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Evaluation of a flue gas driven open absorption system for heat and water recovery from fossil fuel boilers

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ABSTRACT

This paper presents an open absorption system for total heat recovery from fossil fuel boilers using the high temperature flue gas as the regeneration heat source. In this system, liquid desiccant serves as the recycling medium, which absorbs waste heat and moisture contained in the low temperature flue gas in the packed tower and then regenerates in the regenerator by the high temperature flue gas. Water vapor generated in the regenerator gets condensed after releasing heat to the heating water system and the condensing water also gets recycled. The return water collects heat from the solution water heat exchanger, the flue gas water heat exchanger and the condenser respectively and is then used for district heating. Driven by the vapor pressure difference between high humidity flue gas and the liquid desiccant, the heat recovery efficiency of the system is not limited by the dew point of the flue gas, enabling a warmer water to be heated up than the conventional condensing boiler. The performance of this system was analyzed theoretically and experimentally and the results showed that the system operated well for both district heat supply and domestic hot water supply. The system efficiency increased with the moisture content of flue gas and the total heat recovery was about 8.5%, 17.2%, 21.2%, and 9.2% higher than the conventional condensing system in the case of coal fired boiler, fuel oil boiler, natural gas boiler, and coke oven gas boiler, respectively.

1. Introduction

The National Bureau of Statistics of China [1] stated that the total energy consumption in the year 2013 in China was nearly 4169 million t of standard coal, about 69.8% of which was for industrial uses. However, most industrial boilers in operation have low energy efficiency and lack waste heat recovery measures, which results in significant energy dissipation. Moreover, the emission of sulfide, nitrogen oxide, and other solid particles causes serious environmental pollution, especially in northern China [2]. Therefore, comprehensive treatments of industrial flue gases are essential for both energy conservation and environmental protection.

Industrial flue gases have the following characteristics. Firstly, the flue gas usually contains 15–40% of the fuels' heat content, which is released at a wide temperature range from 30 °C to 250 °C [3]. Secondly, the industrial flue gas has a much smaller specific heat capacity than the liquid and solid wastes, the temperature will drop significantly after releasing heat to the cooling medium, which makes waste heat utilization difficult. Thirdly, the latent heat often comprises a large proportion of the total waste heat. In the case of natural gas boilers, the humidity ratio of the flue gas is nearly 120 g/kg dry air and the latent heat accounts for about 15% of the total heat due to its high hydrogen content.

Conventional condensing systems [4,5] recover latent heat by cooling the flue gas down to the dew point, which is realized by equipping a condensing heat exchanger between the flue gas and the cooling water. However, the system efficiency depends on the return water temperature and the heat exchange capacity of the condensing heat exchanger. In Beijing, the return water temperature in the district heating system is over 55 °C [6], which is not cold enough to condense the flue gas. Although electrical heat pump systems [7] and absorption heat pump systems [8–10] have been proposed to reduce the return water temperature, additional high quality heat sources such as the direct-fired unit or electricity are required, which is not economic effective.

The open absorption system [11,12] uses the liquid desiccant as the cycling medium and can recover latent heat at a temperature higher than the dew point. It is mainly composed of an absorber, a generator, and a condenser. The liquid desiccant dehumidifies

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Nomenclature

Abbreviations

HX	heat exchanger
GWHX	flue gas-water heat exchanger
SSHX	solution-solution heat exchanger
SWHX	solution-water heat exchanger
LiBr	lithium bromide

Roman letters

T	temperature (°C)
H	relative humidity
G	flow rate
$\dot{m}$	mass flow (kg/s)
A	heat transfer area (m^2)
cp	constant-pressure specific heat (J/(kg·K))
k	heat transfer coefficient (W/(m^2·K))
h	specific enthalpy (kJ/kg)
x	mass fraction of solution
ω	humidity ratio (kg/kg dry air)
Q	heat transfer quantity (kW)

Subscripts

s	solution
w	water
FG	flue gas
a	dry air
vapor	water vapor
h	hot fluid
c	cold fluid
in	inlet of the heat exchanger
out	outlet of the heat exchanger

the flue gas and gets diluted in the absorber. It is then transported to the steam generator through a solution exchanger. In the steam generator, the diluted solution is heated to the boiling point and regenerated by an external heat source. The water vapor from the steam generator releases heat to the cooling water in the condenser, getting condensed and then recycled.

