



Analysis of Wall Temperature Characteristics of the Panel Superheater in a 600MW Supercritical Circulating Fluidized Bed Boiler

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Abstract. To address the overheating issue in the panel superheater during the operation of a 600MW supercritical circulating fluidized bed boiler, this paper establishes a heat transfer characteristics calculation model for the panel superheater. By integrating actual operational data from the boiler, we calculated the pipe wall temperatures and the mass flow rates of the working medium inside the pipes under three typical operating conditions, and analyzed the heat transfer characteristics of the panel superheater. The theoretical calculations reveal that under identical load conditions, when the thermal deviation is greater, the heat load increases, leading to higher heat absorption by the pipes and consequently larger mass flow rates of the working medium inside the pipes. There is a positive correlation between heat load and the mass flow rate of the working medium. Under the three different loads, the maximum mass flow rates are 0.356 kg/s, 0.533 kg/s, and 0.721 kg/s, while the minimum mass flow rates are 0.149 kg/s, 0.211 kg/s, and 0.261 kg/s, respectively. Under all three operating conditions, the maximum wall temperature of the pipe screen consistently occurs at the penetration point between the panel superheater and the water-cooled wall of the furnace top, specifically on the fin of the 50th pipe. The highest temperatures recorded are 637.76 °C at 60% load, 649.52°C at 80% load, and 652.96 °C at 100% load. Notably, at 100% load, the maximum temperature exceeds the allowable steel temperature by 2.96 °C, resulting in localized overheating and posing a threat to the safe operation of the boiler.

Keywords: SCCFB boiler; panel superheater; theoretical calculations; tube panel over-temperature

1 Introduction

Circulating fluidized bed (CFB) boilers have gained widespread application both domestically and internationally due to their advantages of wide fuel adaptability, low-

cost pollution control, and highly efficient energy utilization. These boilers are also continuously evolving towards higher operating parameters. By the end of 2024, China had commissioned one ultra-supercritical CFB boiler and 54 supercritical CFB boilers[1]. As a critical heat-receiving component of supercritical CFB boilers, the screen superheater is particularly susceptible to tube burst during operation. Therefore, maintaining the temperature of the screen superheater within allowable limits is crucial for ensuring the economic and safe operation of the boiler.

Currently, the overheating status of the screen superheater in circulating fluidized bed boilers is primarily assessed based on the outlet temperature of the working medium[2-4]. However, due to the uneven distribution of heat flux density inside the boiler, variations in the flow rate of the working medium within the tubes, and the influence of the tube screen structure, significant temperature differences can exist among individual tubes. Relying solely on the average outlet temperature cannot accurately reflect the specific temperature distribution across the tube screen. Consequently, localized overheating in single or a few tubes often goes undetected, posing a significant threat to the long-term safe operation of the boiler.

This paper addresses the overheating issue of the screen superheater in a 600MW supercritical circulating fluidized bed boiler under the influence of thermal deviation. Based on actual boiler parameters[5-8], a heat transfer characteristics calculation model for the tube screen was established. The temperatures of the tubes and the mass flow rates of the working medium within the tubes were calculated under three typical operating conditions, and the heat transfer characteristics of the tube screen were analyzed. This study provides an important reference for ensuring the safety of the screen superheater and optimizing the design and safe operation of large high-parameter boilers.

2 Calculation Model for Heat Transfer Characteristics of Tube Panels

2.1 Panel Superheater of Supercritical Circulating Fluidized Bed Boiler

The panel superheater of the supercritical circulating fluidized bed (CFB) boiler analyzed in this paper adopts an asymmetric arrangement, consisting of single-tube welded fins. The tube screen utilizes a membrane wall structure and is vertically arranged. Each tube screen comprises 55 tubes with a pitch of 60.8 mm and a height of 21.7 m. The pipe material is SA-213TP347H, with dimensions of $\Phi 50.8 \text{ mm} \times 11.5 \text{ mm}$. The fin material is 0Cr18Ni9, and the fin flat steel thickness is 6 mm. The thermal parameters of the panel superheater under three typical operating conditions during actual furnace operation are summarized in Table 1. The tube closest to the front wall is designated as Tube 1, while the tube nearest to the center of the furnace is designated as Tube 55. To prevent wear of the panel superheater pipes, wear-resistant materials are installed at the wall-penetrating outlet of the tube screen, the inclined section, and part of the vertical section. The layout configuration is illustrated in Figure 1(a), and the area division of the panel superheater is shown in Figure 1(b).

