Experimental study and safety analysis on the heating surfaces in the 660 MW supercritical CFB boiler under sudden electricity failure

Yinlong Li | Beibei Xie | Lingfeng Bi | Haoyu Yang | Chao Nie | Hao Qing | Dong Yang

1State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China
2Department of R&D Management, Xi'an Thermal Power Research Institute Co. Ltd., Xi'an, Shannxi, China

Abstract
The necessity of equipping with an emergency water supply system in a supercritical circulating fluidized bed (CFB) boiler has long been a controversial topic in the industry. In this study, the heating surface of a 660 MW supercritical CFB boiler at the Pingshuo Power Station of China Coal Group is taken as the research object. And a boiler electricity failure experiment was accomplished at the power plant, and the variations of thermal parameters during electricity failure were obtained from power plant distributed control system. By analyzing the physical process of the heating surfaces during electricity failure, a mathematical model of heat transfer to the heating surface was established and a calculation program in Fortran language was developed. In this study, the effect of different flow rates and operating times of the supply pumps on the safety of the heating surfaces were then investigated. The numerical simulation results show that an emergency supply pump with a flow rate of 250 t/h, activated within 120 s, ensures the safety of the heating surface. The results of this study have important implications for the selection of emergency supply pumps and the determination of flow rates and pressures for supercritical CFB boilers with external beds.

KEYWORDS
electricity failure, emergency water supply pump, experiment, heating surfaces, safety, supercritical circulating fluidized bed boiler

1 | INTRODUCTION

The combustion technology of a circulating fluidized bed (CFB) is a clean coal combustion technology that makes full use of inferior fuel resources. In recent years, China has made breakthroughs in the power generation technology of supercritical CFB boilers, leading the world's development in this field. With the increasing capacity of the CFB boilers, the conflict between heat transfer from combustion in the furnace and heat distribution in the boiler has become increasingly prominent. Currently, one of the main solutions is to arrange parts of the heating surface in the form of an external bed in the material circulation circuit. The presence of an external bed effectively separates the combustion and

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An electricity failure in a CFB boiler means that the power supply to the operation of the boiler is cut off all of a sudden. When an electricity failure accident occurs in a power plant, the main feed pump to the boiler is shut down and the heating surfaces cannot receive make-up water. In addition, the primary and secondary air fans, induced draft fan, and coal feeder will also stop at the same time. Although the coal feed and combustion of the boiler stop under accident, a large amount of heat accumulated in the high-temperature bed material will transfer heat to the heating surfaces of the boiler. If this part of the heat is ignored then the heating surfaces of the boiler may be damaged and serious accidents such as the burning of the heating surfaces may occur. It is therefore important to study and analyze the problem of unsteady heat transfer to the heat surfaces in the accident of a nuclear power plant to determine whether a supercritical CFB boiler needs to be equipped with an emergency water supply system. If the boiler needs to be equipped, then the selection of the pressure head and capacity of the emergency water supply pump has to be considered.

At present, some supercritical CFB units in China are equipped with emergency water supply systems to cope with safety incidents that may be caused by emergency power outages. Considering the overall complexity of the emergency water supply system, its cost is typically over RMB 20 million. In addition to the huge initial investment, emergency water supply systems require regular testing to ensure operational reliability in the event of an accident and are expensive to operate and maintain. However, the probability of an accident occurring is low and there is little chance that the emergency water supply system will be used for the entire design life of the system. Therefore, the necessity for an emergency water supply system in the supercritical CFB boiler remains controversial in the industry. If we can accurately calculate the flow rate and heat transfer to the heating surfaces under accident, and determine the need for an emergency water supply pump and pump selection, then not only can we provide an important reference for boiler design and optimization, but also can bring significant economic benefits for the plant.

The electricity failure is a typical beyond design basis accident and is a significant contributor to the overall risk of a nuclear power plant. At present, nuclear power plants often need to consider the safety of heating surfaces under an accident. The risk analysis of accidents can be an important basis for the safe operation of a nuclear power plant. In the event of an electricity failure in a nuclear power plant, the heat from the first and second circuits cannot be carried out in time by the cooling mass, resulting in a major accident with damage to the heating surfaces. This physical process is very similar to the study in this study. When dealing with this type of accident, the nuclear power plant generally uses a diesel-driven standby pump to deliver the cooling mass while the regulator relief valve on the first circuit is opened and the atmospheric relief valve and safety valve on the second circuit is opened to discharge the steam. The measures used in nuclear power plants to deal with this type of process provide experience for this paper to study the safety of the CFB boiler heating surface in the event of an electricity failure. Kang and Chang performed the safety assessment of OPR-1000 nuclear power plant for a station blackout accident by applying the combined deterministic and probabilistic procedure. Vahman et al. analyzed the station blackout accident and the effects of management measures on the behaviors of the Bushehr Nuclear Power Plant parameters under station blackout with consideration of three scenarios by using the RELAP5 code. Tian et al. developed a thermohydraulic and safety analytical code-TSACC by using Fortran90 language to evaluate the transient thermohydraulic behavior of the China advanced research reactor under a station blackout accident.

In recent years, research on water wall stabilization and heat transfer characteristics of supercritical boilers has received extensive attention. Li et al. conducted an experimental study on water wall tube heat transfer under high-temperature ash accumulation conditions and obtained the burnout time of the water wall without pressure relief. Wang and Xiao obtained the temperature-time curve of the working fluid under electricity failure on the basis of assuming a constant exhaust velocity for the working fluid. Deng et al. have simulated the boiler physical process in a 350 MW supercritical CFB boiler during electricity failure, providing a reference for the necessity of setting up an emergency water supply system for supercritical CFB boilers. Yao et al. studied the heat transfer analysis of a fixed bed in a CFB boiler after a sudden electricity failure. OuYang et al. analyzed the flow instability in a parallel channel system with uniform heating by establishing a numerical code applying a time-domain method. Xie et al. analyzed the flow instability occurring in the water wall of an ultra-supercritical CFB boiler with an annular furnace by developing a numerical computational program called Dynsys in Fortran language. Shen et al. established a general model to extend the study of flow instability in supercritical boilers. The existing research on electricity failure lacks comparison and verification of actual furnace data, with analysis mainly focusing on single heating surface components. Computational studies of the entire furnace system in the event of electricity failure do not exist.

The safety analysis and protection of the heating surfaces of supercritical CFB boiler heating surfaces in the event of electricity failure is one of the key technologies for boiler design and operation, especially for supercritical CFB boilers.
with high-temperature heating surfaces arranged in the external bed. In this study, the water wall, superheaters, and reheaters of the 660 MW supercritical CFB boiler of China Coal Group’s Pingshuo Power Station are used for calculation. And a boiler electricity failure experiment was accomplished at this power plant on July 7, 2020. Meanwhile, the variations of thermal parameters of boiler heating surfaces at all levels were collected through the power plant distributed control system (DCS). A mathematical model consisting of mass, momentum, and energy conservation equations was established. On the basis of the discrete time-domain method, a calculation program for the transient characteristics of the heating surfaces in an accident was developed on the basis of the Fortran language. On the basis of the model, this study briefly calculates the inlet pressure variation pattern of the heating surfaces and the outlet temperature of the working medium with time in the 660 MW supercritical CFB boiler under electricity failure, and safety calculation and analysis of the boiler heating surfaces were carried out. The influence of the flow rate and operating time of the emergency water supply pump on the safety of the boiler heating surfaces in the event of an electricity failure is emphatically studied, providing a basis for the selection of emergency water supply pumps under similar conditions.

2 | CALCULATION MODEL OF FLOW AND HEAT TRANSFER IN THE HEATING SURFACE OF A SUPERCRITICAL CFB BOILER UNDER ELECTRICITY FAILURE

2.1 | Basic assumptions

To simplify the calculations, the following assumptions are proposed:

(1) A one-dimensional model is employed. Compressibility and thermal expansion are considered.

(2) The vapor–liquid phase is in thermodynamic equilibrium and a homogeneous model is used to describe the two-phase region, without considering subcooled boiling and interphase thermal relaxation.

(3) Only heat transfer between the medium and the metal wall in the radial direction is considered.

(4) The temperature and velocity of the working fluid are uniformly distributed in the cross-section and the medium is only distributed in the axial direction, without internal circulation.

(5) The influence of kinetic, potential energy, and viscous dissipation on the energy equation is excluded from the analysis.

(6) Heat storage in the metal tube wall and thermal inert on the working media of the boiler heating surface is not considered under electricity failure.