Existing researches on the open absorption system are focused on natural gas boilers and biomass boilers. Zhao et al. [13] verified the feasibility of sorption systems used for waste heat recovery from conventional heating appliances, which includes liquid absorbents and solid absorbents. Westerlund et al. [14] applied an open absorption heat recovery system to a biomass-fired boiler and conducted an operating test. The test results showed 40% heat production increase with wet biofuel and 33–44% particle content decrease compared to ordinary systems. Lazzarin et al. [11] performed a theoretical simulation of an open absorption system and concluded that the primary energy ratio of the system is much higher than the closed absorption systems and the electrical heat pump systems in the case of natural gas boilers. Wei et al. [15] also set up a simulation model of an open absorption system for exhaust heat recovery and indicated that the system is the best choice for the current prices of electricity and natural gas in Beijing. Ye et al. [16] proposed a new process for latent heat recovery to improve the performance of the open absorption system which can switch between single-stage and double-stage modes based on the heat source temperature.

Researches on the open absorption systems in natural gas boilers are limited to theoretical simulations and use of a direct-fired unit as the regeneration heat source. In fact, the high temperature flue gases from the exit flow of boiler combustion chambers can be used as the heat source for solution regeneration and is more economically viable than the direct-fired units. Such flue gas driven open absorption systems have been tested for biomass-fired boilers [14], however theoretical or experimental studies on these systems for fossil fuel boilers are lacking. The performance of an open absorption system for fossil gas boilers can be very different from biomass fired boiler systems as the flue gases differ in terms of specific heat capacity, humidity ratio, particle content, and others. Moreover, investigation on open absorption systems for different types of fossil fuel boilers is also important as nearly 80% of the industrial boilers in China are coal fired boilers, followed by oil fired boilers, and natural gas boilers.

This paper presents a theoretical and experimental investigation of a flue gas driven open absorption system for waste heat and water recovery from different types of fossil fuel boilers using LiBr solution as the recycling medium. An experimental system was set up to test the operation performance where a flue gas generating module was designed to simulate different types of flue gases. Two application scenarios including district heat supply and domestic hot water supply were analyzed. The heat and water recovery efficiency was calculated and compared with those of the conventional condensing systems

2. Principle of the flue gas driven open absorption system

As shown in Fig. 1, the system includes three pipelines: the flue gas pipeline (marked in gray), the liquid desiccant pipeline (blue[1] and pink solid lines), and the heating water pipeline (dash green line). High temperature flue gas from the boiler furnace first enters the steam generator and serves as the heat source for solution regeneration (FG1 → FG2). Then, it flows into the gas-water heat exchanger (GWHX) and releases heat to the water system (FG2 → FG3). The cooled flue gas then enters a counter-current packed tower, which got dehumidified after fully contact with the liquid desiccant (FG3 → FG4). The liquid desiccant gets diluted after absorbing water vapor in the packed tower (S1 → S2). The diluted solution is transported to the generator through the solution-solution heat exchanger (SSHX) (S3 → S4), where it is boiled and regenerated (S5 → S6). The concentrated solution then returns to the absorber through the SSHX (S7 → S8) and the solution-water heat exchanger (SWHX) (S9 → S10). The heating water supply system gains heat from the SWHX (W1 → W2), gas-water heat exchanger (GWHX) (W3 → W4), and the condenser (W5 → W6) in sequence. The vapor (dot dash red line) from the generator condenses after releasing heat to the water system in the condenser and the condensate water is recycled.

3. Experimental setup

3.1. System installation

As shown in Fig. 2, the experimental system mainly consisted of two parts: the flue gas simulation part and the waste heat recovery part. The flue gas simulation part included a low temperature pre-

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.