Applied Thermal Engineering 113 (2017) 843–850

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Simultaneous heat and water recovery from flue gas by membrane condensation: Experimental investigation

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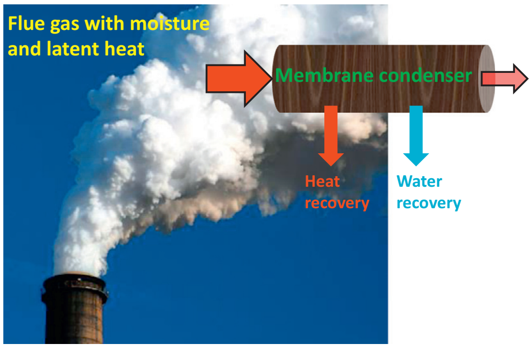
HIGHLIGHTS

- Membrane condenser for water and heat recovery from flue gas is investigated.
- Effect of operational parameters on overall heat transfer coefficient is studied.
- Rise in gas flow rate or water temperature reduces overall recovery performance.
- Rise in water flow rate, gas temperature or humidity improves overall performance.
- This study offers a guideline in optimising parameters in membrane condensers.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 September 2016
Revised 12 November 2016
Accepted 13 November 2016
Available online 14 November 2016

Keywords:
Flue gas
Low-grade heat
Heat recovery
Water recovery
Membrane condenser
Heat transfer

ABSTRACT

A tubular ceramic membrane is investigated as the condenser for simultaneous heat and water recovery from flue gas. The effects of the operational parameters, such as fluid (gas and water) flow rates, temperatures of flue gas and coolant water, and flue gas humidity on the process performance in terms of mass and heat transfer across the membrane are studied. Particularly, the overall heat transfer coefficient is also evaluated. As the gas flow rate increases, water and heat transfer efficiencies and recoveries decline due to the reduced residence time. Increasing the water flow rate or lowing the coolant temperature can effectively improve mass and heat transfer efficiencies and recoveries. Increasing the temperature of the inlet gas can enhance water and heat fluxes and recoveries, but does not improve the overall heat transfer efficiency. The rise in flue gas humidity can dramatically improve water and heat transfer rates and the overall heat transfer coefficient, but has little effect on water and heat recoveries. These results offer a general guideline in optimising the operational parameters in low-grade heat recovery with membrane heat exchangers, and it may greatly advance the development of membrane condensation technology for practical low-grade heat recovery.

1. Introduction

As our world is experiencing energy shortages, utilization of low-grade heat has attracted growing interest [1]. Flue gas from

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http://dx.doi.org/10.1016/j.applthermaleng.2016.11.101
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fossil fuel fired power plants is one of the low-grade heat sources of great interest [2–4]. Wet exhaust flue gas typically has high temperature and moisture, making it a potential source for both energy and water.

The temperature of flue gas varies significantly, depending on the measurement distance from the boiler and the types of power plants. For a coal-fired power plant, generally the flue gas temperature is below 130 °C, and the flue gas contains 10–16% (v/v) water vapor with considerable latent heat. There is no doubt that direct emission of exhaust flue gas into the air causes the waste of energy and water. Considerable energy would be saved if partial waste heat can be recovered from flue gas. It is estimated that 35 million tons of standard coal can be saved annually if half of the latent heat in the flue gas can be recovered [5].

On the other hand, large quantity of water is consumed in power plants, and power plants could be self-sufficient with water if 20% of water vapor in flue gas can be captured [6]. Therefore, recovering low-grade heat and/or water vapor from flue gas has been a technical challenge for the science and engineering communities and industry [5,7–10].

Several technologies, such as organic Rankine cycle (ORC) [2,11,12], absorption systems [13], condensation methods [3,14], waste heat boilers and heat exchangers [9,15,16], have been studied for waste heat and/or water recovery from exhaust gas. However, these methods have their limitations in practical low-grade heat recovery from power plants. For example, ORC systems require extra heat to preheat the ORC working fluid. The relatively low temperature of flue gas also limits the efficiency of using conventional heat exchangers and thus requires large surface areas. High regeneration cost makes the adsorption method too expensive. Efficient alternative technologies are highly needed for recovering the low-grade heat and water vapor from flue gas.

