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Energy and exergy analysis of thermoelectric generator system with humidified flue gas

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ABSTRACT

The flue gas of natural gas boilers contains a large amount of water vapor, and the latent heat of flue gas can be effectively recovered by thermoelectric generation technology. The performance of thermoelectric generation can be significantly improved by gas humidification. In this study, the thermoelectric generation performance of flue gas and humidified flue gas were analyzed and compared using energy and exergy analysis, and irreversible losses in each link of the system were evaluated. The results showed that both generation efficiency and exergy efficiency increased when the flue gas condensed, with a notably larger increase of exergy efficiency. In the direct flue gas thermoelectric generator system, the maximum exergy destruction was caused by convective heat transfer at the hot side of the PN couple. Although the proportion of hot-side exergy destruction decreased with an increase of module area when the flue gas condensed, it was still the largest exergy destruction. The largest exergy destruction in the humidified flue-gas thermoelectric generator system was caused by humidification process at smaller module areas. With an increase in module area, the exergy destruction caused by heat conduction in the PN couple became the largest exergy destruction. Although exergy destruction was caused by flue gas humidification, the large decrease of exergy destruction at the hot side of the PN couple led to increased output power. Moreover, an increase of the heat transfer coefficient could also reduce the module area.

1. Introduction

Natural gas is a widely used clean energy source [1]. There is a large amount of latent heat in the system because of the large quantity of water vapor in the natural gas's flue gas. However, in order to avoid corrosion of the condensate, a higher flue gas temperature of approximately 150–200 °C is required [2], far above the dew point temperature of flue gas (55–65 °C) [3]. With the development of anti-corrosion materials, condensing boilers have been widely used due to their high thermal efficiency and effective recovery of the latent heat from flue gas [4]. In addition, some researchers have proposed the use of the Organic Rankine Cycle (ORC) to recover the waste heat from flue gas. However, the condensation latent heat cannot be fully utilized since the flue gas temperature does not fall to the dew point temperature [5].

A thermoelectric generator (TEG) is a solid-state direct energy conversion device for converting heat into electricity [6–8]. It has been widely used for waste heat recovery because of its convenient installation, simple maintenance, and long service life [9–12]. Thermoelectric generation was proposed for the recovery of energy from low-temperature wet flue gas in [13]. Gas humidification has been proposed to improve generator performance and reduce the module area because of its characteristic high heat transfer coefficient when the flue gas condenses. It is well known that gas humidification leads to a decrease in the temperature of flue gas and a reduction in the exergy of flue gas, as well as an increase in output power. Therefore, the understanding of humidified flue gas thermoelectric generation would be greatly improved by an exergy analysis of humidified flue gas thermoelectric generation and an analysis of the exergy destruction and exergy distribution of the system before and after humidification.

Exergy analysis provides a comprehensive understanding of a thermoelectric generator system because it considers the first and second law of thermodynamics. With this method, irreversible exergy destruction in the system can be located, which has a positive effect on improving the performance of the system [14]. The effects of heat-link, internal dissipation, and finite-rate heat transfer on the thermoelectric system were investigated based on the entropy generation minimization method by Nuwayhid [15]. Wang [16] optimized the heat sink configuration of the thermoelectric cooling system based on the entropy generation analysis method. The energy and exergy analysis of an annular thermoelectric cooler [17] and annular thermoelectric generation

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Nomenclature

Abbreviation

TEG	thermoelectric generator
HTEGs	humidified flue gas thermoelectric generation system
DTEGs	direct flue gas thermoelectric generation system

Symbols

a	length of unit, mm
b	width of unit, mm
c_p	specific heat at constant pressure, J g^{-1} K^{-1}
d	moisture content, g g^{-1}
e	exergy of unit
E	exergy of system
F	superficial area of unit, mm^2
h	specific enthalpy, J g^{-1}
H	enthalpy, J
k	heat transfer coefficient, W m^{-2} K^{-1}
l	length of PN couple, mm
m	mass flow rate, g s^{-1}
n	number of PN couples
P	output power, W
q	quantity of heat, W
r	electricity resistance, Ω m
s	specific entropy, Jg^{-1} K^{-1}
S	module area, m^2
T	temperature, °C
w	width of PN couple, mm
z	height of PN couple, mm

