Energy Conversion and Management 148 (2017) 820–829

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Analysis of thermoelectric generation characteristics of flue gas waste heat from natural gas boiler

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ARTICLE INFO

Article history:
Received 9 April 2017
Received in revised form 7 June 2017
Accepted 11 June 2017

Keywords:
Wet flue gas
Waste heat utilization
Thermoelectric generation
Performance optimization
Natural gas

ABSTRACT

For the large quantity of water vapor present in the exhaust gas of natural gas boilers, the waste heat of the flue gas is not only determined by the sensible heat, but also by the latent heat of condensation. In this study, a generation model was established in order to investigate the thermoelectric generation characteristics of the wasted flue gas heat. The calculated results show that the characteristics curves can be divided into a sensible heat generation region and a mixed power generation region, with the power generation performance of both regions having different characteristics. Considering that the heat transfer coefficient of wet flue gas is higher than that of dry flue gas, this paper proposes to improve the performance of the generator through gas humidification, which not only improves the maximum output power, but also reduces the area of the thermoelectric module required for maximum power output. In addition, a thermoelectric power generation system created by intermediate humidification of flue gas, and which can fully utilize high-temperature flue gas and improves the power performance of thermoelectric generators at a lower temperature is presented. An optimum intermediate humidification temperature that results in maximum output power at the smallest corresponding module area is also determined.

1. Introduction

With global environmental problems becoming increasingly prominent, even though it is viewed as an ideal clean energy, there is widespread concern about the high proportion of carbon and hydrogen in natural gas [1]. Boilers that use natural gas as fuel have become very prevalent in industries and homes. Because the main component of natural gas is methane, the combustion products contain large amounts of water vapor. A considerable amount of heat is released in the form of latent heat of water vapor in flue gas when the temperature is cooled to dew point. The condensation temperature is determined by the composition of the fuel and the excess air coefficient, generally between 55 and 65 °C [2]. When condensation occurs, because flue gas contains SO_X and NO_X, the condensate is usually acidic, which will cause corrosion of the heat exchanger [3]. Therefore, in order to avoid the corrosion, the flue gas temperature is usually in the range 150–200 °C, which leads to the thermal efficiency of the natural gas boiler being only 70–80% [4].

With the application of anticorrosion material, condensing boilers are being used more widely. By reducing the flue gas temperature below the condensation temperature, the latent heat of the flue gas can be recycled, such that the thermal efficiency of the condensing boiler is usually higher [5]. In addition, owing to the dissolution of NO_X, SO_X, HCl, soot, and so on, the flue gas discharged from the condensing boiler is cleaner [6]. In practical applications, the flue gas is used to heat the backwater from the heating system through a heat exchanger; meanwhile, the flue gas condenses and releases latent heat. Thus, the state of the backwater directly affects the condensation performance of flue gas. The calculated results of Searle [7] show that the efficiency of condensation of the reformed boiler has been improved, and the investment recovery period is only 3–4.5 years. However, taking an actual condensing boiler as an example, Boeschen [8] pointed out that the investment recovery period is actually 24 years. This is because the flue gas temperature is always in the range of 50–60 °C during actual operation, which is almost as high as the dew point temperature of flue gas. Consequently, the condensation latent heat cannot be fully utilized. In order to solve the problem of high backwater temperature, Qu [9] designed an absorption heat pump that recovers the waste heat of flue gas. The pump can raise the backwater temperature from 45 °C to 89.7–98.5 °C, and improves the thermal efficiency of the boiler by 5–10%. However, the use of flue gas is seriously affected by seasonal and regional impacts. In non-heating seasons and regions without heating, the

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http://dx.doi.org/10.1016/j.enconman.2017.06.029
0196-8904/

flue gas of an industrial gas boiler cannot be effectively utilized. As a result, Maalouf [2] proposed the use of waste heat for power generation. Because of the low temperature, flue gas cannot be directly used with the traditional water Rankine cycle; however, the Organic Rankine Cycle (ORC) is considered to be an effective method of waste heat recovery. Zhou [10] built a low-temperature flue gas ORC experimental system using R123 as the working fluid. The temperature range of the flue gas in the system was 90–220 °C. The experimental results obtained showed that the output power increases with increasing flue gas temperature, and the maximum output power was 645 W, with a maximum power efficiency of 8.5%. However, in that system, the flue gas temperature did not decrease to the condensation temperature; hence, there was still much condensation latent heat that could be used.

