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Method of flash evaporation and condensation – heat pump for deep cooling of coal-fired power plant flue gas: Latent heat and water recovery

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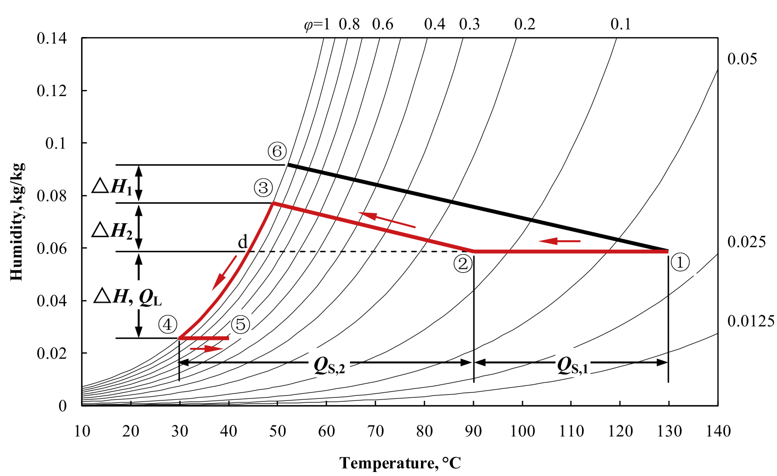
HIGHLIGHTS

- A method is developed for deep cooling of flue gas in coal-fired boilers.
- The method can recover both latent heat and water from flue gas.
- The method utilizes FGD scrubber as a deep cooling exchanger.
- The method adopts the direct heat exchange mode to avoid the corrosion problem.

GRAPHICAL ABSTRACT



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ABSTRACT

Flue gas waste heat recovery and utilization is an efficient means to improve the energy efficiency of coal-fired power plants. At present, the surface corrosion and fouling problems of heat exchanger hinder the development of flue gas deep cooling. In this study, a novel flue gas deep cooling method that can reduce flue gas temperature below the dew point of vapor to recover latent heat and obtain clean water simultaneously is proposed to achieve improved energy efficiency. The heat transfer mode of this method is the direct contact mode, which takes the scrubber, e.g. the flue gas desulfurization (FGD) scrubber, as the deep cooling exchanger. The flash evaporation and condensation (FEC) device and heat pump (HP) are utilized to provide low-temperature medium, such as FGD slurry or water, for washing and deep cooling flue gas, to collect recovered water, and to absorb recovered waste heat. This method is called as the FEC–HP method. This paper elaborated on two optional models of the proposed method. The mechanism for recovering heat and water was also analyzed using the customized flue gas humidity chart, and the method to quantitate recovered heat and water, as well as the results of the case of a 300 MW coal-fired generator set were provided. Net present value calculations showed that this method is profitable in the scenario of burning high-water-content coals. Several potential advantages of this method and suggestions for practical application were also discussed.

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Nomenclature

A_{ar}	ash as received coal (%)
C	flue gas heat capacity (kJ/kg °C)
C_{ar}	carbon as received coal (%)
FEC	flash evaporation and condensation (–)
FGD	flue gas desulfurization (–)
H	humidity (kg/kg)
H_{ar}	hydrogen as received coal (%)
HP	heat pump (–)
LPE	low-pressure economizer (–)
LTE	low-temperature economizer (–)
M_{ad}	air-dried moisture (%)
M_{ar}	moisture as received coal (%)
N_{ar}	nitrogen as received coal (%)
O_{ar}	oxygen as received coal (%)
P	total pressure of air/flue gas (Pa)
P_s	saturated pressure of water vapor (Pa)
P_v	partial pressure of water vapor (Pa)
$Q_{gr,ar}$	gross calorific value as received basis (MJ/kg)
Q_L	latent heat (MW)
$Q_{net,ar}$	net calorific value as received basis (MJ/kg)
Q_S	sensible heat (MW)
S_{ar}	sulfur as received coal (%)
t	temperature (°C)
t_{as}	adiabatic saturation temperature (°C)
t_d	dew point temperature (°C)
V	flow rate of flue gas (m^3/h)
V_{ar}	volatiles as received coal (%)
x	ratio of water's molar mass to flue gas' (–)

Greek abbreviations

γ	water evaporated heat (kJ/kg)
ρ	density of flue gas (kg/m^3)
φ	relative humidity (–)

Subscripts

1, 2, 3, 4, 5, 6 represent the state points of ①, ②, ③, ④, ⑤, ⑥ in Fig. 3, respectively

