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Numerical simulation of the heat transfer of superheater tubes in power plants considering oxide scale

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ABSTRACT

This paper investigates the heat transfer of superheater tubes in one 600 MW boiler combining the 3-D CFD simulation and the 1-D analytical model. To confirm the validity of this method, the simulation results were compared with the on-line measured outlet steam temperature and standard operation data provided by the plant manufacturer. The thickness of oxide scale formed on the steam-side of superheater tubes was measured by the metalloscope, and the influence of oxide thickness on the tube wall temperature over the entire length of superheater tubes was assessed by this model. The maximum outlet steam temperature was found to be 847.5 K, and the highest outlet tube wall temperature was 876.8 K. As the oxide thickness grows up to 152 μm, the tube wall temperature of Tube 7 and Tube 9–11 would exceed the allowable metal temperature (866 K). Therefore, changing the Tube 7 and Tube 9–11 materials to the better heat-resistant steel alloy is suggested to avoid tube overheating.

1. Introduction

Superheater tubes are high-temperature heat exchangers in the boiler, which are often subjected to overheating failure [1]. According to statistics, almost 40% of forced power station outages caused by boiler tube failure are attributed to the material overheating [2]. One common method to avoid tube overheating is employing the high-strength and corrosion resistance steel alloy [3]. In reality, each superheater stage is usually made of different steels because of the high prices of high-temperature alloy [4]. Thus, a better understanding of the heat transfer in superheater tubes is necessary to properly select the steel alloy.

Many theoretical studies have been conducted to calculate the heat transfer of high-temperature components in boiler. Madejski et al. [1] calculated the steady tube wall temperature of superheater with complex shape of cross-section using the control volume based finite element method. The computing time of their proposed model was faster than the complex 3-D model. Taler et al. [5] demonstrated the temperature evolution of the final superheater outlet heater using ANSYS software. They found that the boiler start-up time can be shorted based on the permissible heating rate. Additionally, the artificial intelligence (AI) approach has been used to assess the heat transfer of heat exchanger [6,7]. Krzywanski et al. [8–10] applied the fuzzy logic approach to predicting the local bed-to-wall heat transfer coefficient in the large-scale boiler by the fuzzy logic approach. They presented that the fuzzy logic method could give accurate operating conditions and the overall heat transfer coefficient quickly. Artificial neural network was used to predict the heat transfer from horizontal tube immersed in gas-solid fluidized bed [11,12].

During operation of the boiler, ash deposits (i.e. slagging and fouling) and steam-side oxide scale are formed on the tube surface [13]. Both the fire-side ash deposits and steam-side oxide scale increase heat transfer resistance of superheater tubes [4], resulting in the complex heat transfer on the tube. Many experimental and theoretical studies have been conducted to simulate the steam-side oxide scale and ash deposits. Zhang et al. [14] investigated the oxide behavior of ferritic steel and ferritic-martensitic steel exposed in flowing and static supercritical water (SCW) at 550–600 °C. Ma et al. [15] integrated the Computational Fluid Dynamics (CFD) simulation with ash behavior prediction tool to provide a quantitative description of the deposition processes. Bilirgen [16] conducted a detail coal and ash analyses to understand the root cause of excessive slagging in coal-fired boiler.

The fundamental problem of calculating the heat transfer was determining the boundary conditions of high-temperature components [5]. Duda et al. [17] proposed a method for determining the heat flux on the tube surface of water-wall tubes based on the measured internal temperature. Installing the temperature

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measuring instrument on the superheater tubes was extremely difficult, due to the excessive high temperature of the external flue gas [18]. Purbolaksono et al. [19] utilized the empirical formulae to determine the heat transfer coefficient on the tube surface of one single superheater tube, and calculated tube wall temperature profiles by the finite element method. In practice, the final superheater was consisted of parallel U-tubes. Because of the difficulty in describing the complex tube arrangements and gas thermal processes, few analytical studies contribute to the research on the heat transfer of parallel U-tubes in detail [1]. The CFD provided an effective option to predict the heat transfer in the boiler [18]. Park et al. [20] developed an advanced 3-D CFD boiler model, and simulated the effect of burner and coal blending on the boiler and combustion efficiency. Diez et al. [21] used standard CFD techniques to simulate the fluid flow, heat and mess transfer and major species concentration in the furnace. Although the heat transfer of superheater tubes has been extensively studied in previous works, taking account of a detail tube arrangement and the complex thermal processes in the flue gas is obviously insufficient.

Our previous studies calculated the tube wall temperature of one single superheater tube by 1-D analytical model [22,23], and obtained the radial temperature distribution. In this work, we attempted to predict the heat transfer over the entire length of the final superheater tubes. The key problem of calculating the heat transfer is determining the boundary conditions on the tube surface. The heat flux on the outer and inner surface of tubes is calculated by the 3-D CFD simulation and 1-D analytical model, respectively. This method was permitted to assess the influence of oxide thickness on the tube wall temperature. Finally, the superheater materials could be properly selected to avoid tube overheating failure based on the maximum tube wall temperature.

