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Numerical Simulation Research on Screen Superheater of Supercritical Circulating Fluidized Bed Boiler

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Abstract

In view of the problems such as wear, deformation and tube burst existing in the operation of the screen superheater in the supercritical circulating fluidized bed boiler, a computational quasi-model of the screen superheater was established in this paper. Combined with the actual operation data of the boiler, the temperature distribution and thermal deformation of the screen superheater tube panel under 100% MCR conditions were numerically simulated by ANSYS finite element analysis software. The results show that the maximum wall temperature of the tube panel appears at the penetration wall between the screen superheater and the water-cooled wall of the furnace roof, on the fin of the 50th tube of the tube panel, with the highest temperature reaching 652.97℃, and a local overheating phenomenon occurs. The maximum thermal deviation between the fin and the tube wall is 15.3℃. The maximum thermal deformation of the tube panel is 215.85mm. Among them, the tube panel is freely movable along the Z direction due to the suspension device, with a deformation of 212.33mm, while along the X direction, due to the constraint at the lower part of the tube panel, although there is a thermal deviation, the deformation is only 51.88mm.

Keywords

Supercritical Circulating Fluidized Bed Boiler; Screen Superheater; Thermal Deviation; Finite Element Analysis; Temperature Field; Thermal Deformation.

1. Introduction

The supercritical circulating fluidized bed (SCCFB) boiler has been widely applied both at home and abroad due to its advantages such as wide fuel adaptability, low-cost pollution control, and efficient energy utilization of the supercritical steam cycle. By the end of 2024, China has put into operation one 660MW ultra-supercritical CFB boiler and 57 supercritical CFB boilers [1]. As one of the main heat-absorbing components of the supercritical CFB boiler, the screen superheater is prone to significant thermal deviation between tube screens during long-term operation due to poor heat exchange capacity of the working medium inside the tubes and uneven heat load distribution in the furnace, which may lead to overheating at certain locations, causing considerable thermal deformation and thermal stress. In severe cases, it can result in tube rupture and leakage, threatening the stable operation of the entire unit.

Currently, the analysis of the causes of leakage and tube burst in screen superheaters mainly relies on sampling inspection methods, including on-site inspection, macroscopic analysis, microscopic analysis, thickness measurement analysis, chemical composition analysis, metallographic structure analysis, and hardness analysis of the tubes that have already experienced leakage and burst [2-7]. However, due to the influence of thermal deviation among tube screens, the temperatures and operating conditions of different tubes within the tube screen vary significantly. The selected accident tube sections often cannot represent the overall

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situation of the tube screen. To gain a more comprehensive and accurate understanding of the failure problems of the superheater tube screen under the influence of thermal deviation, numerical simulation of the temperature and deformation of each tube in the screen superheater is an effective approach, which can reveal the distribution law of the temperature field and the influence of deformation on failure in the tube screen. Therefore, conducting finite element analysis of the screen superheater is of great significance. The 600MW supercritical circulating fluidized bed boiler demonstration unit in Baima, Sichuan, has been in operation for over 10 years and has experienced failure problems such as tube screen bending, wear, and fin tearing due to thermal deviation. Moreover, the high material concentration in the furnace makes the tube screen more prone to wear, seriously affecting the safe operation of the boiler. This paper focuses on the failure problems of the screen superheater in a supercritical circulating fluidized bed boiler under the influence of thermal deviation. Based on the actual parameters of the boiler[8-11], the ANSYS finite element analysis software is used to establish a thermal stress analysis and calculation model of the screen superheater, solve and analyze the temperature field distribution and thermal deformation of the tube screen under given boundary conditions, providing certain references for the design and operation of supercritical circulating fluidized bed boilers.

2. Finite Element Computational Model

2.1. Heat Transfer and Elasticity Equations

Based on Fourier's law and the law of conservation of energy, the steady-state heat conduction differential equation in cylindrical coordinates can be obtained.

$$pc\frac{\partial t}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}(\lambda r\frac{\partial t}{\partial r})+\frac{1}{r^2}\frac{\partial}{\partial \varphi}(\lambda\frac{\partial t}{\partial y})+\frac{\partial}{\partial z}(\lambda\frac{\partial t}{\partial z})$$

ρ represents the material density, in kg/m^3; c represents the specific heat capacity of the material, in J/(kg·°C); t represents the temperature of the object, in °C; τ represents the time of the process, in s; λ represents the thermal conductivity of the material, in W/(m·°C); r, φ, z represent the cylindrical coordinates.

$$\varepsilon_x=\frac{1}{E}[\sigma_x-\mu(\sigma_y+\sigma_z)]+\alpha T,\gamma_{xy}=\frac{1}{G}\tau_{xy}$$
$$\varepsilon_y=\frac{1}{E}[\sigma_y-\mu(\sigma_z+\sigma_x)]+\alpha T,\gamma_{yz}=\frac{1}{G}\tau_{yz}$$
$$\varepsilon_z=\frac{1}{E}[\sigma_z-\mu(\sigma_x+\sigma_y)]+\alpha T,\gamma_{zx}=\frac{1}{G}\tau_{zx}$$

In the formula, E represents the elastic modulus, GPa; μ represents Poisson's ratio; T represents temperature, °C; G represents the shear modulus, Pa; α represents the linear expansion coefficient.

2.2. Finite Element Model

The screen superheater of a 600MW supercritical CFB boiler is composed of 55 tubes, with a tube pitch of 60.8 mm, a tube screen height of 21.7 m, and the tube material is SA-213TP347H, with a size of Φ50.8mm×11.5 mm. The fin material is 0Cr18Ni9, and the fin flat steel thickness is 6mm. In this paper, 8-node solid70 elements and solid185 elements are adopted as the thermal analysis and structural analysis elements. After the mesh independence verification and ensuring the calculation speed and accuracy, The finite element calculation model of the screen superheater and the mesh diagrams of its 2D and 3D calculation models are shown in Figure 1, with a total of 4 million meshes.

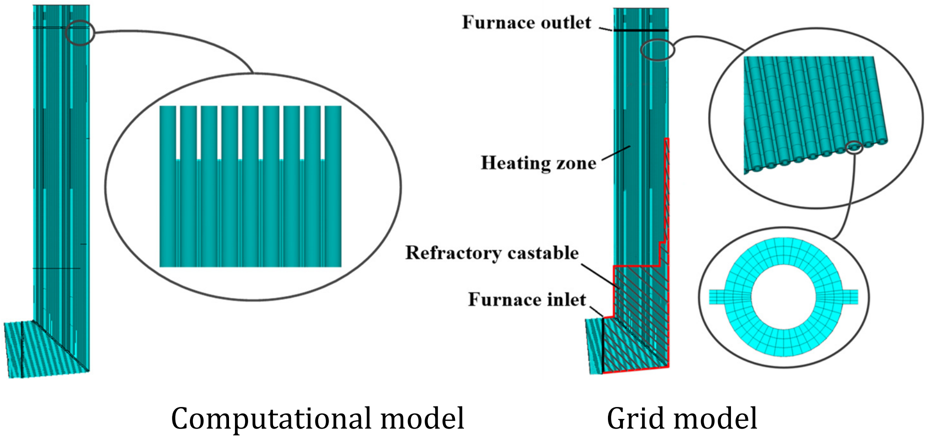

Figure 1. Computational model and grid model of the screen superheater in a supercritical circulating fluidized bed boiler

2.3. Boundary Conditions

2.3.1. Thermodynamic Boundary Conditions

From the heat balance of the screen superheater, it can be known that the enthalpy increase of the working medium in the tube per unit time is equal to the heat absorbed from the outside of the furnace, that is:

$$(h_{out} - h_{in}) \bullet G = Q \tag{1}$$

In the above formula, and are the enthalpy values at the inlet and outlet of the screen superheater, respectively, kJ·kg^{-1}·°C^{-1}. They can be obtained by looking up the IAPWS-IF97 standard based on the measurement results of the inlet and outlet header pressures of the screen superheater and the steam temperature at the outlet measured by the DCS system. G is the mass flow rate of the working medium in the tube, kg·m^{-2}·s^{-1}; the total heat absorbed by the tubes Q can be calculated by the following formula:

