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Energy Procedia 142 (2017) 148–153

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Performance analysis of wet flue-gas thermoelectric generator

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Abstract

Flue gas is generated by the combustion of natural gas, biomass fuel, and domestic waste in boilers. It contains a large amount of water vapor that provides high potential heat. In this paper, a thermoelectric generator is proposed to recover this heat. A mathematical model is established to analyze the power generation parameters, taking into consideration the characteristics of the wet flue gas. The results showed that when the wet flue gas condenses, both the output power and the efficiency curves show an inflection owing to the increase in the heat transfer coefficient. The use of wet flue gas increased the maximum output power by multiple times compared to that of the dry flue gas. Furthermore, the influence of the humidity of flue gas, and the exhaust gas temperature on power generation is analyzed. It was observed that the maximum output power can be increased with the increase of both the humidity and the flue gas temperature.

Keywords: Wet flue gas, Humidity, Thermoelectric generators, Utilization of waste heat

1. Introduction

The flue gas generated by the combustion of natural gas, biomass fuel, and domestic waste in boilers contains a large amount of water vapor. For example, the volume fraction of water vapor in flue gas from the waste incineration boiler is above 30% [1]. Owing to the lower dew-point temperature of the flue gas with large amount of water vapor (wet flue gas), the condensation latent heat cannot be effectively utilized leading to a relatively low efficiency of the boilers. The semiconductor based thermoelectric generator is an energy conversion device that can convert heat into electrical energy [2]. This technology can be effectively used to recycle the residual heat of the flue gas since electricity is generated when there is a temperature difference, irrespective of the temperature, the composition

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Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy .
10.1016/j.egypro.2017.12.024

fluctuation and the mass of flue gas. In addition, the heat transfer coefficient increases when condensation occurs; therefore, the generator performance can be improved. This paper establishes the mathematical model of thermoelectric power generation taking into consideration the heat transfer characteristics of condensation. Moreover, the influence of the area of the power generation module on generator performance is also analyzed. In this paper, we hope to provide a better understanding of the characteristics of flue-gas thermoelectric power generation and the design of thermoelectric power generators.

2. Mathematical model

As shown in Figure 1, the flue-gas thermoelectric power generator consists of $nx \times ny$ PN sections connected in series. The flow direction of flue gas is denoted by i, and its vertical direction is denoted by j. The physical properties of the flue gas is the same as that of the cold fluid in the j direction; therefore, the electrical properties of the ny PN sections (line j) are constant. In the i direction, owing to a gradual reduction in the temperature of the flue gas, the performance of the PN section gradually changes. Thus, it needs to be calculated at each section, for I varying from 1–nx. In the flue gas thermoelectric power generator, heat is transferred between the flue gas and the hot end of the PN section, and the heat is referred as q_h. Part of the heat is converted into electricity p through the PN sections, while the residual heat q_c is absorbed by the cold fluid. Basic assumptions are made for the thermoelectric power generator to simplify the calculation: (1) The PN sections are connected in series and are in steady state; (2) The influences of thermal contact resistance, contact resistance and conductance of copper are ignored; (3) All P-and N-type materials have the same dimensions and physical, structural properties, and their thermoelectric properties are constant; (4) The heat transfer that occurs by conduction along the heat exchanger is neglected, and heat radiation is also ignored.

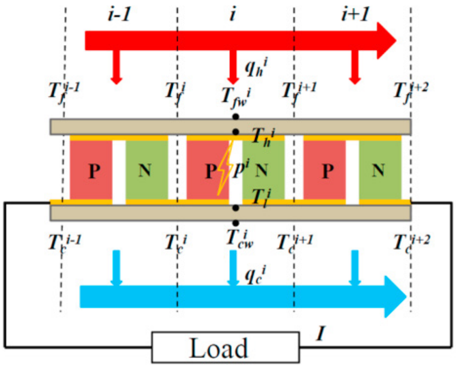

Fig. 1. Mathematical model of the thermoelectric power generator.

The energy equations for the PN sections in line i, are presented below:

$$q_h^i = ny\left[(\alpha_p - \alpha_n)IT_h^i + \frac{(k_p + k_n)lw}{h}(T_h^i - T_l^i) - 0.5I^2\frac{h(r_p + r_n)}{lw}\right] \quad (1)$$

$$q_c^i = ny\left[(\alpha_p - \alpha_n)IT_l^i + \frac{(k_p + k_n)lw}{h}(T_h^i - T_l^i) + 0.5I^2\frac{h(r_p + r_n)}{lw}\right] \quad (2)$$

where α_p and α_n are the Seebeck coefficients, k_p and k_n are the thermal conductance, and r_p and r_n are the electric resistances of P- and N-type materials, respectively; l, w, and h are the length, width and height of the PN section.

The output P and generating efficiency η of the thermoelectric power generator can be calculated as follows: