



Research Paper

Prediction of sulfuric acid dew point temperature on heat transfer fin surface



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HIGHLIGHTS

- Local sulfuric acid dew point on fin surface is predicted for the first time.
- Wall temperature, flue speed and fin effects on acid dew point are firstly studied.
- Sulfuric acid dew point is higher on windward and first row of fin surface.
- Novel types of fin surfaces can reduce sulfuric acid dew point temperature.

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ABSTRACT

Sulfuric acid dew point temperature is an important parameter denoting the dew point corrosion. The sulfuric acid dew point temperature is calculated by considering both the vapor–liquid equilibrium effect and multi-component diffusion effect. In addition, the local distribution of acid dew point temperature on fin surface is numerically predicted for the first time. The influences of fuel type (sulfur content, water content and ash content), wall temperature, excess air ratio, flue gas inlet velocity, fly ash particle (size and quantity) and heat transfer fin structure on the sulfuric acid dew point temperature are discussed. The results show that different types of fuels (which differ in gas composition and combustion temperature) have a great impact on the sulfuric acid dew point temperature. The sulfuric acid dew point temperature decreases with the reduction of excess air ratio, the increasing of wall temperature, and the condensation of sulfuric acid vapor on ash particle surface. The sulfuric acid vapor condensates more seriously on the tube windward than on the leeward. The novel types of heat transfer fins with high heat transfer performance can also reduce the local sulfuric acid dew point temperature, and the maximum reduction of sulfuric acid dew point is 4.1 K between the novel fin surface and the original H-type fin surface.

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1. Introduction

The sulfuric oxides and water vapor in flue gas can condense into sulfuric acid solution on the low temperature surface of heat exchanger when the wall temperature is below the local dew point temperature, which will corrode the wall and lead to equipment failure. Great attention has been paid to the sulfuric acid dew point corrosion and the corrosion rate and morphology have been studied [1–3]. The sulfuric acid dew point temperature plays an important role in the formation of sulfuric acid dew point corrosion.

The existing research methods for the sulfuric acid dew point temperature of flue gas are mainly classified into chart method, empirical equation, neural network method, numerical analysis and experimental measurement etc. The Muller curve is the basis for

predicting the sulfuric acid dew point temperature, and it shows the relationship between the sulfuric acid dew point temperature and the partial pressure of sulfur trioxide vapor in flue gas [4]. However, the influence of the water vapor partial pressure on the sulfuric acid dew point temperature was not considered. Pierce proposed an estimation method to calculate the sulfuric acid dew point temperature when the fuel characteristics and excess air ratio are provided [5]. But the error of this method was large due to the limited accuracy of thermodynamic parameters of sulfuric acid vapor and solution. Once the thermodynamic parameters of sulfuric acid solution and sulfuric acid vapor are calculated accurately [6], the sulfuric acid dew point formula proposed by Verhoff and Banchemo [7] can be applied to high gas temperature. However, the error is still large for the low gas temperature. Okkes proposed a formula for sulfuric acid dew point temperature based on the experimental data from Muller, which is related to the partial pressure of sulfur trioxide vapor and water vapor in flue gas [8]. The Soviet standard formula [9] is widely used among the existing empirical formulas.

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Recently, some other methods for the prediction of the sulfuric acid dew point have also been studied. ZareNezhad and Aminian presented a model of multi-layer feed forward neural network for predicting sulfuric acid dew point over sulfur trioxide and water vapor concentration [10]. A predictive tool was also proposed based on Vandermonde matrix, which accounts for fuel type, sulfur fraction and excess air ratio [11]. Shi et al. proposed the concept of engineering sulfuric acid dew point temperature, at which the heat transfer performance drops sharply due to the influences of both ash deposition and acid condensation in the experiment. It is about 30 K lower than the thermodynamic sulfuric acid dew point temperature [12]. Wang et al. studied the coupling mechanism between ash deposition and dew point corrosion and found that the acid vapor condensed in the main condensation zone rather than directly on the tube wall surface [13].

In summary, although many prediction methods for sulfuric acid dew point temperature have been studied, the effects of specific position and structure of heat transfer surface on the sulfuric acid dew point temperature have not yet been considered in the literature. In this work, we calculate the sulfuric acid dew point temperature of flue gas and compare it with the Soviet standard formula, and a variety of factors (such as fuel type, wall temperature, excess air ratio, inlet velocity, fly ash particles and fin structure) which affect the distribution of sulfuric acid dew point temperature on the heat transfer surface of H-type finned oval tube are evaluated. In addition, the distribution of sulfuric acid dew point temperature on the fin surfaces of tube bank is examined.

