inside the channel. Mohamad [22] compared the heat-transfer performance between part of the filling and the entire filling in the core flow field of a circular tube with a porous medium. They found that when the porous media filling ratio inside the tube was 1.0, the temperature uniformity of the flow field inside the tube was weaker than that when the filling ratios were 0.4 and 0.6. In other words, when the porous medium completely occupied the entire flow field, the heat transfer effect was weakened. This heat-transfer enhancement method, which only requires partial filling of the tube with porous media in the core flow field, is called heat-transfer enhancement core flow.

The heat-transfer enhancement of fluid is known to be often accompanied by an increase in flow resistance. In the process of exhaust gas waste heat recovery, if the engine exhaust backpressure is increased, the output power of the engine will be reduced and the effect of waste heat recovery will be weakened, which