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Thermoelectric generator for industrial gas phase waste heat recovery

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ABSTRACT

A technical solution recycling exhaust gas sensible heat based on thermoelectric power generation is proposed by using finite time thermodynamics. The effects of some key parameters such as exhaust gas inlet temperature, exhaust gas and cooling water heat transfer coefficient on the optimum length of the thermoelectric elements are analyzed. It is found that the gas temperature drops rapidly because of the small specific heat of the exhaust gas. Enhancing the heat transfer of gas can effectively improve the power, but not the efficiency. Exhaust gas inlet temperature and transfer coefficient have significant effects on the optimal thermoelectric element length. Due to the highest hot surface operating temperature limit 200 °C, the optimal length of the thermoelectric elements is about 2 mm. About 1.47 kW electrical energy can be produced per square meter and the conversion efficiency of 4.5% can be achieved for exhaust gas at 350 °C. The payback period of the waste heat recovery device is about 4 years for the price and performance of thermoelectric products made in China.

1. Introduction

An energy shortage has become one of the main problems which restrict the development of China [1]. The recovery and utilization of different kinds of waste heat can effectively reduce energy consumption. Take the sintering process in the steel industry as an example, the sintering process energy consumption accounts for about 10% of total energy consumption. However, nearly 50% of sensible heat is discharged into the atmosphere in the form of sinter exhaust. Take advantage of this waste heat is of great significance for reducing energy consumption and emissions [2]. Thermoelectric generator is known as a promising potential power generation technology. Nowadays with improved conversion efficiency and dropped cost of thermoelectric materials, thermoelectric power generation technology has moved frontiers such as the military and aerospace towards to the low-grade waste heat utilization [3]. Therefore, thermoelectric generator technology recycling industrial waste heat has become one of the research hotspots [4,5]. In general, conventional non-equilibrium thermodynamics [6] is used to analyze the performance of thermoelectric devices. However, the external heat transfer between the thermoelectric modules and the heat sources is not considered. In order to obtain more accurate results for the thermoelectric generators, the external finite rate heat transfer of the device cannot be neglected. The theory of finite time thermodynamics (FTT) [7–22] is a powerful tool for performance analysis and optimization of practical thermodynamic processes and devices, including thermo-economic analysis and multi-objective optimization [23–34]. The study of thermoelectric devices [35,36] based on finite time thermodynamics have been applied to the analysis of thermoelectric generators [37–54], thermoelectric refrigerators [55–58], thermoelectric heat pumps [59,60], and combined thermoelectric devices [61–64]. This paper will present a thermoelectric generator technology-based gas phase waste heat recovery solution and establish a finite time thermodynamic model of the device. The numerical examples are provided to analyze the key design parameters of the device. Finally, economic and application analysis is performed adopting commercial thermoelectric module specifications. The results may provide guidelines for the application of thermoelectric power generation technology in industrial waste heat recovery.

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2. The device design and the finite time thermodynamic model

The heat transfer and energy conversion of recycling process based on thermoelectric power generation technology can be described as: the hot fluid (exhaust gas) temperature decreases gradually along the flow. Meanwhile, part of the heat released is taken away by the cold fluid (cooling water at ambient temperature); the other part of the heat is converted to electrical energy and recovered by the thermoelectric power generation modules. The cross-section of the heat exchanger flow channel is shown in Fig. 1. The exhaust gas waste heat recovery system mainly composed of two parts. One part is thermoelectric power generating modules which convert thermal energy to electrical energy. Another is the heat exchanger in the hot and cold sides of modules. The heat exchanger consists of a square exhaust gas channel side length of d_1 and a cooling water passage width of d_2. The heat exchanger separator thickness is δ_{ex}. The Length of the channels is L_f. In order to enhance the heat transfer of flue gas, the structure of internal ribbed tube is adopted.

Due to the insulation requirements and process limitations, thermoelectric elements cannot be closely arranged and then air gap exists inside the module. This causes part of the heat flows through the air gap directly. The packing factor $\theta(0<\theta\leq 1)$ of the thermoelectric power generation module is defined as $\theta = 2AN/A_{cp}$ [65]. The finite time thermodynamic model of the exhaust gas driven thermoelectric generator is shown in Fig. 2. In the figure, $T_1(x)$ and $T_2(x)$ are the exhaust gas and cooling water temperatures, respectively. $T_h(x)$ and $T_c(x)$ are the thermoelectric elements hot and cold junction temperatures, respectively. Q_1 and Q_2 are the exhaust gas discharged and cooling water absorbed heat flow rates, respectively. Q_h and Q_c are the thermoelectric modules absorbed and discharged heat flow rate, respectively. R_L and I are the load resistance and electrical current output of the generator, respectively. The Length of the channels is L_f. The thermal network of the system is shown in Fig. 3. R_{cp}, R_{ex} R_{cv} and R_g are the thermal resistances of the ceramic substrate, heat exchanger separator, convective heat transfer and air gap. According to finite time thermodynamics and non-equilibrium thermodynamics, one can obtain differential equations about $T_1(x)$, $T_h(x)$, $T_c(x)$, $T_2(x)$ as follows