Table 1. Thermal Parameters of the panel superheater under Three Typical Operating Conditions in Actual Furnace Operation.

Project	Inlet temperature	Outlet temperature	Flow rate G
Unit	°C	°C	t/h
60%Load	480.5	566.4	1083.4
80%Load	489.3	567.6	1427.8
100%Load	500.8	566.3	1792.7

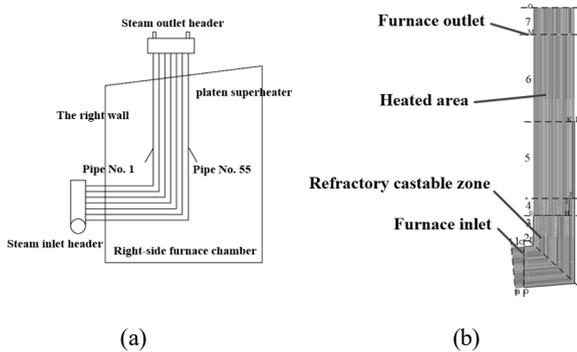


Fig. 1. 600 MW SCCFB boiler plate superheater model. (a, pipe number; b, grid model)

2.2 Theoretical Model for Heat Transfer Calculation

This paper performs theoretical calculations of the wall temperature for the panel superheater pipes by integrating the actual operating parameters of the boiler, furnace heat transfer theory, and the inlet and outlet temperatures of the tube screens [7-8]. The panel superheater pipes are segmented, and a method assuming a constant mass flow rate is employed to facilitate these calculations.

From the heat balance of the panel 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:

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

In the aforementioned equation, h_{out} and h_{in} denote the specific enthalpy values at the outlet and inlet of the panel superheater, respectively, measured in $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{°C}^{-1}$. G represents the mass flux of the working fluid within the tube, expressed in $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The total heat absorbed by the tubes, Q , can be determined using the subsequent equation:

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

In the formula, A denotes the surface area of the heat-absorbing section of the tube, measured in m^2 , and \bar{q} represents the average heat flux density on the tube surface, in

$\text{kW}\cdot\text{m}^{-2}$. The value of \bar{q} can be determined by integrating the function describing the heat flux density distribution along the height of the furnace, as follows:

$$\bar{q} = \frac{\int_{H_{in}}^{H_{out}} q(H)dH}{H_{out} - H_{in}} \quad (3)$$

Among them, H_{out} and H_{in} denote the inlet and outlet heights of the heated section of the tube, in meters m; $q(H)$ represents the heat flux density as a function of height along the furnace [5-6]. By combining equations (2), (3), and (4), the mass flow rate within the tube can be determined using the following equation:

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

The local heat flux density at any position along the panel superheater is determined using the thermal deviation across the furnace width, as proposed in reference[7].

That is, the local heat load on the panel superheater tube wall at a distance x from the furnace water-cooled wall surface is:

$$q_0 = q(H) \cdot Y(x) \quad (5)$$

In the above equation, $Y(x)$ denotes the thermal deviation coefficient of the tube at a distance x from the centerline of the furnace water-cooled wall.

Based on the parameters of the working medium inside the panel superheater tubes and the tube dimensions, formula (6) should be used to calculate the heat transfer coefficient of the working medium within the tubes, thereby achieving a better fit with the experimental data[9-12].

$$Nu = 0.00459 \text{Re}_w^{0.923} \text{Pr}_w^{-0.613} \left(\frac{\rho_w}{\rho_b} \right)^{0.231} \quad (6)$$

In the above equation, the subscript "b" denotes the value at the mainstream steam temperature of the working medium within the tube, while "w" denotes the value at the wall temperature. Re represents the Reynolds number, Pr represents the Prandtl number, and ρ represents the density of the fluid.

The mass flow rate distribution for the screen superheater tubes is calculated using the following formula.

$$h_{i,n}^{out} = h_{i,n}^{in} + \bar{q}_{i,n} s l_{i,n} / \omega_{i,n} \quad (7)$$

$$\omega_{i,n} = \bar{q}_{i,n} s l_{i,n} / (h_{i,n}^{out} - h_{i,n}^{in}) \quad (8)$$

In the above equation, $h_{i,n}^{out}$ and $h_{i,n}^{in}$ are the enthalpy values of the working medium at the inlet and outlet of pipe section n, respectively ($J \cdot kg^{-1}$); $\bar{q}_{i,n}$ is the average heat flux density of pipe section n ($W \cdot m^{-2}$); s is the pitch between pipes (m); $l_{i,n}$ is the length of pipe section n (m); and $\omega_{i,n}$ is the mass flow rate of pipe section n ($kg \cdot s^{-1}$). The subscript "n" denotes the pipe section number. $\bar{q}_{i,n} = \int_{H_{n,in}}^{H_{n,out}} q(H) dH$, In the formula, $q(H)$ represents the distribution function of heat flux density along the height of the furnace; $H_{n,in}$ and $H_{n,out}$ are the heights at the inlet and outlet of pipe section n, respectively (m).

