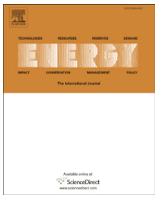
Energy 91 (2015) 1–9

Contents lists available at ScienceDirect

Energy

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



Optimization design method of thermoelectric generator based on exhaust gas parameters for recovery of engine waste heat

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ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form
16 April 2015
Accepted 11 August 2015
Available online 30 August 2015

Keywords:
Waste heat
Exhaust gas
Fluctuation
Thermoelectric generator

ABSTRACT

This paper presents an advanced mathematical model of a thermoelectric generator that includes the effect of the temperature gradient in the flow direction. The parameters of the exhaust gas from an engine may fluctuate during engine operation; thus, the influence of this fluctuation in the exhaust gas parameters on the optimal thermoelectric performance was considered with the objective of maximizing the total power output through the aid of Fortran. The optimum module areas corresponding to the maximum power output were found to be greatly affected by the flow rate of the exhaust gas but not by the gas temperature. The effect of the fluctuation in exhaust gas parameters on the performance of the corresponding thermoelectric generator at the maximum power output was also studied. A power deviation analysis method was introduced in order to design the optimal TEG module area for a high power output. Based on the results, the optimal design areas were 0.22 m^2 for the co-flow and 0.3 m^2 for the counterflow. The counterflow arrangement is recommended because it maintains a smaller deviation from the peak power output than a co-flow arrangement at their respective optimal design areas if there is sufficient system space.

1. Introduction

A TEG (thermoelectric generator) offers simple and reliable energy conversion that is also environmentally friendly. A TEG module has many other advantages such as no moving parts, so it is compact, quiet, and highly reliable. Because of these merits, many industries have comprehensively examined the use of a TEG to harvest waste heat [1]. Thermoelectric generation plays a significant role in saving energy on a national scale as well as reducing carbon dioxide emissions by enhancing the efficiency of energy utilization. The recycling of waste heat to electrical energy using a TEG has recently attracted attention for use in areas where a considerable amount of heat energy is wasted, such as vehicles. A variety of analytical TEG models have been developed for performance optimization by a number of authors [2,3]. Rezania et al. studied the geometric effect of the TEG on the heat transfer characteristics of a micro-heat sink [4]. Yilbas et al. presented the influence of the slenderness ratio and external load parameter on the thermoelectric power and device efficiency. With regard to the TEG structure, the power output from a module can be significantly increased by modifying the geometry of the thermoelectric elements [5]. Jang et al. optimized the TEG module spacing and spreader thickness used in a waste heat recovery system [6]. Fankai et al. introduced a complete numerical model for a commercial TEG with finned heat exchangers that considers inner and external multi-irreversibilities [7]. Chen et al. analyzed the effects of the finite-rate heat transfer between a thermoelectric device and its external heat reservoirs on the performance of a single-element TEG by applying finite-time thermodynamics [8,9]. Because a TEG is a multi-element device composed of many fundamental thermoelectric elements, Chen et al. then investigated the characteristics of a multi-element TEG with the irreversibility of finite-rate heat transfer, Joule heating generated inside the thermoelectric device, and heat leaks through the thermoelectric couple [10]. Gou et al. established a low-temperature waste heat TEG system model and indicated that adding TE models in series improves the system [11]. They also developed a dynamic model to assess the influence of a heat reservoir and heat sink; they found that enhancing the

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http://dx.doi.org/10.1016/j.energy.2015.08.022

heat dissipation on the cold side is crucial to improving the output performance of a TEG [12].

However, despite the numerous promising results, most studies have developed models assuming an isothermal surface, that is, every TE element works at the same temperature [13,14]. This does not accurately represent the fact that, in practice, the temperature decreases across the TEG surface in the fluid flow direction owing to the continual recovery of heat energy. The isothermal surface assumption is only applicable if a small fraction of the available energy is extracted from the exhaust heat. Consequently, a new analytical TEG model is necessary that not only considers the internal and external irreversibility of the TEG system but also the temperature variation on the TEG surface in the fluid flow direction. This is an increasingly active area of research. Yu et al. presented a numerical model based on an elemental approach and demonstrated its ability to simultaneously analyze the temperature change in a TEG and its performance under operating conditions. Their simulation results showed that the temperature variations of the fluids in a TEG are linear [15]. Weng et al. explored the influence of the number and coverage rate of thermoelectric couples on the heat exchanger of a TEG via simulations [16]. Simon et al. optimized the design of a TEG that was placed in the wall of a crossflow heat exchanger with a numerical model, where the total power output was the objective function and the number of modules and current in each control volume of the mesh were the design variables [17]. Many studies have indicated that the thermoelectric behavior of a TEG system that includes the temperature variation clearly differs from that which assumes a constant temperature [18,19].

