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Research Paper

Experimental research of fouling layer and prediction of acid condensation outside heat exchanger used in coal-fired boiler

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HIGHLIGHTS

- Effects of Re_{water}, T_{in}, T_{gas} and Re_{gas} on heat transfer efficiency of fouling layer are obtained via field experiments.
- 1-D model is built for prediction of acid condensation. Influences of $T_{wall,o}$, y_A and y_W on acid condensation are studied.
- The safety operation of heat exchanger is recommended considering the experimental results and acid condensation analysis.
- The enhancement of heat transfer efficiency and boiler thermal efficiency by reducing fouling is analyzed.

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ABSTRACT

Research on the fouling layer covering heat exchangers is of practical value to increase the efficiency of heat exchangers and even that of boiler, especially when considering coupled effects of ash deposition and acid condensation. The field experiments are carried out using a special designed pipe in a 300 MW sub-critical unit. The effects of internal Reynolds number of water (Re_{water}), inlet temperature of water (T_{in}), flue gas temperature (T_{gas}) and external Reynolds number of flue gas (Re_{gas}) on heat transfer efficiency have been analyzed via the calculation of fouling factor (ε) as well as external Nusselt number of flue gas (Nu_{gas}). Apart from this, the 1-D model to describe the acid condensation has been built in light of the thermodynamic results of water vapor and sulfuric acid vapor obtained by former research. In this model, both gas-liquid equilibrium effect and multi-component diffusion effect have been well considered. Furthermore, the acid condensation can be influenced to different extents by the exterior wall temperature of the pipe, acid vapor and water vapor contents of flue gas. Consequently, the efficiency of heat exchangers is enhanced by the rise of exterior wall temperature according to the experimental results and acid condensation analysis.

1. Introduction

The thermal power plants are currently providing most electricity in China, and the advanced utilization of flue gas becomes a popular method to save energy. Former researchers have been focused on the waste heat utilization to relieve energy shortage and environment pollution caused by the coal fired boiler [1–5]. The efficiency of boiler in the waste heat utilization systems mainly depends on the heat transfer efficiency and flowing resistance, i.e. the higher heat transfer efficiency and less resistance, the higher efficiency of boiler. In past decades, many kinds of finned tubes were studied experimentally and numerically to enhance thermo-flow performances, but nearly all studies failed to consider the fouling layer in practical applications [6–8]. The thermo-flow performances of heat exchangers tend to be influenced by the operating environment, especially when the gas contains particles. Specifically, when the flue gas of coal-fired boilers typically contains fly ash and some acidic gases such as NO_x, SO_2, and SO_3, the acid vapors like HNO_3, H_2SO_3 and H_2SO_4, will generate when they come across and then react with H_2O (g). Worse still, these vapors are condensed while the temperature is lower than acid dew point (ADP). Moreover, the mixture of condensed droplets and fly ash further stick on the metal heating surface, leading to the fouling layer. The fouling layer, thus, increases thermal resistance of heat exchangers, deteriorating the thermal performance of waste heat utilization system and even that of boiler. To fill this blank, research on fouling layer outside heat exchangers considering coupled effect of ash deposition and acid condensation is necessary in the waste heat utilization of coal-fired boiler.

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Nomenclature

A	heat transfer area, m^2
a_i, b_i, c_i	heat capacity constants of pure component *i* at 298 K, J/mol·K
C	specific heat capacity of water, J/(kg·K)
C_A	acid solution concentration, %
$\bar{c}_i^l$	partial molar heat capacity of species i in sulfuric acid solution at 298 K, J/mol·K
d	diameter, m
$D_{i,j}$	binary diffusivity, m^2/s
$D_{i,\max}$	effective diffusivity of component i, m^2/s
G	volume flow rate of water, m^3/s
h	convective heat transfer coefficient, W/(m^2·K)
K	overall heat transfer coefficient, W/(m^2·K)
K_0, K_1	chemical reaction equilibrium constants, –
l	characteristic length, m
L	depth of test pipe, mm
$\bar{L}_i^l$	partial molar enthalpy of species i in sulfuric acid solution at 298 K, J/mol
$ln\bar{a}_i$	logarithmic of activity of species i in sulfuric acid solution at 298 K, –
M	molar mass, g/mol
Nu	Nusselt number, –
p_i	partial pressure of species i at the gas-liquid interface, Pa
P_i	apparent partial pressure, Pa
Pr	Prandtl number, –
Q	total heat transfer rate, W
R	ideal gas constant, J/mol·K
$R_{fouling}$	thermal resistance of ash fouling outside test pipe, (m^2·K)/W
$R_{furring}$	thermal resistance of furring inside test pipe, (m^2·K)/W
R_i	condensation rate, 10^{-6}g/m^2·s
R_{wall}	thermal resistance of pipe wall, (m^2·K)/W
T	temperature, °C
t_{ADP}, ADP	acid dew point, °C
u	velocity, m/s
y_A	acid vapor content of flue gas, ppm
y_W	water vapor content of flue gas, %
Y_i	concentration of component i, g/m^3

