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Research Paper

Heat exchange and water recovery experiments of flue gas with using nanoporous ceramic membranes

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HIGHLIGHTS

- A 20 nm pore-sized ceramic membrane was used to recover water and heat from flue gas.
- Experimental analysis of ceramic membrane for water and heat recovery was conducted.
- Water vapor condensation and capillary condensation were investigated.
- Effect of vacuum in water side on water recovery was studied.

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ABSTRACT

The application of a 20 nm pore-sized porous ceramic membrane for condensation heat transfer in artificial flue gas was presented in this work, and the phenomenon of capillary condensation was investigated. A parametric study was conducted to illustrate the behavior of heat transfer and water recovery by varying the parameters of feed gas, cooling water and vacuum in water side. Results indicate that the amount of recovered water and heat increase with the growth of the feed gas flow rate, feed gas temperature, relative humidity, but decrease with the increase of cooling water inlet temperature. Within a certain range of vacuum (above −5 kPa), changing the cooling water flux has little influence on water recovery. The water recovery rate of the module can be up to above 80% and the heat recovery efficiency can be up to above 40% as well, using the low temperature cooling water. These values can both reach 90% in proper conditions. In addition, when the cooling water temperature is higher than the feed gas dew point, the water recovery rate can still reach above 20% with the help of capillary condensation.

1. Introduction

The installed power-generating capacity (above 6 MW) has reached up to 1.49 billion kilowatts in China by the end of March 2016, of which the thermal power unit accounts for 67.79% [1]. As for China's current energy structure, the thermal power will still be in the dominate state for a long time in the future. Thermal power plants consume a huge amount of water, a report called "Evaluation of Chinese Water Saving energy policy" shows that the amount of water required in thermal power plants is about 903 billion tons in 2015, accounting for 15% of the nation's water consumption. Meanwhile, coal-fired power plants consume about 1.79 billion tons of coal per year, it is the half of the nation's total coal consumption [2]. Considering the present situation of enormous energy consumption and severe shortage of water resources, the thermal power plants should take responsibility for the national energy saving.

In order to avoid corrosion problems in boiler tail flue gas duct, the exhaust gas temperature is usually set above 110 °C. The heat loss of exhaust gas accounts for 4–8% when the large and medium-sized boilers operate in normal state [3], which is the largest part of the heat loss. It estimates that the water vapor content of flue gas from coal-fired boilers is 4–13%, and for gas-fired boilers the content is about 15–20%. Currently, the total amount of water vapor in flue gas emissions is about 1.01 billion tons per year in China. If calculated by the exhaust gas temperature at 80 °C, its latent heat of vaporization is 2538.8 trillion kilojoules, which equals to nearly 100 million tons of standard coal. Therefore, the flue gas from thermal power plants exists great potential for water and energy saving.

In recent years, deep researches on energy saving of the exhaust flue gas have been widely concerned all over the world, mainly

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Nomenclature

J	flux (kg/m^2 h)
$\dot{m}$	mass flow rate (kg/h)
A	area (m^2)
η	efficiency (%)
q	recovered heat flux (J/m^2 h)
t	temperature (°C)
c_p	specific heat (J/kg)
γ	latent heat of vaporization (J/kg)
Subscript	
rev	recovered water
v	water vapor
i	inner diameter of tube
o	outer diameter of tube
in	inlet
out	outlet
h	heat
c	cooling water
max	maximum
g	gas
w	tube wall
s	saturation

