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Experimental and numerical studies on actual flue gas condensation heat transfer in a left–right symmetric internally finned tube

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ABSTRACT

To improve the thermal efficiency of gas fired equipment, latent heat recovery from the flue gas is a very important concept. Based on the analysis of heat transfer enhancement mechanism in an internally finned tube, in this paper, a new type left–right symmetric internally finned tube is proposed. The heat transfer characteristics of the new type left–right symmetric internally finned tube, the centrosymmetric finned tube and the smooth tube is numerically and experimentally investigated. The numerical simulation results indicate that the left–right symmetric internally finned tube has a promising potential for enhancing the convection heat transfer, in particular, its heat transfer coefficient is 4–8 times higher than that of the reference smooth tube and 1.3–1.8 times higher than that of the centrosymmetric finned tube. The experimental results show that the excess air coefficient, the cooling water flow rate, the water inlet temperature, and the *Re* number have prominent effects on the convection-condensation heat transfer. The left–right symmetric internally finned tube can effectively decrease the radial temperature gradient, reduce the thickness of the non-condensable gas layer and significantly strengthen the water vapor condensation. The convection-condensation heat transfer coefficient of 10 fins left–right symmetric internally finned tube is about 4.1 times higher than that of the forced convection without condensation. A dimensionless number *Tv* is derived, which takes into account the effects of the water vapor saturation temperature, the average flue gas temperature, the average internal wall temperature and the inlet water temperature. They are represented in an empirical formula for the condensation heat transfer process.

1. Introduction

Recently, most energy consumed in China is from coal and the most serious problem from coal combustion is air pollution. Due to the rising living standard and the emphasis on biological and environmental safety, natural gas as a kind of clean energy is more and more widely used in China, especially as the fuel of gas-fired boilers. Compared with coal, natural gas has obvious superiorities, such as high caloric, high combustion efficiency and low pollution. However, for a conventional boiler, in order to avoid dew-point corrosion, the exhaust flue gas temperature is usually over 150 °C, sometimes as high as 250 °C [1]. Under these temperature conditions, the water vapor in the flue gas is incondensable. While natural gas is used as the fuel of the boiler, as high as a 20% volumetric fraction of water vapor in the combustion products will be generated [2]. The flue gas generated from 1 m^3 natural gas carries in theory 1.5 kg of water vapor which contains 3.6 MJ of latent heat. Consequently, there is a large quantity of latent heat in heat loss of the exhaust gas from gas-fired boilers. If the latent heat and sensible heat are recovered simultaneously, the overall energy efficiency can be improved about 10%. The detailed variation of the latent heat, sensible heat and thermal efficiency changing with the flue gas temperature are shown in Table 1. It can be seen that the waste heat recovery by means of condensation heat transfer is promising.

To recover the latent heat of the water vapor in the flue gas, condensing boiler was put forward in 1970s. Up to now, condensing boilers have been developed and widely applied in most country [3]. A large number of studies on condensing boilers have been conducted. Makansi [4] investigated the influence of the materials, design and upkeep schemes on the performance of the flue gas recuperators for industrial boilers and furnaces. Kuck [5] gives a thermodynamic analysis of the PAVE process in combination with indirect-contact condensing boilers. Rosa and Tosato [6–8] discussed the effects of various factors on the seasonal efficiency or annual efficiency of condensing boilers. Ganapathy [9] and Goldstick [10] proposed some general methods for designing condensing heat exchangers. Idem et al. [11,12], Idem and Goldschmidt [13], Jacobi et al. [14] and Jocobi and Schmidt

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Nomenclature

h	heat transfer coefficient, W/(m^2 K)
c	vapor molar concentration, mol/L
r	vaporization latent heat, J/kg
r	radius, m
M	vapor molecular weight, g/mol
P	pressure, Pa
R	universal gas constant, J/(mol K)
T	temperature, K
H	enthalpy, J/kg
A	heat transfer area, m^2
Q	heat transfer quantity, W
a, b, c	experimental constants
Re, Le, Pr, Tv	dimensionless Parameter
m	mass flow rate, kg/s
c_p	specific heat, J/(kg K)

Greek symbols

ρ	density, kg/m^3
ω	condensation ratio, %
ξ	latent heat proportion, %
φ	volume fraction of water vapor in flue gas, %

