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Research Paper

Experimental study on flue gas condensate capture and heat transfer in staggered tube bundle heat exchangers

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HIGHLIGHTS

- Effects of factors on condensate capture rate and heat transfer are presented.
- Compound HT coefficient is 2–4 times the pure convective HT coefficient.
- Condensate capture rate can reach above 50%.
- Empirical formula of the heat transfer coefficient is fitted.

ARTICLE INFO

Keywords:
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Condensation
Capture rate
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ABSTRACT

Experiments on the flue gas condensation in multi-row staggered tube bundle heat exchangers are carried out. The effects of the flue gas velocity, water vapor volume fraction, cooling water flow rate, cooling water temperature, and cooling water flow arrangement (series or parallel) on the condensate capture rate and heat transfer coefficient are presented and discussed. The compound heat transfer coefficient can attain a value 2–4 times that of the pure convective heat transfer coefficient, and the condensate capture rate can attain a value above 50%. There is a suitable cooling water flow rate with an adequately low wall temperature and an adequately high heat transfer coefficient and condensate capture rate. However, the condensate capture rates of the heat exchangers in the series arrangement are apparently lower than those in the parallel arrangement. With the increase of the cooling water temperature, the condensate capture rate decreases; however, the heat transfer coefficient increases under a similar condition. Finally, the empirical formula of the heat transfer coefficient of multi-row staggered tube bundle heat exchangers is determined, and it exhibits good agreement with the experimental data.

1. Introduction

As a motivating force for economic and social development, energy is experiencing significant worldwide demand [1,2], and power plants are the primary source of energy consumption. The flue gas latent heat loss of power plants that consume fossil fuels and biomass fuel has increased to 5–10% owing to the direct exhaustion of water vapor [3–5]. If the flue gas temperature falls below the dew point, the water vapor could condense, both the sensible heat and latent heat of the flue gas could be recycled, and the water vapor in the flue gas could be captured. Therefore, it is important to reduce the flue gas heat loss as well as recycle the flue gas moisture.

The core of flue gas condensation is water vapor condensation in the presence of a significant amount of non-condensable gas, which has been studied in various situations by several researchers. For example, the effect of air on the static saturated vapor condensation on a smooth horizontal tube was studied by Othmer [6].

The experimental results revealed that an air volume fraction of only 0.5% can reduce the heat transfer coefficient by over 50%. In addition, vapor condensation on a vertical tube in the presence of pure steam, steam–air mixed gas, and steam–helium mixed gas was studied by Kuhn et al. [7]. Furthermore, condensation on a staggered tube recuperative exchanger for a boiler flue gas was investigated by Osakabe et al. [8,9]. The condensation of steam–air mixed gas in a horizontal tube was studied by Ren et al. [10]. The results revealed that the overall heat transfer coefficient decreased as the inlet non-condensable gas fraction increased. Two correlations for the stratified flow and annular flow were developed. An increase in the inlet mass flux can enhance the heat transfer rate and the overall heat transfer coefficient.

Based on these experimental studies, theoretical studies have also

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Nomenclature

q	volume flow rate, m^3/s
V	flue gas velocity, m/s
d	diameter, m
d_H	humidity ratio, kg (vapor)/kg (dry air)
h	heat transfer coefficient, $W/(m^2 K)$ or $W/(m^2\ °C)$
p	pressure, Pa
t	temperature, °C
l	length, m
Q	heat transfer, W
A	area, m^2
c	specific heat, J/(kg K)
W	water vapor volume fraction, %
Δt	logarithmic mean temperature difference, °C

Greek symbols

φ	correction factor, 0.942 [23]
φ_a	relative air humidity, %
λ	thermal conductivity, W/(m K)
ρ	density, kg/m^3
η	dynamic viscosity, Pa s
η_0	dynamic viscosity of water at 0 °C, 1.792×10^{-3} Pa s