Greek symbol

α	seebeck coefficient, V K^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
η	generation efficiency, %
φ	exergy efficiency, %

Superscripts

0	reference state
i	line number

Subscripts

con	condensate water
d	dew point
f	flue gas
fin	inlet flue gas
$fout$	outlet flue gas
g	dry flue gas
h	hot side of PN couple
c	cooling water
ir	exergy destruction
l	cold side of PN couple
pn	PN couple
s	system
t	TEG
u	humidification
v	water vapor
w	water

[18] were conducted by Manikandan et al. The effects of shape parameter, dimensionless temperature ratio, and other factors on energy/exergy efficiency were studied. Moreover, the Thomson effect also changes the energy/exergy efficiency of the system. Tipsaenporm [19] proposed a thermodynamic analysis in a compact thermoelectric air conditioner. The results indicated that the coefficient of performance (COP) of the system is 3.8–9.5 times higher than the exergy efficiency. Li [20] proposed an integrated thermoelectric generator and regenerative cooling system for power generation in a scramjet. The exergy analysis and exergy distribution at different points of the system showed that the heat from cooling the scramjet was the biggest exergy destruction.

Based on previous literature, exergy analysis has been applied in thermodynamic systems and TEG analysis, but not in the thermoelectric generation system of wet flue gas. Not only are the power characteristics of wet flue gas clearly different from that of dry flue gas due to condensation, but also the exergy distribution is significantly different. Moreover, although the output power increases after gas humidification, the decreased flue gas temperature indicates that humidification is a process of exergy destruction that changes the exergy distribution of the system, which has not been reported in previous studies. In this study, an energy and exergy analysis of the thermoelectric generation system with direct flue gas and humidified flue gas was conducted. The exergy distribution characteristics under both modes are determined, and the effects of flue gas condensation and gas humidification on the energy and exergy of the system are analyzed. This study has a positive effect on understanding of thermoelectric generation performance of low-temperature wet flue gas and the influence of gas humidification.

2. Mathematical model

2.1. Thermoelectric generator system

The configuration of the direct flue gas thermoelectric generation system (DTEGs) is illustrated in Fig. 1. The input flue gas and the low temperature cooling water are regarded as the hot and cold sources of thermoelectric generator, respectively. Electric power is generated when both junctions are at different temperatures. The thermoelectric generation system with humidified flue gas (HTEGs) is shown in Fig. 2. In contrast to direct power generation, the flue gas first enters the humidifier and directly contacts the humidification water. The moisture of the flue gas increases while the temperature decreases. As a result, the

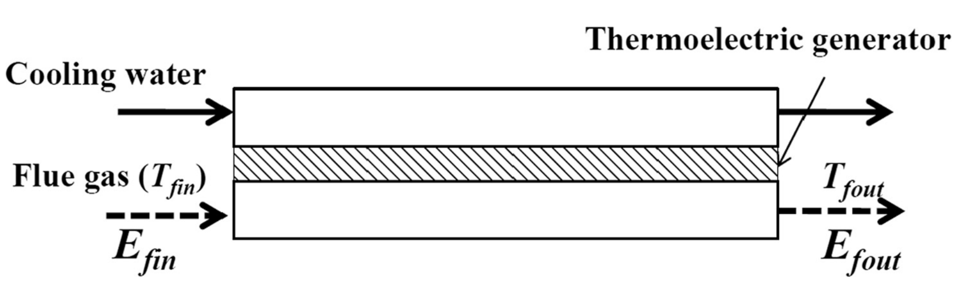

Fig. 1. Direct flue gas thermoelectric generation system (DTEGs).