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Research Paper

Numerical investigation on the coupling of ash deposition and acid vapor condensation on the H-type fin tube bank

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HIGHLIGHTS

- Particle deposition is studied with combined acid vapor condensation and fly ash deposition.
- Factors of particle diameter, flue gas velocity, acid vapor content and tube bank are considered.
- Distribution and deposition mass of low temperature bonding ash and loose ash are discussed.
- The low temperature bonding ash is largest on the first row tube in in-line tube bank.
- Loose ash is largest on the third row in staggered tube bank.

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ABSTRACT

There usually occurs a serious fouling on the heating surface of the low temperature economizer in boilers. The deposited ash on the surface could cause clogging and corrosion of the heat exchanger and even result in serious safety incident. Especially the low temperature bonding ash will corrode the surface severely. The distributions of the low-temperature bonding ash and the loose ash on the surface are numerically simulated in this study based on the theory of the particle transportation model, particle deposition model, force analysis of the particle and the acid point temperature model. The effect of fly ash particles on the content of the acid vapor in the flue gas is considered. Various factors on the distribution of deposited ash are investigated including the particle diameter, flue gas velocity, content of the acid vapor and the tube bank arrangement. The low temperature bonding ash is the largest on the first row tube in the in-line tube bank. However, both modes of deposited ash are largest on the third row tube in the staggered tube bank and they are difficult to remove.

1. Introduction

The economizers in coal-fired boilers usually face three significant problems: low heat transfer efficiency of the flue gas, serious tube acid corrosion and fouling. Many researchers have presented effective solutions to improve the heat transfer [1–4]. However, the other two problems remain to be solved. The deposited ash particles on the surface will decrease the heat transfer coefficient and clog the surface [5]. The ash deposition mode has been studied by various methods. The fouling process on a single tube was simulated by the Boltzmann method and the results showed that the inlet velocity and the particle diameter have important effects on the fouling rate [6]. Some researchers studied the characteristics of the deposited ash experimentally [7–9]. In the experiments, the deposited ash sample was analyzed using the scanning electron microscope and the characteristic of the deposited ash was obtained. The ash deposition was also studied by combining the simulation and the experiment and the effects of particle diameter and the Stokes number were considered [10].

On the other hand, the acid dew point corrosion is a problem with widespread concern in heat exchanger. The sulfur trioxide and the water vapor in the flue gas will condense into the acid solution on the heat transfer surface when the wall temperature is lower than the acid dew point temperature [11]. The acid solution on the surface will corrode the heat exchanger surface. So the study for the acid dew point temperature is of significance. The acid dew point temperature was predicted by both experiments [12,13] and simulation method [14]. In the simulation various factors were considered which could affect the acid dew point temperature. When the sulfuric acid vapor condenses on the surface, at the same time the particles also deposit on the wall surface with condensed sulfuric acid solution. The coupling mechanism of the acid vapor condensation and the deposited ash needs to be discovered. Experimental studies are usually carried out due to the