1. Introduction

Coal-fired power plants consume large quantities of coal and water resources. Consequently, energy saving and water saving are consistent pursuits in this industry. Numerous energy- and water-saving technologies have been used in power plants. Among these technologies, flue gas waste heat recovery and utilization of boilers have been of wide concern. Ordinarily, the boiler discharges flue gas at the temperature of 130–150 °C, which contains large amounts of heat energy. Meanwhile, water and hydrogen in fuels will exist in the form of vapor, which will account for 12–16% of the flue gas volume [1]. Wet flue gas desulfurization (FGD) or other flue gas purification techniques can further increase the humidity of flue gas [2]. Normally, vapor is discharged to the atmosphere together with flue gas. If the flue gas temperature can be decreased below the dew point of the vapor before being discharged, part of the vapor will condense into water and the latent heat will be recovered. The utilization of recovered heat will improve energy efficiency.

Previous studies on flue gas waste heat recovery were concerned with different fuels, such as natural gas [3,4], oil [5], and coal [6], and major methods are mostly realized using indirect cooling exchangers. Low-temperature economizers (LTEs) [7] or low-pressure economizers (LPEs) [8,9] are the kinds of exchangers used in coal-fired power plants. These exchangers are set in the flue behind the air pre-heaters to recover waste heat of flue gas for heating the condensation water of turbine. Exhaust gas temperature can then be reduced from 130–150 °C to approximately 90 °C. This method is called the LTE method, and it has been widely applied in China. During application, the LTE method mainly addresses the surface corrosion and fouling of heat exchangers caused by flue gas dewing. Coal-fired flue gas contains acid steam, vapor, and dust. If the temperature of the exchanger surface, which comes in contact with flue gas, is lower than the dew point [10,11], acid and water will condense on the surface of the metallic heat exchanger and cause the so-called low-temperature corrosion [12], which will shorten the life of exchanger. Otherwise, when the flue gas dews, the condensate will make the exchanger surface wet and the wet surface will be prone to adhere the dust contained in flue gas, which may cause the fouling problem. The fouling will not only increase the heat transfer resistance but also imperil the operation when the fouling blocks up the narrow flue gas passageway between tubes of exchanger. Therefore, the multiple factors of flue gas dewing, corrosion, fouling and narrow flue gas passageway hinder the LTE method further decreasing coal-fired flue gas temperature. In the current commercial application of coal-fired flue gas waste heat recovery, corrosion-resistant materials and controlling the exchanger surface temperature higher than the dew point are usually adopted to prevent low-temperature corrosion and fouling. Thus, the LTE method fails to recover the vapor latent heat in flue gas and only recovers part of the sensible heat. The degree of flue gas cooling is not significantly deep.

Given that low exhaust gas temperature may obtain high energy efficiency, scholars have been conducting studies on the deep cooling of coal-fired flue gas. For example, Espatolero et al. [13] adopted a "plastic" heat exchanger to resist low-temperature corrosion in an attempt to decrease the exhaust gas temperature of coal-fired boilers to 80–90 °C or even less. However, this temperature remained higher than the dew point of water vapor. Hence, no vapor condensation occurred, and only sensible heat instead of latent heat was recovered. Only when the flue gas temperature was lower than the dew point of water vapor (approximately 50 °C) could considerable latent heat and water be recovered. Jeong et al. [14] studied the heat and mass transfer processes of coal-fired flue gas latent heat recovery but did not consider the problems of corrosion and fouling.

For natural gas, little dust, nitrogen oxides, and hardly any SO_2 are present in its flue gas, and thus the problems of corrosion and fouling are not serious [3]. Corrosion-resistant materials such as titanium are also adopted to manufacture heat exchangers [15], making the latent heat recovery for natural gas relatively easy. Chen et al. [4] reported a method using a condensing boiler to recover latent heat and water from the flue gas of a natural gas boiler. The flue gas temperature decreased to 30 °C, and the recovered heat was utilized for district heating. This method adopted an indirect heat exchanger, and polypropylene-coated carbon steel tubes or stainless steel tubes were selected to resist corrosion. Westerlund et al. [16] reported an open absorption system for flue gas purification and heat recovery in burning biomass scenarios. However, the flue gas ingredients of a coal-fired boiler contains more pollutants; as a result, deep cooling and latent heat recovery are more difficult, and no study has been found to report relevant methods in the case of burning coal. Accordingly, the present study intended to find a feasible solution to this problem.