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A total heat recovery system between the flue gas and oxidizing air of a gas-fired boiler using a non-contact total heat exchanger ☆

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HIGHLIGHTS

- A novel non-contact total heat recovery system of gas-fired boiler is proposed.
- The oxidizing air is heated and humidified by recovering total heat of flue gas.
- The temperature of boiler flue gas after heat recovery is about 30 °C in winter.
- The energy saving potential is close to the system using AHP for heat recovery.
- The initial investment is so low that the payback period is shorter than 1 year.

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ABSTRACT

Recovering heat from the flue gas of a gas-fired boiler can both improve boiler efficiency and decrease pollutant emissions. To improve the efficiency of the gas-fired boiler in a more cost effective and higher efficient way, a non-contact total heat recovery (NCHR) system is proposed for recovering heat from flue gas for use in heating and humidifying the oxidizing air of the boiler. A mathematical model of a boiler with an NCHR system was established, and the performance of the NCHR system was compared with that of other heat recovery systems. It is shown that the efficiency of a boiler with an NCHR system can reach 103.4% for an inlet oxidizing air temperature of 0 °C, which is 13.4% higher than the efficiency of a traditional boiler. According to the case study, the energy saving potential of a boiler with an NCHR system is 12.97% compared to that of a traditional boiler. As for the economic analysis, the payback period of a boiler with an NCHR system to traditional boiler and the condensing boiler is 1 year and 3 years, respectively. In addition, the operation cost of an NCHR system is less than that of a boiler with an absorption heat pump for heat recovery (AHPB) system, indicating that the NCHR system has obvious economic benefits.

1. Introduction

Building energy consumption in China has increased rapidly over the past three years, reaching over 7.56 billion tce (tons of coal equivalent) in 2013 [1], which equates to approximately 24% of primary energy consumption [1]. Among all types of energy consumption, coal-fired boilers account for about 85% of the entire heating and power generation process [2]. However, the primary energy efficiency of a coal-fired boiler in terms of heating is approximately 55–75% [3], which is lower than that of a gas-fired boiler which typically has an efficiency of above 90% [4]. Additionally, the coal-fired boiler emits more pollutants (particles and poisonous gas) than the gas-fired boiler [5,6]. Therefore, the use of gas-fired boilers has increased rapidly in recent years because of the environmental protection efforts and policies of the Chinese government.

The energy efficiency of a gas-fired boiler is approximately 90%, and the temperature of the emission flue gas is approximately 150–200 °C [7,8]. Significant energy is wasted if the high-temperature flue gas is discharged directly. Therefore, much recent research has focused on recovering heat from the emission flue gas of boilers. The methods for heat recovery of the flue gas can be classified into three types according to the heat recovery depth. The first method is sensible heat recovery, where flue gas is used to preheat oxidizing air and return water [9]. The configuration is simple, but the temperature of the emission fuel gas can reach

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Nomenclature

A	heat transfer area, m^2
C	initial investment, CNY
Cp	specific heat capacity, kJ/(kg K)
d	humidity ratio, kg/kg
G	hourly gas consumption, m^3/h
Gy	year-round gas consumption, m^3
h	convective heat transfer coefficient, W/(m^2 °C)
i	enthalpy, kJ/kg
L	building load, kW
LCV	low caloric value, 35,000 kJ/m^3
m	mass flow rate, kg/s
Nu	Nusselt number
O	operation cost, CNY
P	pressure, kPa
PB	payback period
Pr	Prandtl number
Q	heating capacity, kW
r	latent heat of vaporization
Re	Reynolds number
Rg	ideal gas constant
RH	relative humidity
T	temperature, °C
Δt_m	logic mean temperature difference, °C
v	volume flow rate, m^3/s
w	mass transfer rate, kg/s
y	running cost per year
Z	running cost each year, CNY/a

Greeks

β	efficiency of the conductive heat transfer
δ	thickness, m
ε	boiler efficiency
η	rib effect coefficient
λ	conduction heat transfer coefficient, W/(m °C)
ρ	density, kg/m^3