Dimensionless groupings

Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number

Subscripts

s	saturation
f	flue gas
w	tube wall or cooling water
i	inlet
o	outlet
NG	natural gas

been conducted by a few researchers. In 1934, Colburn et al. [11] proposed the double membrane model for vapor condensation in the presence of non-condensable gas; then, a differential and algebraic method for solving the heat and mass transfer of water vapor condensation in gas–vapor mixture flows was presented by Li et al. [12]. Theoretical studies on water vapor condensation in natural gas were conducted by Chantana et al. [13], and the influence of pressure on the local and average condensation heat transfer in a vertical tube was investigated by Berrichon et al. [14]. Zschaeck et al. [15] validated a mathematical model for wall condensation in the presence of non-condensable gas using ANSYS CFD. Vyskocil et al. [16] presented a condensation model for both compressible and incompressible flow, and Terhan et al. [17] used a one-dimensional finite-difference method to design a waste heat recovery unit for a natural-gas-fired boiler. In addition, Wang et al. [18] presented a case study on the recovery of the waste heat of the exhaust flue gas in a 600 MW power plant, and Shi et al. [19] investigated a finned tube compact heat exchanger for latent heat recovery from exhaust flue gas.

Although the condensation in the presence of non-condensable gas has been studied for some time, the condensate capture performance has received little attention. Moreover, the effect of different factors on the flue gas condensation process has not been investigated in detail. In this study, experiments on water vapor condensation and heat transfer in multi-row tube bundle heat exchangers have been performed. The effects of the influencing factors such as the flue gas velocity, water vapor volume fraction, cooling water flow rate, cooling water temperature, and cooling water flow type, on the flue gas water vapor condensation and heat transfer were studied.

2. Experimental system and conditions

2.1. Experimental system

The experimental system for the flue gas condensate capture is

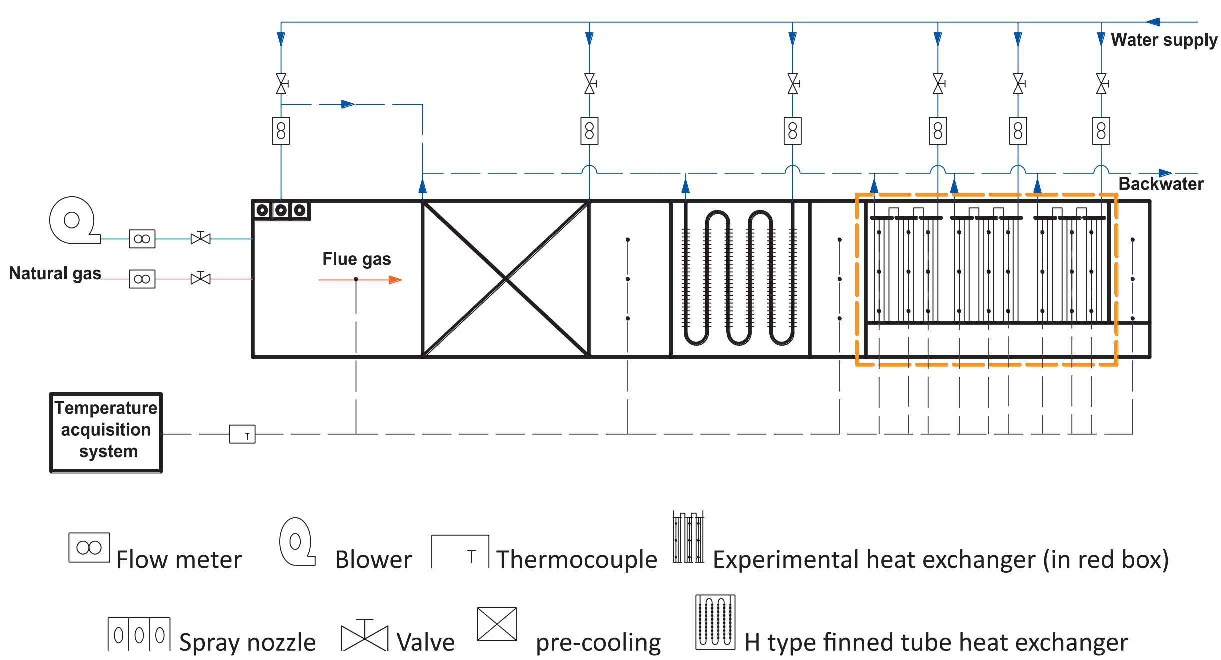

Fig. 1. Diagram of the experimental setup.