2. Model description and numerical method

2.1. Physical model

A multiple-row oval tube bank based on the H-type fin with compound dimples and rectangular longitudinal vortex generators is shown in Fig. 1. Four types of fin tubes are studied, which are the original H-type finned oval tube, the fin surfaces with bleeding dimples (Dimple), with -30° rectangular longitudinal vortex generators (LVG) and with compound dimples and rectangular longitudinal vortex generators (Dimple-LVG). The dimple in the present study is modified by carving a bleed hole inside to make the fluid flow through. The geometry parameters of the oval tube bank and four types of fins are listed in Table 1. The flue gas consisting of air, water vapor and sulfuric trioxide flows across the tube while the water flows inside the tube.

2.2. Governing equations and boundary conditions

The calculation domain is marked in the blue solid box, as shown in Fig. 1a and 1b. The extended zones are set at the inlet to ensure the uniform inlet flow and at the outlet to prevent the fluid backflow. The top and bottom surfaces of the calculation domain are periodic boundary, and the left and right surfaces are symmetry boundary. The velocity inlet and pressure outlet are adopted in the numerical simulation. Assumptions and simplifications performed in the present simulation are listed below.

- (1) The temperature of the tube wall is constant.
- (2) The thermal resistance of the liquid film on the fin surface is neglected as its contribution to the total thermal resistance is below 3% [14].
- (3) The flue gas is assumed to be an ideal gas mixture with a variety of gas compositions.
- (4) Only the velocity of flue gas in the x direction is considered and the velocities in other directions caused by diffusion are ignored.

The mass, momentum and energy conservation equations and the RNG k- ϵ turbulence model are presented as follows.

Continuity:

$$\nabla \cdot \mathbf{U} = 0 \quad (1)$$

Momentum:

$$\mathbf{U} \cdot \nabla \mathbf{U} = \nu \nabla^2 \mathbf{U} - \frac{1}{\rho} \nabla P \quad (2)$$

Energy:

$$\nabla \cdot (\mathbf{U}T) = \nabla \cdot \left(\frac{\lambda}{\rho c_p} \nabla T \right) \quad (3)$$

The Reynolds number of flue gas flow in the simulations ranges from 12,253 to 28,000, so the turbulent flow is considered and the RNG k- ϵ equation model is employed [15].

$$\frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\alpha_k (\eta + \eta_t) \frac{\partial k}{\partial x_j} \right] - \rho \epsilon + G_k \quad (4)$$

$$\frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\alpha_\epsilon (\eta + \eta_t) \frac{\partial \epsilon}{\partial x_j} \right] - C_{2\epsilon} \rho \frac{\epsilon^2}{k} - R_\epsilon + C_{1\epsilon} G_k \frac{\epsilon}{k} \quad (5)$$

where the effective viscosity $\eta_t = c_\mu \rho k^2 / \epsilon$ with $c_\mu = 0.0845$, and α_k and α_ϵ are the inverse effective Prandtl numbers for k and ϵ , respectively, G_k is the generation of turbulence kinetic energy due to the mean velocity gradient with $G_k = \eta_t S^2$, R_ϵ is the rate of strain term, $C_{1\epsilon} = 1.42$ and $C_{2\epsilon} = 1.68$.

The key to obtain the sulfuric acid dew point temperature is to solve the sulfuric acid vapor distribution in flue gas. And the distribution of sulfuric acid vapor partial pressure in flue gas is solved with the commercial software Fluent combined with the user-defined function, based on which the distribution of sulfuric acid dew point temperature, is calculated. We also simulate the condensation of the sulfuric acid vapor on the fly ash particle surface. They are discussed in the next subsection.

2.3. Theoretical and numerical models for sulfuric acid dew point temperature

The sulfuric acid dew point temperature of flue gas can be solved by the thermodynamic theory [16], given by

$$T_a = 1 / \left(\frac{1}{T_{a,0}} - \frac{R}{\Delta Q} \ln \frac{P_a}{c_a P} \right) \quad (6)$$

where T_a and $T_{a,0}$ are the sulfuric acid dew point temperature of flue gas and pure sulfuric acid vapor, respectively, ΔQ is the heat of vaporization for pure sulfuric acid estimated by the Watson formula and correlations [17], P_a is the sulfuric acid vapor partial pressure in flue gas, P is the pressure of flue gas, c_a is the sulfuric acid solution concentration, and R is the ideal gas constant.

To obtain the sulfuric acid dew point temperature, the sulfuric acid solution concentration and the sulfuric acid vapor partial pressure should be calculated. In the case of known fuel type, lower heating value and excess air ratio, the partial pressure of water vapor P_w and sulfuric acid vapor P_a in flue gas can be solved according to the material balance and heat balance equations [18], and the process is presented in Part I of Fig. 2. Different from P_a , the partial pressure of species i at the gas-liquid interface P_i is affected by the concentration and temperature of sulfuric acid solution at the interface. However, both c_a and P_i are unknown. They can be calculated by iteration [19] from Eqs. (7)–(9), and the process is shown in Part II of Fig. 2.

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