A semiconductor thermoelectric generator is a device that uses thermoelectric effects to convert heat directly into electricity. Because of merits such as no chemical reaction and no mechanical moving parts, it produces no noise, no pollution, has no wear, is portable, and has a long life [11,12]. In recent years, as a result of improvement in performance and reduction in cost, commercial application of semiconductor thermoelectric modules has become possible. It has attracted widespread attention from various circles of ceeusro. Semiconductor thermoelectric generators are widely used in the recovery of various types of waste heat to generate electricity, including solar energy, geothermal energy, and automobile exhaust heat [13–16]. In the power generation process, the larger the temperature difference between the hot side and the cold side is, the better the power performance is. However, because of the heat transfer resistance between the fluid and the generator, the temperature difference between the hot and cold sides is much smaller than that of the hot and cold sources. Therefore, many researchers hope to improve the heat transfer performance between the heat resource and the generator. By reducing the heat transfer resistance, the temperature of the generator is as close as possible to the temperature of the fluid, thereby increasing the temperature difference between the cold side and the hot side of the generator and improving the generating performance. Changing the shape of the channel or adding fins to the heat transfer surface is a common way of improving the heat transfer coefficient. For example, Liu [17] compared two types of thermoelectric generators with different channel shapes, and obtained results that showed that the output power of chaos-shaped channels increases by 14.4% over fishbone-shaped channels. A rectangular pillar and two triangular prisms were installed to face the forward and reverse directions of the exhaust gas flow in a generator by Byung [18]. The power generated from the rectangular pillar was around 6.2 W under the highest load condition, followed by around 5.5 W for the forward and reverse-facing triangular prism. Lu [19] proposed to improve the performance of the generator by inserting foam metal into the exhaust channel.

In summary, the heat utilization of low-temperature flue gas is seriously affected by climate, and seasonal and geographical conditions; thus, the condensation latent heat cannot be fully used. Although the power generation is not affected by the above factors, the ORC cycle has many disadvantages, such as complex structure, inconvenient maintenance, larger initial investment, and the fact that it can equip only some large gas boilers. The semiconductor thermoelectric generator has advantages such as convenient installation and reliable operation. When using semiconductor thermoelectric generation technology to recover the waste heat of low-temperature flue gas, it is rarely affected by the scale of the flue gas. It is worth noting that, when wet flue gas condenses, the heat transfer coefficient of the flue gas increases owing to water vapor condensation [20]. This differs from the generation characteristics of high-temperature flue gas without condensation; specifically, there are two stages in the heat-releasing process at gas side: small heat transfer coefficient in the high-temperature stage and large heat transfer coefficient in the low-temperature stage. It will not only result in improved TEG generation performance, but also affect the position of the maximum output power, which has not been previously reported. In this paper, a mathematical model of low-temperature wet flue gas is established to analyze the generation characteristics. On this basis, flue gas humidification is proposed to improve system performance. The results obtained significantly enhance understanding of the thermoelectric generating characteristics of wet flue gas and the design of thermoelectric generators.

2. Mathematical model

2.1. TEG model of wet flue gas

A thermoelectric generator (TEG) is composed of two types of materials with different Seebeck coefficients (P-type and N-type) connected in order. When there is a temperature difference between the hot side and the cold side of the thermoelectric generator, the generator generates an electric potential. Subsequently, if it is connected to an external load circuit, current will flow. As shown in Fig. 1(a), when the flue gas flows through the hot side, and the cold fluid flows through the cold side, a temperature difference forms between the two sides of the thermoelectric generator, which ultimately results in electricity being generated. The structure of a basic unit in TEG is shown in Fig. 1(b); it consists of a PN element and insulating ceramic chips on both ends. The entire TEG module consists of a total of $n_x \times n_y$ PN elements connected electrically in series. The coordinates along and normal to the gas flow redirection are i and j, respectively. In the j direction, it is considered that the physical properties of the flue gas and the cold water are the same; that is, the n_y PN couples of line i have the same power generation performance. In the i direction, the generation performance of PN couples decrease as a result of the reduction in the flue gas temperature.

As shown in Fig. 1(c), the PN couples in line i were chosen as the research unit to establish the mathematical model. For a flue gas TEG, the heat transferred from the flue gas ($q_{\rm h}$) to the hot side of the module is matched with the electric power generation (p) and the heat (q_c) taken away by the cooling water. In order to simplify the calculation, the following assumptions are made for the TEG: (1) The PN couples are connected in series and are in a steady thermal and flow state. (2) The contact thermal resistance and influence of conductive copper are neglected. (3) All P- and N-type materials have the same dimensions, and their thermoelectric properties are constant. (4) The heat transfer that occurs by conduction along the heat exchanger is negligible, and all heat radiation is also omitted. (5) The Thomason effect is neglected.

2.1.1. Basic equations of the TEG module

For the PN couples in line i, the energy equations are determined as follows:

$$q_h^i = n_y[\alpha_{pn} I T_h^i + K_{pn}(T_h^i - T_l^i) - 0.5 I^2 R_{pn}] \quad (1)$$

$$q_c^i = n_y[\alpha_{pn} I T_l^i + K_{pn}(T_h^i - T_l^i) + 0.5 I^2 R_{pn}] \quad (2)$$

where

$$\alpha_{pn} = \alpha_p - \alpha_n \quad (3)$$

$$K_{pn} = \frac{(k_p + k_n) l w}{h} \quad (4)$$

$$R_{pn} = \frac{h(r_p + r_n)}{l w} \quad (5)$$

$$I = \frac{\alpha_{pn}(T_h - T_l)}{R_{pn} + R_L} \quad (6)$$