Therefore, the mass flow rate of the working fluid within the pipe is:

$$\omega_\gamma = \omega_{i,n} / A \tag{9}$$

In the formula, A denotes the cross-sectional area of the water-cooled wall tube, measured in square meters (m^2).

The mass flow rate, working medium temperature, inner wall heat transfer coefficient and local heat flux density of each section of the screen superheater can be calculated by using the above formula. The inner and outer wall temperatures, midpoint temperature and fin temperature of each section of the screen superheater can be calculated by the following formulas.

Inner wall of the pipe:

$$t_{w,in} = \bar{t} + \delta t_T + q_{max} / \alpha_2 \tag{10}$$

Outer surface of the pipe:

$$t_{w,out} = \bar{t} + \delta t_T + q_{max} (1 / \alpha_2 + s / (\lambda_M (1 + \beta))) \tag{11}$$

Average value of the inner and outer walls of the pipe:

$$t_{w,m} = (t_{w,in} + t_{w,out}) / 2 \tag{12}$$

Due to the small dimensions and narrow spacing of the panel superheater tubes, the fins can be approximated as rectangular fins. Based on heat transfer principles, the temperatures at the fin tip and along the fin surface of the superheater tube can be calculated using the following formula:

$$t_{qg} = \bar{t} + \delta t_T + q_{(x)} \eta_{qg} (\ln(d_o / d_i) d_o / 4 \lambda_M + 1 / \alpha_2) \tag{13}$$

$$t_{qd} = t_{qg} + q_{(x)} \eta_{qd} ((s - d_w) / 2)^2 / 2 \lambda_M \delta \tag{14}$$

In the above equation, \bar{t} is the average medium temperature of the pipe section, °C; δt_T is the deviation of the medium temperature from the average value of the pipe section,

$^{\circ}\text{C}$; $q(x)$ is the local heat flux density in the pipe fitting, $\text{W}\cdot\text{m}^{-2}$; λ_M is the thermal conductivity of the metal, $\text{W}\cdot(\text{m}\cdot^{\circ}\text{C})^{-1}$; α_2 is the convective heat transfer coefficient between the working medium inside the pipe and the pipe wall, $\text{W}\cdot(\text{m}^2\cdot^{\circ}\text{C})^{-1}$; d_o and d_i are the outer and inner diameters of the superheater tube, m; η_{qt} , η_{qg} respectively represent the uniformity coefficients of the heat flux density at the fin tip and fin root. s is the pitch between fins, m; δ is the fin thickness, m.

3 Results and Analysis

3.1 Analysis of Mass Flow Rate of Each Pipe in the Tube Screen

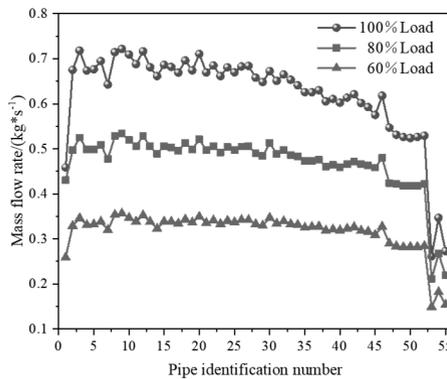


Fig. 2. The mass flow distribution of single tubes under three typical loads.

Figure 2 shows the mass flow distribution of a single tube in the panel superheater under three typical loads. It can be seen from the figure that the mass flow variation trend in the tubes of the panel superheater under the three typical loads is basically the same. As the tube screen number increases, the mass flow in the tubes shows a fluctuating change. Under different loads, the mass flow of the working medium in tubes 47 to 55 of the panel superheater is relatively lower than that in the other tubes of the tube screen. The wear-resistant material of the panel superheater is laid in a stepped manner, and the lower part of tubes 47 to 55 has a larger coverage area of wear-resistant material. To ensure that the temperature deviation at the outlet of the tube screen is not too large, the mass flow of the working medium in the tubes needs to be controlled by throttling rings, especially for tubes 53 to 55. Due to the largest coverage area of wear-resistant material and the shortest heating section of the tubes, if the mass flow of the working medium in the tubes is not properly controlled, it is more likely to cause other tubes to overheat due to low flow and pose a danger. Since the thermal deviation reflects the amount of heat absorbed by the tubes from another aspect, combined with the thermal deviation curve in reference [7], it can be found that under the same load, the tubes in the panel superheater with larger thermal deviation have higher heat load, absorb more heat, and have larger mass flow of the working medium. The heat load and the mass