Subscripts

a	air
f	flue gas
g	gas
gas	natural gas
i	hourly system performance
md	convective mass transfer rate, kg/s
re	chemical reaction
rhc	rated heat capacity
sw	heat transfer medium
tb	traditional boiler
w	water

Abbreviations

AHP	absorption heat pump
AHPB	boiler using AHP for heat recovery
ESR	energy saving ratio
NCHR	non-contact heat recovery system

100 °C. The boiler efficiency is approximately 93% because only part of the sensible heat of the flue gas is recovered [10]. However, large amounts of latent heat (which can significantly promote boiler efficiency if recovered) will be wasted [11,12]. The second boiler heat recovery method involves a condensing heat recovery system, where the emission flue gas temperature can be decreased below the dew point, and the boiler efficiency can reach 98% [13]. Weber et al. analyzed the feasibility of recovering waste heat from flue gas using a condensing heat exchanger, and the results showed that boiler efficiency could be significantly improved, and CO_2 emissions decreased [14]. However, because of acid gas, the heat exchanger can be corroded. Therefore, the anticorrosion properties of the materials used in the heat exchanger are very important for promoting boiler efficiency. Wang et al. investigated the system performance and application of a corrosion resistant heat exchanger. Their results showed that the energy saving ratio of the system could be increased by 10% by using condensing heat recovery [15,16]. Pezzuolo et al. investigated the heat recovery for biomass boiler using the ORC cycle [17,18], and the heat recovery method is similar but the recovered heat is used to generate power. From the abovementioned methods, the emission flue gas temperature is over 55 °C. If the flue temperature can be decreased to 25–35 °C, the boiler efficiency can be increased by over 12% [19]. Therefore, absorption heat pumps (AHPs) have been used for the heat recovery of the flue gas, which is the third heat recovery method. The AHP is driven by natural gas, and the flue gas is the heat source for the evaporator. Simultaneously, the recovered energy is used to heat the return water. The boiler efficiency reaches approximately 104%, and the emission flue gas temperature can be reduced to about 30 °C. Zhu et al. analyzed the performance of AHP heat recovery in a real case and found that boiler efficiency could be increased to 13.6%, with a flue gas temperature of 30 °C [20]. Fu et al. simulated an absorption heat pump heat recovery system and found that its efficiency could be increased by 11% relative to that of the condensing heat recovery system [21]. Qu et al. integrated an AHP with natural gas-fired boilers to improve boiler efficiency; their results showed that efficiency could be increased by over 10% [22]. However, initial investment is high due to the AHP [23].

From the above mentioned methods, the low temperature oxidizing air isn't well utilized. If the total heat of the flue gas can be recovered by the oxidizing air, in which the oxidizing air is heated and humidified by the flue gas without direct contact, higher heat recovery efficiency with lower costs can be achieved.

To improve the boiler efficiency in a more cost effective and higher efficient way, this study proposes a total heat recovery system between the flue gas and oxidizing air of a gas-fired boiler using a non-contact total heat exchanger. In order to analyze the heat recovery performance of the proposed system, a mathematical model is established. Then, the boiler efficiency of different methods is compared. To investigate the energy saving potential and payback period of this system, technical and economic analyses are conducted for a case study in Beijing.

2. Working principle of total heat recovery of the flue gas

A traditional boiler uses a direct heat exchanger. Its flue gas can only be used to increase the temperature of oxidizing air or return water. The heat transfer process is shown as 1–2′ in Fig. 1. If the humidity ratio of the oxidizing air can be increased to point 3, the enthalpy difference between point 1 and 3 will be much greater than that between points 1 and 2′ for the same temperature difference. In this case, the temperature of the emission flue gas will be close to the ambient temperature. Therefore, this kind of heat transfer process typically saves more energy.

As the moisture in the flue gas cannot be directly recovered to the oxidizing air because of corrosion, direct total heat recovery cannot be used in this situation. To achieve the heat transfer process of 1–3 in Fig. 1, a novel non-contact total heat recovery

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