2. Methods and modeling

2.1. The geometry and materials of superheater tubes

The simulation in this work is based on final superheater tubes of one 600 MW pulverized coal boiler. Fig. 1 shows the superheater arrangement of this boiler. The superheater has a capacity of 1913 t/h at the design pressure of 25.4 MPa and the design temperature of 844 K. The partition platen superheater and rear platen superheater is placed above the combustion chamber. The final superheater arranged above the furnace nose is assembled by 82 serpentines. The detailed tube arrangements of one serpentine are shown in Fig. 2a. The final superheater is consisted of two U-tube panels, which are named the hot part and the cool part. In this paper, each tube is divided into seven sections along the steam flow path (Fig. 2a), which are consisted of three bend sections (B1, B2 and B3) and four straight sections (S1, S2, S3 and S4). The straight section 1 (S1) and the straight section 2 (S2) are located in the cold part. The straight section 3 (S3) and the straight section 4 (S4) are arranged in the hot part. The superheater tubes are made of different steels to decrease the cost of materials. As shown in Fig. 2a, superheater materials are consisted of T23, T91 and TP347HFG steels. The thermophysical properties of each material are listed in Table 1. The tube length of each steel grade within superheater is given in Table 2.

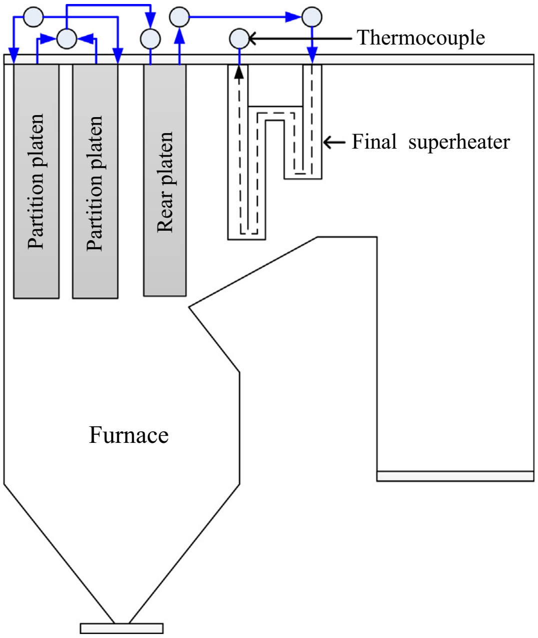

Fig. 1. Superheater tubes arrangement of the boiler.

Each serpentine is made up of 12 tubes, which are represented by Tube 12–1, as given in Fig. 2b. Additional suspended tubes are

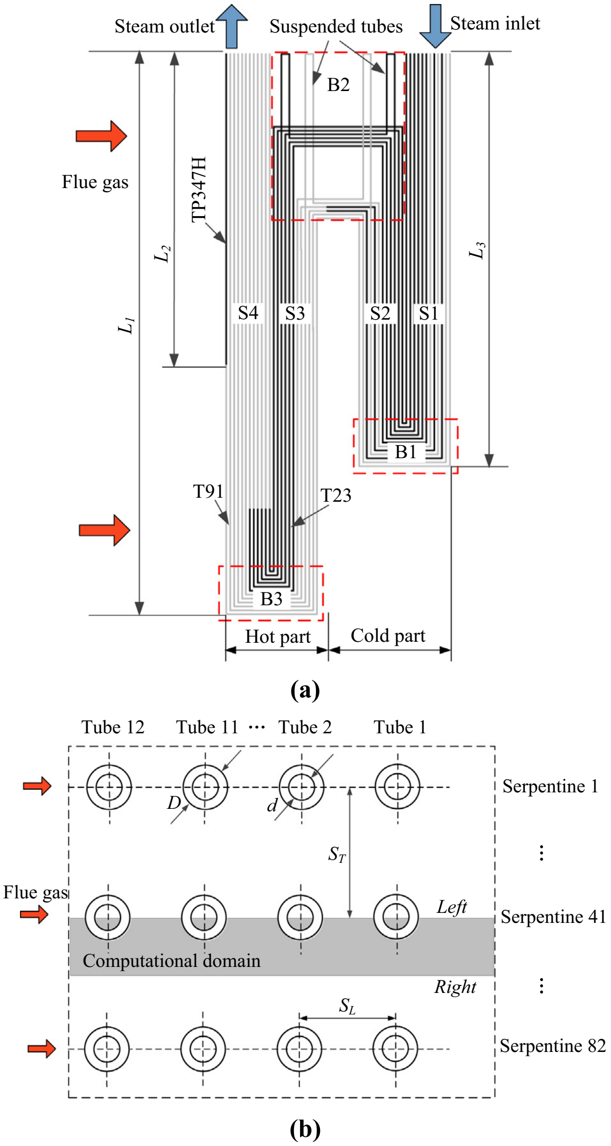

Fig. 2. Geometry and materials of the final superheater tubes: (a) the front view; (b) the vertical view.