flow of the working medium show a positive response characteristic. Among them, tube 1 mainly has a smaller mass flow due to the smaller thermal deviation at the tube's location and less heat absorption. Therefore, the calculated mass flow of the tube is also smaller, lower than that of tubes 47 to 55. Under 100% load, the maximum mass flow is 0.721 kg/s and the minimum mass flow is 0.261 kg/s; under 80% load, the maximum mass flow is 0.533 kg/s and the minimum mass flow is 0.211 kg/s; under 60% load, the maximum mass flow is 0.356 kg/s and the minimum mass flow is 0.149 kg/s.

3.2 Analysis of the Temperature Field of the Tube Screen

Based on boiler principles and existing research, the wall temperature of panel superheater tubes within the furnace increases progressively with height, reaching its peak at the top wall penetration outlet (i.e., the outlet of zone 6). Figure 3 illustrates the wall temperature distribution at the top wall penetration point for each tube under three typical load conditions. As shown in the figure, under different loads, as the tube number increases, the wall temperature exhibits a fluctuating trend, primarily attributed to thermal deviation within the tube screen and the influence of refractory material distribution. Comparing the wall temperature distributions across the three load conditions reveals that, as the load increases, the wall temperature at the same tube number generally rises, consistent with the established principle: an increase in heat load leads to higher combustion intensity within the furnace, resulting in greater heat generation and consequently higher wall temperatures. Specifically, under the 60%, 80%, and 100% load conditions, the highest wall temperatures occur at tube No. 53, tube No. 50, and tube No. 50, respectively, with corresponding peak temperatures of 626.74°C, 644.33°C, and 647.19°C.

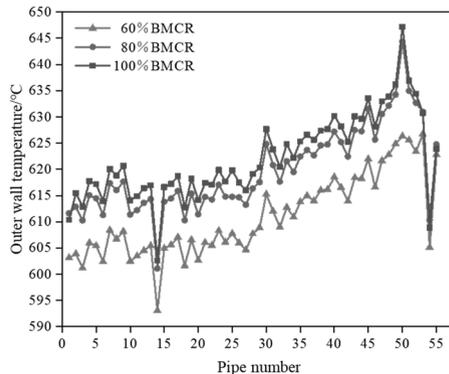


Fig. 3. The calculated tube wall temperatures at the furnace outlet of the tube screen under three typical load conditions

Under three typical load conditions, the wall temperature distribution along the height of the furnace was analyzed for pipes 1, 25, 50, 53, and 55 of the tube screen, considering factors such as mass flow rate, the stepwise application of wear-resistant materials, and

the maximum pipe wall temperature. The results are presented in Figures 4, 5, and 6. Since the inlet section (area 1) and outlet section (area 7) of the screen superheater pipes are located outside the furnace and are not exposed to heat, their pipe wall temperatures are identical to the working fluid temperature. Additionally, the working fluid temperature in area 7 of the panel superheater corresponds to the outlet working fluid temperature from area 6. Therefore, the analysis of the wall temperature distribution along the height of the furnace primarily focuses on areas 2 to 6. Under all three load conditions, the bottom of the panel superheater is covered with wear-resistant materials, resulting in a relatively low heat load and minimal temperature changes in this region. Consequently, the temperature differences between the working fluid, inner wall, and outer wall temperatures of the pipes are small. As the height of the tube screen increases, the pipe wall temperature rises sharply once the height of each pipe exceeds the wear-resistant layer. The maximum temperature occurs at the penetration point between the tube screen and the water-cooled wall of the furnace roof. Theoretical calculations indicate that under the three typical loads, the highest temperature is located at the center of the fin of pipe 50, with peak temperatures of 637.76°C, 649.52°C, and 652.96°C, respectively. At 80% load, the highest temperature of the tube screen is only 0.48°C below the allowable temperature of the steel material, while at 100% load, it exceeds the allowable temperature by 2.97°C. This phenomenon is mainly attributed to the longer wear-resistant layers covering pipes 47 to 55, which result in less overall heat absorption and a slower increase in the working fluid temperature inside these pipes. Given the lower heat transfer efficiency of each pipe in the tube screen, the lower working fluid temperature provides better cooling for the tube screen. Under the combined influence of thermal deviation and mass flow rate within the pipes, the highest temperature occurs at the fin of pipe 50. Prolonged over-temperature operation of the superheater tube screen under 100% load can lead to an over-temperature burst pipe phenomenon, posing a significant threat to the safe operation of the boiler. From the distribution diagrams of each pipe along the height of the furnace, it is evident that under deteriorated heat transfer conditions, the temperature difference between the pipe wall and the working fluid temperature significantly increases. This is because the working fluid inside the pipe cannot effectively absorb heat from the pipe wall, causing the pipe wall temperature to continue rising. Ultimately, this leads to an over-temperature condition in the pipes, which poses a serious threat to the safe operation of the boiler. To effectively prevent over-temperature in the pipes, it is essential to comprehensively consider factors such as the operating conditions of the boiler, heat transfer characteristics, and the allowable temperature of the pipe wall material. Optimizing the operating parameters of the boiler, such as adjusting fuel supply and controlling air volume, can improve combustion conditions within the furnace, thereby reducing pipe wall temperatures. Regular maintenance and inspection of the boiler, including timely replacement of aged or damaged components, are also critical measures to ensure the safe operation of the boiler.

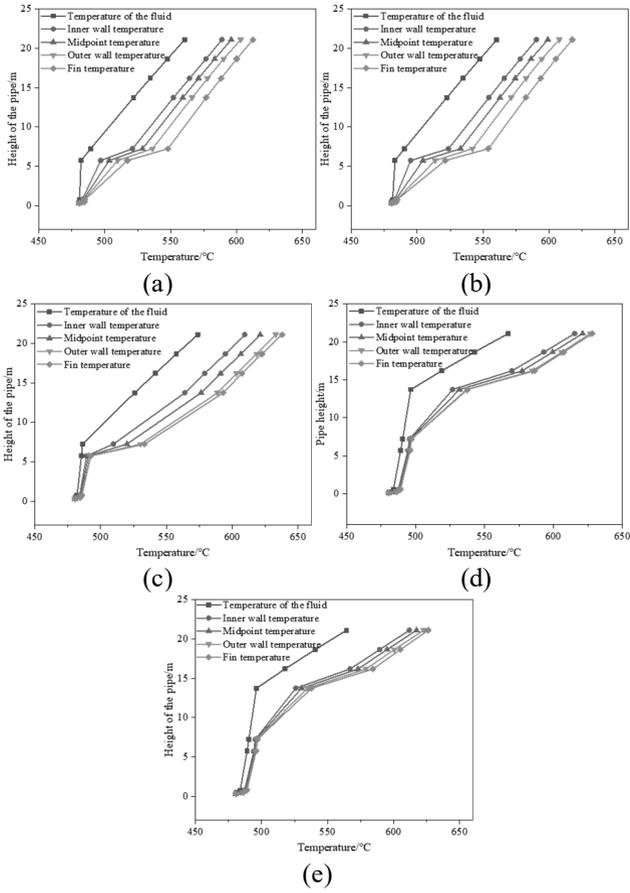
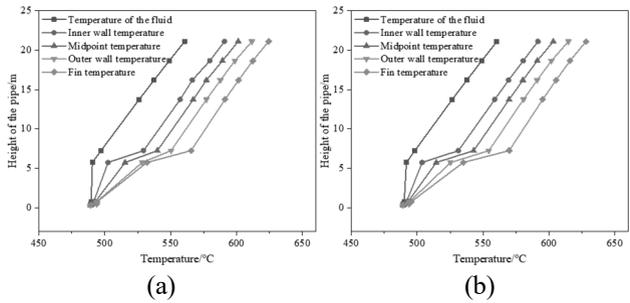


Fig. 4. The temperature distribution of the pipeline along the height of the furnace at 60% load. (a, No. 1 tube; b, No. 25 tube; c, No. 50 tube; d, No. 53 tube; e, No. 55 tube)



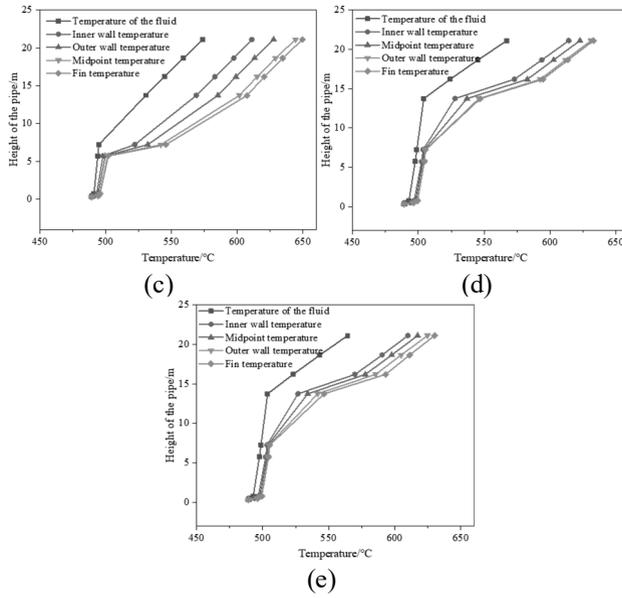
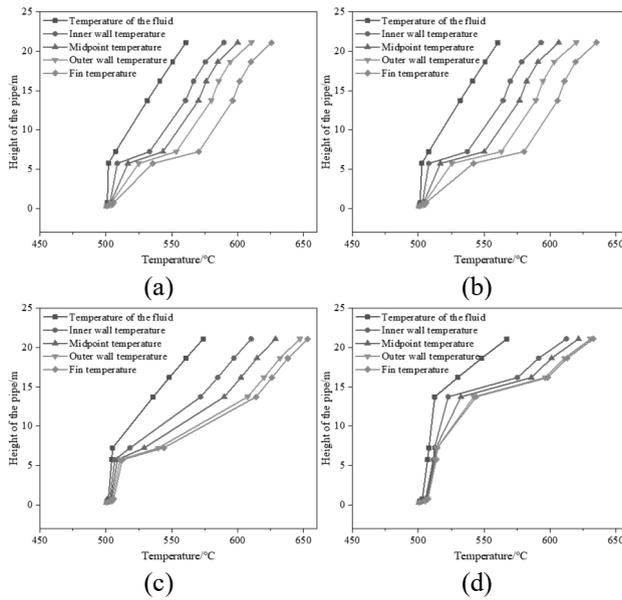


Fig. 5. The temperature distribution of the pipeline along the height of the furnace at 80% load. (a, No. 1 tube; b, No. 25 tube; c, No. 50 tube; d, No. 53 tube; e, No. 55 tube)



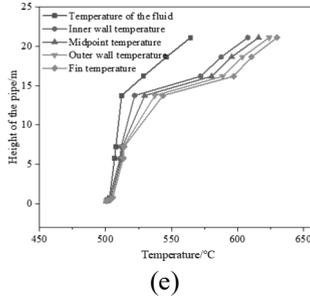


Fig. 6. The temperature distribution of the pipeline along the height of the furnace at 100% load. (*a*, No. 1 tube; *b*, No. 25 tube; *c*, No. 50 tube; *d*, No. 53 tube; *e*, No. 55 tube)

4 Conclusions

This study conducts a comprehensive analysis, research, and calculation on the overheating issues of the tube screen in a specific supercritical circulating fluidized bed boiler's panel superheater under the influence of thermal deviation, leading to the following conclusions:

(1) Theoretical calculations indicate that the mass flow rate within individual tubes increases with higher load conditions. Specifically, at 100% load, the maximum mass flow rate is 0.721 kg/s and the minimum is 0.261 kg/s; at 80% load, the maximum mass flow rate is 0.533 kg/s and the minimum is 0.211 kg/s; and at 60% load, the maximum mass flow rate is 0.356 kg/s and the minimum is 0.149 kg/s.

(2) Wall temperature analysis was performed on tubes No. 1, No. 25, No. 50, No. 53, and No. 55. Under the three typical load conditions, the highest temperatures of the tube screen were consistently located at the fin position of No. 50 tube, with peak temperatures of 637.76°C, 649.52°C, and 652.96°C, respectively. At 100% load, the maximum temperature exceeded the allowable material temperature by 2.96°C, leading to localized overheating of the tube screen and posing a significant threat to the safe operation of the boiler.

(3) In the event of deteriorated heat transfer, the working fluid within the tube is unable to effectively absorb heat from the tube wall. This results in a significant increase in the temperature difference between the tube wall and the working fluid, leading to a continuous rise in the tube wall temperature. Ultimately, this condition can cause over-temperature conditions and tube rupture in the tube screen.

These findings provide a critical reference for ensuring the safety of screen superheaters and for optimizing the design and safe operation of large high-parameter boilers.

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