One of the most promising technologies, membrane condensation, has emerged to recover heat and water from wet exhaust flue gas from coal-fired power plants [17–19]. Membrane condensers as novel heat exchangers can overcome the disadvantages of conventional technologies (e.g. corrosion, fouling and high energy consumption [14]) in water and heat recovery [10,20–22]. A membrane heat exchanger may also offer higher heat recovery efficiency than conventional heat exchangers because both mass and heat transfer occurs across the membrane [23].

Two types of membrane condensers based on different mechanisms have been employed for heat and/or water recovery from flue gas. Wang et al. [8,10] developed hydrophilic ceramic membranes as transport membrane condensers for water and heat recovery from flue gas, where water vapor transfers through the membrane via capillary condensation. The recovered heat and water can be used for boiler makeup water. More recently, this condensation technology has been used for water recovery from internal combustion engine exhaust gas [24] and heat recovery in carbon capture [25]. Macedonio et al. [20–22,26] employed hydrophobic porous polymer membranes for water recovery from flue gas, where water vapor condenses and is then collected on the feed side and non-condensable gases permeate through the membrane.

In our previous studies, saturated gas streams at relatively low temperatures (<85 °C) were studied with both monochannel and multichannel ceramic tubes [19,27]. In the current work, we employ a new method to generate simulated flue gas (relatively humidity: 11–14 vol.% at 100 °C) and explores the feasibility of employing nanoporous tubular ceramic membranes for simultaneous water and heat recovery from simulated flue gas. Influences of operational parameters, such as gas flow rate, coolant water flow rate, inlet gas temperature, coolant water temperature and flue gas humidity on process performance are investigated. This study offers a guideline in optimising the operational parameters in low-grade heat recovery with membrane heat exchangers, and it may greatly advance the development of membrane condensation technology for practical heat and water recovery from power station flue gas.

2. Materials and methods

2.1. Membrane preparation

We prepared membranes using the method that can be found elsewhere [28]. Briefly, titania sol was synthesized through the colloidal sol-gel method. The prepared sol was coated on a tubular α-Al_2O_3 mesoporous support via dip-coating [29], and then calcined at 400 °C for 3 h. The support (OD: 12 mm, ID: 8 mm, length: 85 mm, average pore size: 20 nm) was obtained from Jiangsu Jiuwu Hi-tech Co. China.

The tubular ceramic membrane has its separation layer on the inner side, and its thickness is ~100 nm. Average pore size of the separation layer is ~7 nm, based on the gas bubble method [30,31]. The ceramic membrane has an effective area of 0.0021 m^2.

2.2. Flue gas

Simulated flue gas containing air and water vapor was produced by the following system. Measured water vapor contents within the simulated flue gas (i.e. humidity ratios) were 85–100 g/kg, which corresponds to 11–14 vol.% in flue gas at 100 °C. Humidified air has been simulated as engine exhaust gas in a similar lab-scale investigation [24].

2.3. Experimental setup

A bench-scale setup was designed for artificial flue gas generation and heat and water recovery (Fig. 1). First, dry air was humidified and preheated with a heating water bath, and its flow rate was measured by a mass flow controller (Bronkhorst High-Tech). The humidified air flowed into a steam generator (HGA-M-01, United States) coupled with a temperature and power control system by which the flue gas temperature from the steam generator and the input power could be finely controlled. The generated artificial flue gas (i.e. air and water vapor) flowed into tube side of the membrane. The humidity of inlet flue gas was monitored by a humidity transmitter (HMT337, Vaisala, Finland) and the gas temperature was measured with a thermocouple. Cold water countercurrently flowed on the shell side of the ceramic tube. The whole system was thermally insulated.

Temperature of the coolant water increased gradually due to the transferred heat from the hot gas side. Heat transfer can be determined based on the flow rate, inlet and outlet temperatures of water. Mass transfer can be calculated according to the weight change of the liquid water with a balance. When mass transfer and heat transfer became relatively steady, data recording was commenced. The time to reach a relatively steady state varied from 20 to 50 min depending on the experimental conditions. For each experimental condition, the weight and temperature data were recorded for 50 min at a time interval of 2 min.

2.4. Flux and recovery determination

In a membrane heat changer, simultaneous mass and heat transfer occurs across the membrane. Water and heat fluxes and recoveries are important parameters for assessing the membrane process performance.

Water flux (J_w) and heat flux (q) can be respectively described by