$$Q = \bar{q} \cdot A \tag{2}$$

In the formula, A represents the surface area of the heat absorption section of the tube, m^2, and is the average heat flux density on the tube surface, kW·m^{-2}, which can be obtained by integrating the function of the heat flux density along the height of the furnace, that is:

$$\bar{q} = (\int_{Hi_n}^{H_{out}} q(H)dH) / (H_{out} - H_{in}) \tag{3}$$

where Hout and Hin are the inlet and outlet heights of the heat absorption section of the tube, m; is the function of the heat flux density along the height of the furnace. In this paper, the heat load curve along the height of the furnace centerline of the water-cooled wall is obtained by using the temperature measurement points installed on the membrane water-cooled wall tubes as proposed in reference[9]. For each tube of the screen superheater, the distribution trend of the heat flux density along the height of the furnace is the same, but the values are different. The calculation is based on the thermal balance of a single tube. Combining formulas (1), (2), and (3), the mass flow rate inside the tube can be calculated by the following formula:

$$G = \frac{l_n \cdot \bar{s} \cdot \int_{Hi_n}^{H_{out}} q(H)dH}{(H_{out} - H_{in})(h_{out} - h_{in})} \tag{4}$$

Due to the heat absorption deviation of the tube screen and the influence of the length of the heat absorption section, the mass flow rate of the working medium inside each tube is different. Therefore, when calculating the flow distribution inside the tube screen, it is necessary to first determine the distribution of the heat flux density along the width of the tube screen. Since there are few reports on the distribution of the heat flux density along the width of the furnace, considering the differences brought by the research object, this paper uses the thermal deviation along the width of the furnace of the screen superheater proposed in reference[10] to calculate the local heat flux density at any position of the screen superheater.

Therefore, the local heat load on the wall of the screen superheater tube screen at a distance X from the water-cooled wall of the furnace is:

$$q_0 = q(H) \cdot Y(X) \tag{5}$$

In the above formula, Y(X) is the heat deviation coefficient of the tube at a distance x from the centerline of the furnace water-cooled wall.

Based on the comparison and evaluation of the working medium parameters inside the tubes of the screen superheater, the tube dimensions, and the test data, when the working medium inside the screen superheater has deviated significantly from the high specific heat capacity region, the heat transfer coefficient inside the tube should be calculated using formula (6) to better fit the data [11-12].

$$Nu = 0.00459\,\mathrm{Re}_w^{0.923}\,\overline{\mathrm{Pr}_w}^{0.613}\left(\frac{\rho_w}{\rho_b}\right)^{0.231} \tag{6}$$

In the above formula: the subscript b represents the value at the mainstream steam temperature inside the tube, and w represents the value at the wall temperature; Re is the Reynolds number, Pr is the Prandtl number, and ρ is the density of the fluid.

The heat flux density distribution obtained by using Formula (3) and Formula (5) can be used to calculate the working fluid flow distribution within the tube screen, the working fluid temperature distribution along the furnace height within the tubes, and the single-tube heat load distribution along the furnace height. Then, by applying Formula (6) and relevant heat transfer theories, the heat transfer coefficient distribution along the furnace height on the inner wall of the tube screen and the inner wall temperature distribution along the furnace height can be determined. The theoretical calculated heat load variation along the furnace height direction on the wall surface of the screen superheater, the inner wall temperature distribution and the inner wall heat transfer coefficient distribution are applied to the finite element calculation model as the boundary conditions for thermal analysis calculation.

2.4. Mechanical Boundary Conditions

The screen superheater is free to expand inside the furnace. To ensure the accuracy of the calculation, it is necessary to minimize the mechanical constraints on the screen superheater model during the calculation. Therefore, it is necessary to analyze the structure and force conditions of the tube screen to determine the mechanical constraints on the tube screen. During operation, the spring suspension of the outlet distribution header of the screen superheater mainly moves up and down (Z direction) relative to the superheater tube screen. However, on the cross-section where the tubes connect to the outlet header, the tubes are stationary relative to the superheater tube screen. Therefore, the constraints of the top outlet header on the tube screen in the furnace are UX = UY = 0, and UZ is not constrained. The inlet header has a relatively large rigidity. When the superheater tube screen enters the water-cooled wall, to enhance the sealing, the constraints on the tube screen at the inlet can be considered as being stationary in all directions relative to the water-cooled wall. Therefore, the constraints at this location are UX = UY = UZ = 0. The rest of the tube screen is free to expand.

3. Results and Analysis

3.1. Tube Screen Temperature

Figure 2 shows the calculated results of the temperature field of the tube screen. It can be seen from the figure that the lowest temperature of the tube screen is located in the inlet area of the tube screen, which is outside the furnace and has no heat load, so the temperature of this part is the same as the temperature of the working medium inside the tube. The second lowest temperature is in the area covered by wear-resistant materials. Considering that complete insulation is not possible, the heat load of this part is calculated at 10% of the original heat load, so the temperature of each tube in this part is close to the temperature of the working medium inside the tube. As the height of the tube screen increases, the temperature of each tube in the tube screen rises sharply after exceeding the height of the wear-resistant layer. This is mainly due to the poor heat exchange capacity of the superheated steam inside the tube and the poor heat transfer conditions inside the tube. Along the depth direction of the furnace, the temperature of each tube in the tube screen shows a trend of first rising and then falling. The main reason is that from tube No. 47 to tube No. 55, there is a longer wear-resistant layer covering, resulting in less overall heat absorption and a slower increase in the temperature of the working medium inside the tube. Under the condition that the heat transfer effect of each tube in the tube screen is not high, the lower working medium temperature has a better cooling effect on the tube screen. However, due to the distribution difference of thermal deviation between tube screens, the thermal deviation at tube No. 50 is relatively large, and the mass flow rate inside the tube is relatively low, resulting in a poor cooling effect at this location. Therefore, the maximum wall temperature of the tube screen occurs at the penetration between the screen superheater and the water-cooled wall of the furnace roof, on the fin of tube No. 50 of the tube screen, with a maximum temperature of 652.97℃. The allowable temperature of 0Cr18Ni9 steel is 650℃, and the maximum operating temperature should not exceed 700℃. Therefore, when the screen superheater is in a heat transfer deterioration state, some areas of the tube screen will exceed the allowable temperature of the material and experience overheating. Long-term operation at an overheated state will cause overheating and tube burst in the superheater, seriously affecting the safe operation of the boiler.

Figure 3 shows the calculated results of the stress field of the tube screen. It can be seen from the figure that the maximum stress occurs at the center of the fin of the tube screen, with a maximum stress of 318.9 MPa, which is less than the tensile strength of 520 MPa.

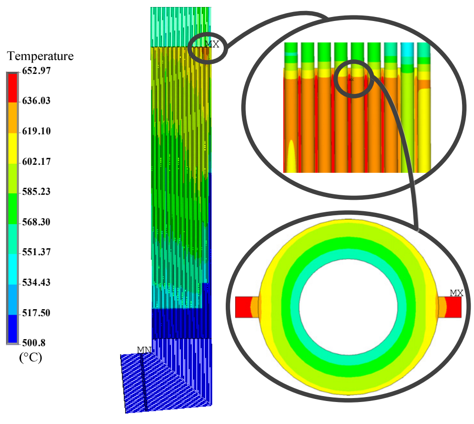

Figure 2. Calculation results of screen superheater temperature

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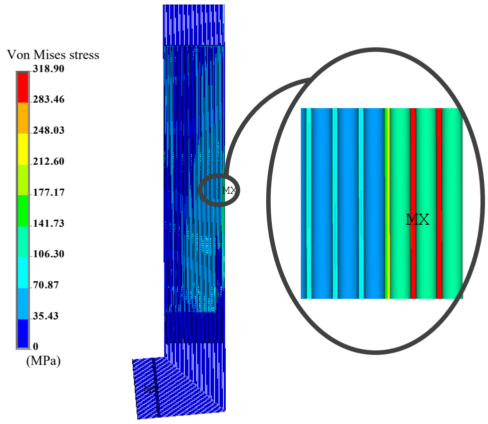
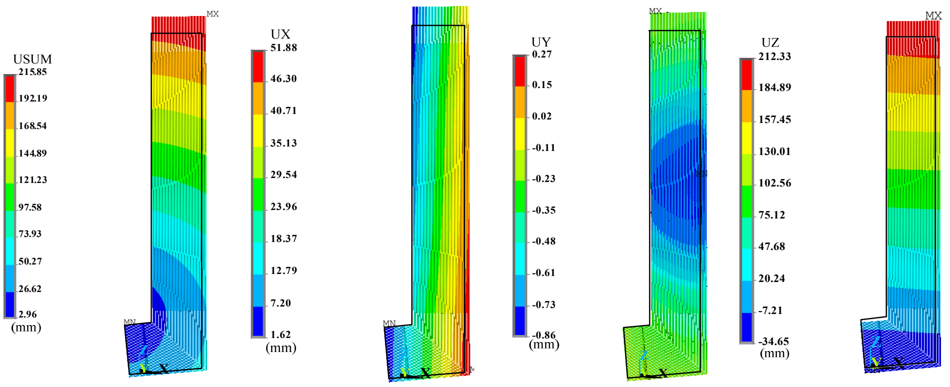


Figure 3. Calculation results of thermal stress for screen superheater

3.2. Tube Screen Temperature

Figure 4(a) shows the distribution of the total deformation of the tube panel. The black-framed part in the picture is the un-deformed tube screen model in the original model.As can be seen from Figure 4, the maximum deformation of the tube panel occurs at the connection between the top of the panel superheater and the header, with a maximum deformation of 215.85mm. Figure 4(b) shows the deformation in the X direction of the tube panel. It can be seen from the figure that the total deformation of the tube panel is only 51.88mm. Due to the constraints on the degrees of freedom in the X, Y, and Z directions at the inlet area of the tube panel, the tube panel is well constrained and cannot move freely in the X direction. Although there is a thermal deviation in the X direction, the constraints at the bottom of the tube panel limit its displacement, directly reducing the deformation in the X direction. Therefore, the deformation of the tube panel in the X direction is only 51.88mm. Figure 4(c) shows the deformation in the Y direction of the tube panel. In the Y direction, the tubes expand freely along the normal to the cross-section, with a deformation range of -0.86mm to 0.27mm. Figure 4(d) shows the deformation in the Z direction of the tube panel. The deformation in the Z direction of the tube panel is 212.33mm. The tube panel is free to move in the Z direction. The thermal deformation of the tube panel caused by the thermal deviation in the X direction accumulates as the height of the tube panel changes, so the thermal deformation of the tube panel increases along the height of the furnace. When it reaches the furnace outlet, it reaches the maximum of 212.33mm. However, the deformation is relatively uniform overall, reducing the possibility of tube panel bending.



(a) Total deformation (b) X-direction (c) Y-direction (d) Z-direction

Figure 4. Calculation results of tube panel deformation amount

4. Summary

This paper analyzes the temperature distribution and thermal deformation of the tube screen of the supercritical circulating fluidized bed boiler screen superheater under the influence of thermal deviation, and reaches the following conclusions:

(1) The finite element analysis results of the tube screen show that the maximum wall temperature of the tube screen appears at the penetration point between the screen superheater and the water-cooled wall of the furnace roof, on the fin of the 50th pipe of the tube screen, with the highest temperature reaching 652.97℃, exceeding the allowable temperature of 0Cr18Ni9 steel. Therefore, when the screen superheater is in a heat transfer deterioration state, the tube screen will experience overheating in some areas, seriously affecting the safe operation of the boiler.

(2) The thermal deformation analysis of the pipe shows that under the given boundary conditions, the maximum deformation of the tube screen is 215.85mm. The tube screen is free to move along the Z direction, so the deformation along the Z direction reaches 212.33mm. At the lower part of the tube screen, due to the constraint in the X direction, although there is thermal deviation in the X direction, the constraint at the lower part of the tube screen limits the displacement of the tube screen and directly reduces the deformation in the X direction. Therefore, the deformation of the tube screen along the X direction is only 51.88mm.

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