Subscripts

f	flue gas
w	finned tube wall, water
v	vapor
i	near wall region
in	inner surface
out	outer surface
m	average value
cond	condensation
conv	convection
s	vapor saturated temperature
wi	finned tube inside wall

[15,16] studied the heat and mass transfer performance of a finned-tube condensing heat exchanger both experimentally and analytically. Park et al. [17] proposed a correlation of vapor-side heat transfer coefficients for condensation of a steam–air mixture on a vertical surface. Cao et al. [18] experimentally investigated the forced convective heat transfer of heat exchangers used in gas boilers with steam condensing. Osakabe [19,21], Osakabe et al. [20,22,24,25] and Osakabe and Itoh [23] experimentally studied the condensation heat transfer of an actual flue gas from a natural gas boiler on horizontal stainless steel tubes. The parametric studies concerning the effects of tube stages, gas velocities, SO_2 in the flue gas and Teflon-lined tubes were conducted at a wide range of tube surface temperature. They also utilized real flue gas with different vapor mass fractions to test the heat transfer on horizontal smooth tubes and spiral fin tubes. Cui and Qian [26] studied the natural flue gas condensing heat transfer of single-row plate-fin-tube heat exchanger. Jia et al. [27] theoretically and experimentally studied the effects of water vapor condensation on the convection heat transfer of wet flue gas in a vertical tube. Che et al. [28] and Liang et al. [29] analyzed the heat and mass transfer process of high moisture flue gases flowing downward in a bank of horizontal carbon steel tubes. They also studied the forced convection heat transfer with water vapor condensation both theoretically and experimentally when wet flue gas passes downwards through a bank of horizontal tubes. Besides, they [30] experimentally and theoretically investigated the utilization of finned tube compact heat exchanger for a heat recovery steam generator to recover both sensible and latent heat. However, some of the previous studies above-mentioned were concerned with condensation of vapor–air mixture not the actual flue gas. The property of vapor–air mixture is different from the actual flue gas in a large temperature range. For the actual flue gas produced by natural gas combustion, the condensation heat transfer process is quite more complex than the vapor–air mixture. Besides, the tubes for latent heat recovery in the previous studies above-mentioned are smooth tubes or outer finned tubes, and few tubes are internally finned tubes. Even if it is a finned tube, there is a large thermal contact resistance between the fins and the parent tube. The actual flue gas flew outside the tube rather than inside the tube. Moreover, there are few studies on the heat transfer performance of internally finned tube including sensible and condensation heat transfer performance simultaneously. To deal with such a complex problem, in this paper, a new type left–right symmetric internally finned tube is proposed. Firstly, its sensible heat transfer performance is numerically studied and the appropriate fin structure is determined. Then the condensation heat transfer performance of the appropriate structure is experimentally investigated under the condition that the actual flue gas flows inside the new type left–right symmetric internally finned tube. Ultimately, an empirical formula for calculating the condensation ratio is put forward based on the experimental study.

Table 1
Heat transfer and thermal efficiency.

Temperature (°C)	220–120	220–45	120–45
Sensible heat transfer (kJ/m^3)	1415.24	2714.49	1299.25
Latent heat transfer (kJ/m^3)	0	1971.5	1971.5
Sensible heat/latent heat (%/%)	100/0	57.9/42.1	39.7/60.3
Total heat transfer (kJ/m^3)	1415.24	4686.01	3270.77
Thermal efficiency increase (%)	4.4	13.97	9.55

2. Theoretical analysis

The Colburn–Hougen model (Fig. 1) has been widely used to calculate the condensation heat transfer coefficient in a heat-exchanger with a mixture of non-condensable and condensable gas being cooled [31]. The caloric transporting through the gas phase boundary layer equals to that passing through the liquid phase condensation film in this model. The caloric is composed of sensible heat emitted by the non-condensable gas convection and latent heat released by the condensable gas condensation. The heat resistances of condensation heat transfer mostly concentrate in the non-condensable gas boundary layer. Since the non-condensable gas accounts for over 80% volume fraction in practical application, and the heat resistances in the liquid phase condensation film are much smaller so that it can be ignored. It can be assumed that the convection heat transfer coefficient h of flue gas in the inside tube wall equals to the convection condensation heat transfer coefficient h', and the temperature difference between condensation film and tube wall can be further neglected. Subsequently, in case of $Le = 1$, the convection heat transfer coefficient h can be written as: