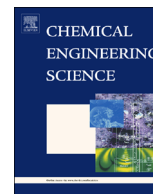




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A numerical study of the deposition characteristics of sulfuric acid vapor on heat exchanger surfaces



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HIGHLIGHTS

- Condensation of sulfuric acid in presence of non-condensation gas is simulated.
- Coupling boundary conditions of sulfuric acid and water vapor is calculated.
- Transport and condensation are achieved by using multi-component diffusion theory.
- The distributions of condensation rate and condensate concentration are provided.
- The influences of parameters on condensation rate are also investigated.

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ABSTRACT

Accurate predictions of the sulfuric acid condensation behavior on the surfaces of heat exchangers are crucial for understanding the local low-temperature corrosion characteristics of heat exchangers and designing them. In this paper, a new numerical model has been developed to predict the condensation rate of sulfuric acid and condensate acidic solution concentration on heat exchanger surfaces. By correlating the vapor–liquid equilibrium (VLE) data of $\text{H}_2\text{SO}_4\text{--H}_2\text{O}$ solutions from experiments and in conjunction with multi-component diffusion theory, the proposed model obtains numerical solutions of condensation heat transfer under the conditions of a coupled wall and fluid boundary condition and a multi-component mixture of flue gas and the sulfuric acid solution (saturated partial pressure of sulfuric acid and water vapor). The numerical model has been validated by a comparison of the simulation results with available experimental data, and applied to an analysis of the H-type finned tube heat exchanger, which has been widely used in the field of waste heat recovery. The distributions of the condensation rate and condensate concentration on the fin surface are also calculated. The results show that the three dimensional distribution of acid solution concentration is consistent with the fin temperature. An increase in water vapor could result in a sharp reduction of the acid solution concentration and an increase in deposition, which may indicate a serious risk for low-temperature corrosion. In contrast, increasing the flue gas temperature will reduce the corrosion risk by reducing the condensation rate and increasing the acid concentration.

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1. Introduction

Simultaneous sulfuric acid and water vapor condensation occurs on waste heat recovery equipment whenever the surface temperature is below the local acid solution dew point temperature in the exhausted gas. Typical applications include air preheaters, economizers, and condensing heat exchangers that utilize low-grade waste heat recovery systems in coal and oil-fired power plants. Condensate from flue gas containing sulfuric acid forms an acidic solution, which could lead to low-temperature

corrosion and metal equipment operation failure. [Moskovits \(1959\)](#) indicated that a proportional relationship exists between the acid deposition rate and the corrosion rate, and predicting the corrosion behavior was feasible after calculating the acid deposition rate and the concentration of condensate.

Deposition by the flue gas is a complicated phenomenon accompanying the heat and mass transfer process of water and sulfuric acid vapor in the presence of non-condensable gases. A large amount of work on the performance of heat exchangers applied in air-conditioning and power generation industries under condensation conditions has been reported. [Webb and Wanniarachchi \(1980\)](#) investigated the effect of non-condensable gases in finned tube heat exchanger by solving the Colburn–Hougen equation. [Osakabe \(2000\)](#) and [Osakabe et al. \(2003\)](#) experimentally studied the condensation

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heat transfer of flue gas on stainless-steel bare and finned tube heat exchangers. Wang et al. (1997, 2000, 2001), Pirompugd et al. (2005, 2006), Lin et al. (2001) carried out a series of experimental studies concerning fin performance in both dry and wet conditions, and visually observed the dehumidifying phenomenon. Jeong et al. (2010) developed an analytical model to predict the heat and mass transfer processes in a flue gas condensing heat exchanger system. A pilot test was also conducted to validate their analytical model. Shi et al. (2011) experimentally and theoretically investigated the combined convection-condensation heat transfer of a compact heat exchanger for both sensible and latent heat recovery. To further understand the local fin performance under wet conditions, Comini et al. (2007) presented a numerical procedure to predict the moist air-cooling process in compact heat exchangers under ideal drainage conditions.

The foregoing studies present a substantial data set and provide a fundamental understanding of the condensation process, but most of these studies focused only on the heat exchanger performance with water vapor condensing on the heat exchanger surface. Fossil fuel generally releases a small amount of sulfur trioxide (SO_3) during combustion. When the flue gas temperature is below 200°C , more than 99% of the SO_3 reacts with water vapor to form sulfuric acid (H_2SO_4). Although the amount of sulfuric acid is small, even a small concentration of sulfuric acid vapor can drastically increase the dew point of the flue gas (Kear, 1955; Jaworowski and Mack, 1979), and the resulting dew point is much higher than that of water. Most heat recovery systems operate at lower exhaust gas temperature conditions. As a result of these operating conditions, both the water vapor and the sulfuric acid gas condense. To better understand the effect of acidic gas condensation on heat exchanger performance in waste heat recovery systems, the condensation of sulfuric acid vapor should also be taken into account.

When considering the condensation of acid and water vapor, providing a full mathematical description of the boundary interfaces between the fluid and the solid surfaces is a complex task, and vapor–liquid equilibrium (VLE) models are required to determine the local mass fraction of water vapor and acid vapor corresponding to the saturation pressure at the wall temperature and concentration of the condensate. Abel (1946) originally derived the liquid fugacity equations for aqueous sulfuric acid and assumed the vapor phase to be an ideal gas. The liquid fugacities are expressed in terms of calorimetric parameters and temperature functions, and the partial pressure of H_2O can be reasonably predicted. Gmitro and Vermeulen (1964) modified the fugacity equation by considering the dissociation of H_2SO_4 to SO_3 and H_2O in the vapor phase with updated thermodynamic parameters. Wilson and Stein (1989a) re-estimated the coefficient for the liquid phase fugacity expression, and considered solvation between the acid species and H_2O on the basis of Gmitro and Vermeulen's model, which improved the prediction of the sulfuric acid partial pressures. More recently, Pessoa et al. (2006) developed a new model that used Prigogine and Defay Chemical Theory to calculate the vapor–liquid equilibrium of H_2O – H_2SO_4 solutions and considered both of the dissociation reactions in the liquid phase and the complex formation reactions in the vapor phase.

Although sulfuric acid condensation from the flue gas and its impact upon power plant operation have been widely recognized and experimentally investigated (Taylor, 1951), efforts to use mathematical models to predict the deposition rate onto the surface of heat exchanger equipment have received less attention (Dietz and Marchal, 1977). In recent years, with the development of computational fluid dynamics technology, investigating local corrosion on the actual devices has become possible. In 2004, Valencia (2004) performed a numerical simulation for the condensation of nitric acid, sulfuric acid and water vapor in the presence of air on a vertical water-cooled plate using the commercial code FLUENT and a user defined subroutine to solve the

diffusion rate of acid species and water vapor near the cold surface. However, the dew points of the species were treated as constants in their study.

In this study, a numerical model has been developed to predict the condensation rate of sulfuric acid and water vapor in presence of a non-condensable gas. The model treats the flue gas as a ternary mixture of sulfuric acid, water vapor and air to simplify the simulation process using the commercial computing software FLUENT, and combining the software with user defined functions to compute the physical properties, boundary conditions of species equations, and source terms of the mixture. The procedure provides a visual understanding of the condensation behavior by offering distributions of condensate on heat exchanger surfaces, and can be applied to complex geometries in a large temperature range without relying on a particular numerical technique. Comparing our numerical results with the experimental results of Levy and co-workers assesses the accuracy and reliability of the methodology. An H-type finned tube economizer typically used in the field of waste heat recovery system was selected as the research object. The effects of the operating conditions on the condensation rate of sulfuric acid, including the flue gas flow-velocity, flue gas temperature and components concentration have also been considered.

2. Model descriptions

2.1. Physical model

Fig. 1(a) shows the core region of the H-type fin heat exchanger used in this paper, which is typically used for waste heat recovery. The cold fluid flows inside the tube, and hot flue gas flows across the tube and fin in the heat exchanger. The heat exchange can be conducted through the tube and fin surface without mixing fluids. Actually there are many rows of finned tubes with the same geometry size in the spanwise direction (z -direction) and the longitudinal direction (x -direction). Here only one-row finned tube is given in the figure for brevity. The geometric parameters for the H-type finned tube are shown in Table 1. Some assumptions and simplifications in this study are made to perform the present simulation, which are described as follows.

- (1) Consider the flue gas compositions as a ternary mixture of sulfuric acid vapor, water vapor and air.
- (2) Neglect the influence of the liquid film; in practice, the contribution of the liquid film to the total heat resistance is below 3%, typically 1–3% (Goldbrunner, 2003).
- (3) Assume the temperature of the condensate to be equal to the wall surface temperature.
- (4) Neglect condensation in the gas phase itself.
- (5) Neglect the thermal resistance of the tube, and the tube temperature is set as a constant.

2.2. Governing equations and boundary conditions

Fig. 1(b) presents a pictorial view of the computational domain, where the region is extended to ensure uniform incoming and outgoing flow conditions at the inlet and exit, respectively (Lei et al., 2010). The airflow direction is the x -direction, the fin pitch direction is the y -direction, and the fin span wise direction is the z -direction. Due to the periodic geometric character in the y -direction and the symmetry in the span wise direction for the finned tube heat exchanger, only a fin unit is extracted from the physical model to investigate the local condensation behavior on the fin surface along the airflow direction. The geometry of the H-type finned tube heat exchanger is presented schematically in

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