Greek symbols

ΔH_i^v	molar evaporation enthalpy of pure component *i* for at 298 K, J/mol
ΔS_i^v	molar evaporation entropy of pure component *i* for at 298 K, J/mol·K
ΔT	temperature difference between the inlet and outlet of water, K
ΔT_m	logarithmic mean temperature difference, K
α	conversion rate of SO_2 to SO_3, %
α_i	partial molar heat capacity constant of species i in sulfuric acid solution at 298 K, J/mol
β	influence factor of reducing SO_3/H_2SO_4 by the reaction of fly ash and condensed acid droplets, %
δ	thickness of tube, mm
δ_T	thermal boundary layer thickness, mm
δ_C	mass-transfer boundary layer thickness, mm
ε	fouling factor, (m^2·K)/W
η	dynamic viscosity, Pa·s
τ	time, hour
λ	thermal conductivity, W/(m·K)
ν	Kinematic viscosity, m^2/s
ρ	density of water, kg/m^3
σ	error, –
Φ_i	fugacity coefficient of component *i*, –

Subscript

c	cooling tubes
clean	clean surface
furring	furring inside the pipe
fouling	ash fouling outside the pipe
gas	flue gas
h	thermostatic water tank
i	inner
in	inlet
o	outer
out	outlet
p	test pipe
wall	wall of pipe
water	water
A	acid
W	water

In general, fly ash with different sizes/shapes easily deposits on the outside walls of heat exchangers. The phenomenon of ash deposition has been studied by a number of numerical studies [9–12]. For the effect of fouling on heat transfer efficiency, Teruel et al. [9] described a systematic approach to predict ash deposits in the furnace wall of coal-fired boilers by means of artificial neural networks. Then, Kaptan et al. [10] numerically investigated the effects of fouling diameter and eccentricity by using conjugated heat transfer approach. To predict the particle deposition rate on the heat exchanger surface, Han et al. [11] developed a numerical model and examined the effects on fouling rate at six different kinds of parameters, like particle diameter, flow velocity, spanwise tube pitch, longitudinal tube pitch, tube geometry shape, and arrangement. So as to make clear the fouling processes, Tong et al. [12] proposed a numerical method and analyzed the effects of velocity and particle diameter on fouling rate. All the previous numerical studies did not take acid vapor of flue gas into consideration, yet just concentrated on the ash deposition. As known, the condensed mixture can lead to the acid corrosion and lower the heat transfer efficiency. Wherein, the low temperature corrosion is mainly caused by H_2SO_4 condensation in the waste heat utilization of coal-fired boiler [13]. Several field experiments have been carried out to figure out the effect of fouling outside heating surfaces on heat transfer efficiency. Shi et al. [14] carried out an experiment of helical finned tubes in staggered or in-line arrangement to evaluate the influence of ash deposition on heat transfer performance of finned tubes. Engineering Acid Dew Temperature (EADT) is proposed in light of the hot-state experiments results on double-pipe heat exchanger [15,16]. To discuss the formation of fouling covering heat exchangers, the influences of flue gas properties on ash particle accumulation was investigated, especially gas temperature, contents of water vapor and sulfuric acid vapor, dust concentrations [17,18]. Besides, the influence of both acid-ash coupling deposition and water-ash coupling deposition on heat transfer efficiency is evaluated by a field experiment with H-type elliptical finned tubes [19]. Vuthaluru et al. [20] undertook a chemical and mineralogical study via collecting and analyzing several deposit samples to figure out the deposit formation in the air heater sections of the boiler. All results show that the fouling characteristics are decided by the coupled effect of ash deposition and acid condensation. Nevertheless, the previous experiments merely focus on the ash deposition process with no regard for the calculation