Engine exhaust gas typically carries a great deal of heat energy at a high temperature into the atmosphere, which can cause serious thermal pollution and excessive energy consumption. TEG technology is a good choice for recycling the heat energy from engine exhaust gas [20]. When a TEG is applied as an engine exhaust heat recovery system, the exhaust parameters (i.e., mass flow and gas temperature) fluctuate because the engine operates under unsteady conditions, as shown in Fig. 1 [21]. The design of thermoelectric power generation systems that work optimally over a broad dynamic range of thermal input power is a difficult technical challenge. When systems operate within a narrow range of thermal power conditions, the thermoelectric waste heat recovery system design is simplified. For applications with a wide range of operating conditions, the recovery system must be designed to operate near the peak overall power recovery. Therefore, fluctuations in the exhaust parameters complicate the optimization of the TEG design because the TEG also works under unsteady conditions. Crane [22] described a design concept for maximizing the performance of a thermoelectric power generation system where the thermoelectric power generation device is broken into multiple sections. Each section can then be optimized for a much smaller range of operation conditions. However, this concept is again based on a model assuming an isothermal surface and thus has the associated limitations.

This paper presents the simulation and analysis of a TEG system where the temperature change in the fluid flow direction was considered. A mathematical model and computer program were developed to explore the influence of the exhaust gas parameters on the optimal thermoelectric performance. The maximum total power output was taken as the objective function, and the optimal module area, fluid flow directions, and thermoelectric performance were analyzed in situations where the exhaust gas parameters fluctuate. Based on the results, a new design method is introduced for a thermoelectric recovery system that can operate near the peak power output condition despite large fluctuations in the exhaust gas parameters. It is an effective and simple design concept for exhaust heat thermoelectric recovery systems where an optimal TEG size and fluid flow direction are chosen to achieve a high level of power recovery for a much wider range of engine operating conditions.

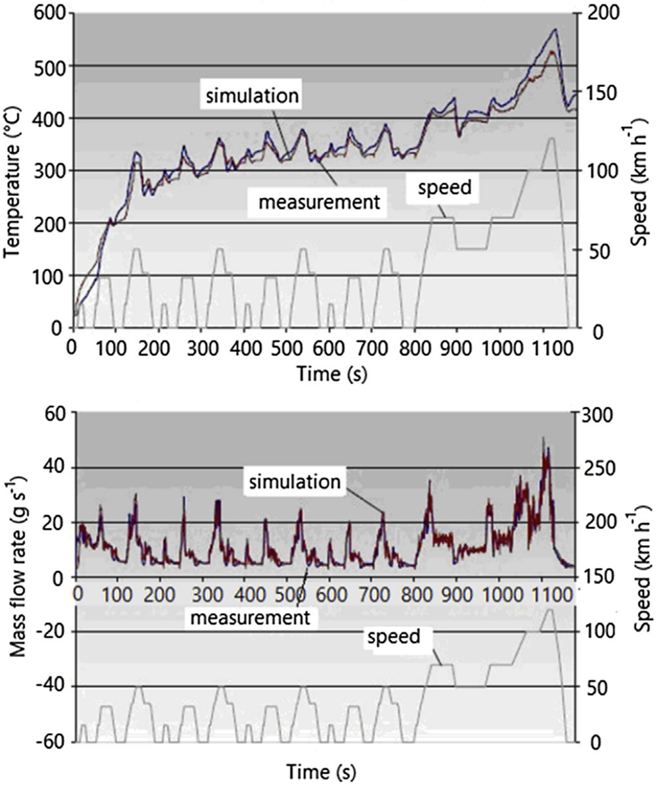

Fig. 1. Temperature and mass flow rate profiles of exhaust gas. Based on [21], GT-Cool (Gamma Technologies) was selected as the vehicle model platform, and a state-of-the-art BMW 530i with an inline six-cylinder gasoline engine was chosen as the automotive vehicle for the project.

2. TEG system modeling

2.1. Mathematical model

The TEG is a solid-state energy converter that generates electric power from the temperature difference between its two sides; this produces a voltage from the thermoelectric effect. The thermoelectric module can function between a hot fluid channel and cold fluid channel because of the temperature difference between the two sides when it is connected with an external load circuit. As shown as Fig. 2, when the cold fluid flows in the same direction as the hot fluid, this is a co-flow heat exchange; when the flows are in opposite directions, this is a counterflow heat exchange. Both heat exchanger arrangements were considered in this study.

Fig. 3 illustrates the mathematical model of a co-flow-type TEG. The whole TEG module is divided into a total of $n_x \times n_y$ calculation units, where a single P–N element is one TE unit. Here, n_x P–N elements are aligned with the fluid flow (x direction), and n_y P–N elements are placed across the fluid flow (y direction). For each P–N element, the P and N units are connected along the y direction. The identifying coordinates for each TE unit are written as (i, j) in the (x, y) coordinate system, where i is numbered from 1 to n_x and j is from 1 to n_y. All of the P–N elements are connected in series and have a uniform distribution. The inlet temperatures for the hot and cold fluids are T_{fin} and T_{cin}, respectively. By using the outlet temperature of the previous unit as the inlet temperature for the following unit, the calculation can be performed continuously.