including the condenser technology research. Study of condensing flue gas came from the early condensing boiler technology research. In 1971, the original researcher, Gaz de France and L' Industrial de Chauffage, found that this technology was of great significance for the heat recycling and water recovery. Subsequently, condensing boilers had been widely used in heating in the western countries [4]. Lei et al. [5] who conducted a series of experimental studies on the condenser used in the brown coal boiler flue gas, found that the water recovery rate increased with the increasing of the cooling water flux and steam volume, and decreased as the gas velocity increased. In studies, the maximum water recovery efficiency could reach as high as 51.57%. Zhuang et al. [6] designed a recuperative heat exchanger using the single-row bare-tubes for studying the condensation heat transfer of flue gas. And the vapor partial pressure, cooling water flow rate and humidified hot air flow rate were proved to be the main influencing factors of the vapor condensation. Water vapor condensation rate was 40–75% within a relatively wide range of humidified hot air temperature (100–200 °C) and vapor content (4–16%). Jeong [7] established a small-scale water recycling system using boiler feed water and combustion air as the cooling medium, the temperature of flue gas could be cooled down to 40 °C, and the water recovery rate was 10–35%. Copen et al. [8] built a pilot scale system for water vapor recovery, the rate of which was 23–63%. Liang et al. [9] simulated the heat transfer of the gas-fired boiler exhaust using the mixture of air and water vapor in a horizontal tube heat exchanger. The simulation results indicated that the convection-condensation heat transfer coefficient increased with the increasing of gas-vapor mixture flow rate and the water vapor content, and it was 1–3.5 times that of the forced convection heat transfer without condensation in the experimental range. Jeong et al. [10] developed an analytical model for a flue gas condensing heat exchanger system and conducted some experiments to validate it. Results showed that the flux of cooling water had an important influence on the condenser performance, and found that the condensation efficiency would range from 10 wt.% to 30 wt.% when the ratio of $\dot{m}_c/\dot{m}_{g,in}$ was varied from 0.5 to 1.0 (a low ratio). For a 60 MW gas-fired heating system, an economic analysis of the waste heat recovery unit was done by Terhan and Comakli [11]. They found that 10.6% of fuel could be saved, the period of payback was less than one year, and hot-water required by 184 flats could be supplied while the temperature of flue gas could be decreased from 158 °C to 40 °C.

Besides the conventional heat exchangers using metals or plastics mentioned above, there are membranes used as the heat exchangers. The character of membrane condensers is that the condensate can permeate through the membrane along with the heat transfer, and the quality of the condensed water is higher. In 2006, Gas Technology Institution (GTI) developed the transport membrane condenser (TMC), based on the hydrophilic ceramic membrane. This technology could save 20% of energy consumption applied to the gas-fired boiler [12–17]. Macedonio et al. [18] investigated a membrane condenser with microporous hydrophobic PVDF (Polyvinylidene Fluoride) hollow fibers. And the membrane-based process performance simulated results achieved a 20% water recovery efficiency, which could make the plant self-sufficient in water, meanwhile the temperature reduced about 5 °C (for the flue gas, the temperature was 50–90 °C and the RH was 90–100%), in a good accordance with those experiments. Wang et al. [19] used a nanoporous membrane tube bundle to recover both water vapor and latent heat from the flue gas. The mass and heat transfer flux could be improved by increasing flue gas inlet temperature, inlet flow rate and cooling water flux. And increasing cooling water flux or decreasing flue gas inlet flow rate could promote the recovery performance. The increasing of pressure difference through the membrane had no impact on the water and heat recovery efficiency, but could increase the recovered water and heat amount. In this study, the water and heat recovery efficiency reached 20–60% and 33–85%, respectively. As shown in literatures, these membrane technologies have drawn great attention in China as well, but relevant research results are few so far. Therefore, it's necessary and urgent for the theoretical and applied research in this filed.

The aim of the present work is to investigate, based on prior theoretical research, the influence of experimental parameters on the recovery of water and heat from flue gas. Most of experiments were conducted for the low-temperature saturated flue gas after FGD.

2. Experimental and methods

2.1. Porous ceramic membranes and capillary condensation

Nanoporous ceramic membranes consist of three layers (the selective layer, the intermediate layer and the substrate) corresponding to the different pore sizes, as schematically presented in Fig. 1. The nanoporous ceramic membrane has two different kinds of structure, inner side coating and outer side coating (as shown in Fig. 1a and b), depending on where the selective layer is located. Fig. 1a shows a single-channel membrane of inner side coating, the selective layer is located at the innermost. Actually it is commonly shaped into the multi-channel membrane tube. The outer side coating indicates the outermost layer of membrane is the selective layer, as depicted in Fig. 1b. And the membrane is often shaped into single channel membrane tubes. Ordinarily the pore size of selective layer is at the nanoscale and the one of substrate is at the microscale. Hollow micro nanoporous ceramic membrane in this paper refers to the single-channel multilayer