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Nomenclature

a_i, b_i, c_i	ideal-gas heat capacity coefficients
$\bar{a}_i$	activity
c_a	concentration of sulfuric acid solution
c_p	specific heat, J·kg^{-1}·K^{-1}
C_d	drag coefficient
C_{lv}	lift coefficient
C_{pi}^{l}	partial-molar heat capacity, J·mol^{-1}·K^{-1}
C_r	particle real concentration, kg·m^{-3}
$C_{1\varepsilon}$, $C_{2\varepsilon}$	turbulence model constants
D_{am}	effective diffusion coefficient for sulfuric acid vapor, m^2·s^{-1}
D_p	particle diameter, m
F	contact load, N
F_a	adhesion force, N
F_b	Brownian force, N
F_d	drag force, N
F_{el}	limited elastic deformation contact load, N
F_g	gravity, N
F_{lv}	lift force, N
F_n	contact force, N
F_{th}	thermophoretic force, N
ΔH_i^v	heat of vaporization, J·mol^{-1}
k	turbulent kinetic energy, m^2·s^{-2}
K_0, K_1	equilibrium constants
L_i^l	partial-molar enthalpy, J·mol^{-1}
m_d	deposition mass of particles, kg·m^{-2}
n_{cr}	critical deposition number of particles
n_{in}	incident number of particles
N	deposition number of particles
N_a	flux of sulfuric acid vapor, mol·m^{-3}·s^{-1}
P	pressure, Pa
P_a	acid vapor partial pressure, Pa
$P_{a,o}$	apparent acid vapor partial pressure, Pa
P_i	monomer partial pressure, Pa
P_w	water vapor partial pressure, Pa
ΔQ	heat of vaporization, J·mol^{-1}
$Q_{A,a}$	surface adhesive energy of particle, J
$Q_{A,r}$	adhesion energy of particle, J
Q_{el}	limited elastic energy, J
Q_{in}	kinetic energy of particle, J
Q_p	energy loss, J
Q_{pe}	stored plastic deformation energy, J
r_{el}	contact radius, m
R	ideal gas constant, J·mol^{-1}·K^{-1}
R_c	curvature radius, m
Re	Reynolds number
Re_p	particle Reynolds number
R_p	radius of particle, m
R_ε	rate of strain term, s^{-1}
S_{in}	inlet surface area, m^2
ΔS_i^v	entropy of vaporization, J·mol^{-1}·K^{-1}
T	temperature, K
T_a	acid dew point temperature, K
$T_{a.0}$	pure acid dew point temperature, K
v_a	critical adhesion velocity, m·s^{-1}
v_g	velocity of flue gas, m·s^{-1}
v_{in}	incident velocity of particles, m·s^{-1}
v_m	critical remove velocity, m·s^{-1}
v_p	velocity of particles, m·s^{-1}
v_r	rebound velocity of particles, m·s^{-1}
y	elastic load limit, N

Greek symbols

λ	thermal conductivity, W·m^{-1}·K^{-1}
α_i	partial-molar heat capacity coefficient, J·mol^{-1}
η	turbulent viscosity, kg·m^{-1}·s^{-1}
μ	flue gas dynamic viscosity, N·s·m^{-2}
α_k, α_ε	inverse effective Prandtl number for k and ε
ε	turbulent energy dissipation rate, m^2·s^{-3}
ρ	density, kg·m^{-3}
$\phi_{a,0}$	apparent fugacity coefficient of acid vapor
Γ	surface energy, J
δ	interpenetration distance of particles, m
δ_{cr}	critical deposition thickness, m

Subscripts

a	sulfuric acid or adhesion
g	flue gas
in	inlet
w	wall or water
p	particle

complex coupling mechanism. Wang et al. [15] analyzed the elemental composition, micro-morphologies and weight loss of the fouling deposition on the blade in a 330 MW coal-fired power plant. The ash deposition could be divided into three stages: mere ash deposition, acid-ash coupling deposition, and acid-water-ash coupling deposition [16]. The adhesion ash and the corrosion characteristics in a rotary air preheater were also studied. It is found that the serious corrosion and adhesion ash deposition are caused by the sulfuric acid vapor condensation rather than the ammonium bisulfate deposition [17]. To prevent the corrosion from coupling the ash deposition and dew point corrosion, various tube materials were compared within different temperature ranges [18].

The existing simulations are all limited to the dry loose ash on the heat transfer surface due to the complex coupling mechanism. Although coupling acid dew point corrosion and ash deposition were studied experimentally in some literature, the experimental study requires high cost and long running time. In addition, the numerical simulation will efficiently help to reveal the coupling mechanism of coupling acid dew point corrosion and ash deposition. In this paper, the distribution of the deposited ash on the heat transfer surface is numerically studied by coupling the theory of ash deposition and acid vapor condensation. There are usually two modes of deposited ash on the surface, the low temperature bonding ash and the loose ash. The deposited mass of the two modes of deposited ash affected by various factors is studied with the Fluent software combined with the user define functions (UDFs). The distribution of the deposited ash on the surface in both the in-line and staggered tube banks are also considered. The results could shed light on the complex mechanism of ash deposition and guide the control and cleaning of the deposited ash on the heat transfer surface.

2. Model description and numerical model

2.1. Physical model

Two types of three-row H-type fin oval tube banks are studied, the in-line tube bank and the staggered tube bank. All the geometry parameters are detailed in Fig. 1 and Table 1. The flue gas outside of the tubes consists of the air, water vapor, sulfuric trioxide and fly ash particles. The physical properties of the flue gas and the fly ash particles are tabulated in Table 2.