$$T_1'(x) = \{4K_1[T_1(x) - T_h(x)]d_1\}/(-G_1c) \tag{1}$$

$$K_1(T_1(x) - T_h(x)) = \left[\alpha T_h(x)I + K(T_h(x) - T_c(x)) - I^2R/2\right]\theta \Big/ (2A) + K_g(T_h(x) - T_c(x))(1-\theta)/L \tag{2}$$

$$K_2(T_c(x) - T_2(x)) = \left[\alpha T_c(x)I + K(T_h(x) - T_c(x)) + I^2R/2\right]\theta \Big/ (2A) + K_g(T_h(x) - T_c(x))(1-\theta)/L \tag{3}$$

$$T_2'(x) = 4K_2[T_c(x) - T_2(x)]d_1/(-G_2c_{p2}) \tag{4}$$

where G_1 and G_2 are the mass flow rate of water, respectively. c_{p1} and c_{p2} are the specific heat capacity of the exhaust gas and cooling water at constant pressure, respectively. α, K and R are the total Seebeck coefficient, thermal conductance and electrical resistance of a thermoelectric element, respectively.

The power output from the device is the exhaust gas discharged heat minus the cooling water absorbed heat:

$$P = G_1c_{p1}\left[T_1(0) - T_1\left(L_f\right)\right] - G_2c_{p2}\left[T_2\left(L_f\right) - T_2(0)\right] \tag{5}$$

The conversion efficiency of the device is the power output divided by the exhaust gas discharged heat:

$$\eta = 1 - G_2c_{p2}\left[T_2\left(L_f\right) - T_2(0)\right] \Big/ \left\{G_1c_{p1}\left[T_1(0) - T_1\left(L_f\right)\right]\right\} \tag{6}$$

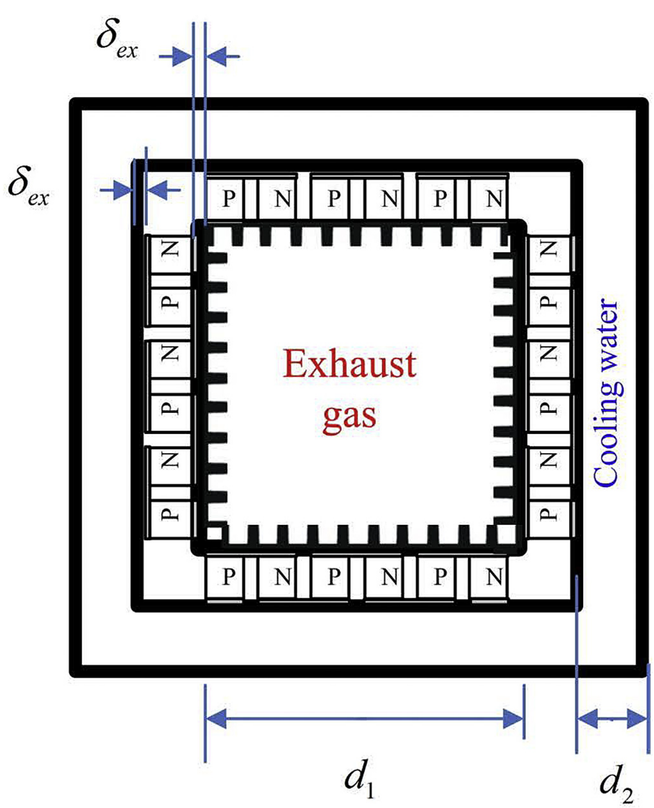

Fig. 1. Schematic diagram of the heat transfer passage cross section.

3. Numerical simulation and economic analysis

As the exhaust gas temperature is less than 400 °C, the most appropriate thermoelectric material is bismuth telluride (Bi_2Te_3) semiconductor thermoelectric materials. The physical parameters of the commercially available material by Melcor at the average temperature 125 °C are adopted for this simulation. Parameters set in the numerical simulation are list in Table 1. It is assumed that the exhaust gas composition is $\phi_{CO_2} = 0.13$, $\phi_{H_2O} = 0.11$ and $\phi_{N_2} = 0.76$.

3.1. Thermoelectric elements geometry optimization

3.1.1. Effects of exhaust gas inlet temperature

Figs. 4 and 5 show effects of cooling water heat transfer coefficient on power and efficiency versus thermoelectric elements length. Fig. 6 shows effects of gas heat transfer coefficient on module hot surface temperature versus thermoelectric elements length. It is found that for the given thermoelectric elements length, when the exhaust gas temperature increases, power, efficiency and module hot face temperature increase. Many literatures showed that there exists an optimal length of thermoelectric