2.2 | Boundary conditions and control equations

The boundary conditions of the flow and heat transfer model in the heating surface are the pressure, flow rate, and enthalpy of steady flow. These parameters can be determined by the boiler steady-state inlet parameters. The inlet flow and outlet pressure of the heating surface under electricity failure are known. On the basis of the basic assumptions of the calculation model, the flow in the tube is described by the following equation:

Mass conservation equation:

\[ \frac{\partial M}{\partial z} + A \frac{\partial \rho}{\partial t} = 0. \]  

Momentum conservation equation:

\[ \frac{\partial M}{\partial z} + A \frac{\partial (\rho \vec{v})}{\partial z} + A \frac{\partial (\rho \vec{v} \cdot \vec{a} \delta)}{\partial z} = -\rho g A \sin \theta - \left[ \frac{f}{d_e} + K_{in} \delta_d(z) + K_{ex} \delta_d(z - I) + K_{j} \delta_d(z - z_{jl}) \right] \frac{M^2}{2 \rho A}. \]  

Energy conservation equation:

\[ A \frac{\partial (\rho h)}{\partial t} + A \frac{\partial (\rho \vec{v} \cdot \vec{a} \delta)}{\partial z} = q_l. \]  

State equation:

\[ \rho = f(P, h). \]

The physical parameters of the above equation correspond to those of the phase when it is a single phase. The reduced parameters are used when it is two-phase.

2.3 | Discretization method

The internal node method is used to mesh the control volumes. The tubes are divided into several groups along the flow direction according to the heat flux distribution, and the heat flux of each group is equal. Then, the tube group is evenly divided into \( n \) tube sections. The control equations are discretized by the control volume integral method. In this
method, the discretization is performed through the first-order upwind scheme in space and the implicit difference scheme in time. According to the first-order upwind scheme, the physical state parameters on the junction are equal to those of the adjacent upstream control volume. Figure 1 shows the schematic of the control volume.

Integration of the governing equations on every control volume yields the following equations:

Mass conservation equation:
\[ A \frac{\rho_i^{j+1} - \rho_i^j}{\Delta t} + \frac{M_i^{j+1} - M_{i-1}^{j+1}}{\Delta z} = 0. \] (5)

Momentum conservation equation:
\[ \frac{M_i^{j+1} - M_i^j}{\Delta t} + \frac{1}{\Delta z} \left( \frac{M_i^j}{\rho_i^j} \right)^{j+1} - \left( \frac{M_i^j}{\rho_i^j} \right)^{j+1}_{i-1} \right) + A \frac{P_i^{j+1} - P_{i-1}^{j+1}}{\Delta z}
= -\rho_i^{j+1} g A \sin \theta - \frac{f_i^{j+1}}{d_i} + K_{in} \delta_d(z) + K_{ex} \delta_d(z - L)
+ K_{jb} \delta_d(z - z_{jb}) + K_{ez} \delta_d(z - z_{ez}) \right] = 0. \] (6)

Energy conservation equation:
\[ A \left( \frac{ph_i}{p} \right)^{j+1} - \left( \frac{ph_i}{p} \right)^{j+1}_{i-1} \right) + \frac{(Mh_i)^{j+1} - (Mh_i)^{j+1}_{i-1}}{\Delta z} = q_{li}^{j+1}. \] (7)

State equation:
\[ \rho_i^{j+1} = f\left( P_i^{j+1}, h_i^{j+1} \right). \] (8)

Steady-state equations are obtained by setting the time terms of Equations (5)–(8) as 0 to solve the initial steady-state values of each control volume.

\[ M_i^0 = M_i^{-1}, \] (9)

\[ \frac{1}{\Delta z} \left( \frac{M_i^0}{\rho_i^0} \right)^0_{i-1} + \frac{M_i^0}{\rho_i^0} = -\rho_i^0 g A \sin \theta
+ f_i^0 \frac{d_i}{d_i} + K_{in} \delta_d(z) + K_{ex} \delta_d(z - L)
+ K_{jb} \delta_d(z - z_{jb}) \right] \frac{1}{\Delta z} \left( \frac{M_i^0}{\rho_i^0} \right)^0_{i-1}
= 0, \] (10)

\[ \frac{(Mh_i)^0 - (Mh_i)^0_{i-1}}{\Delta z} = q_{li}^0. \] (11)

2.4 Steady-state and transient calculations

Before steady-state and transient calculations, grid sensitivity analysis is conducted to balance efficiency and accuracy. Figure 2 shows the temperature variations with the time step and space step. The difference between the temperature at time steps of 0.5 and 1 s is small. The calculation results are less sensitive to the space step, but taking into account the thermal deviation in the direction of the tube length and the structure of the tube, a space step of 0.5 m is taken. Therefore, integrating computational accuracy and efficiency, a time step of 1 s and a space step of 0.5 m are selected in the following calculations.

The steady-state equations are solved to provide initial values for the transient computation. The spatial step \( \Delta z \) is
approximately 0.5 m, and time step \( \Delta t \) is 1 s to ensure the independence between time and spatial steps. The difference scheme used in the above equations is stable and conservative and has sufficient calculation accuracy. On the basis of the steady-state results, the dynamic characteristics of each time step are obtained for further calculations and studies. On the basis of the above computational model, a program based on the Fortran language was developed to calculate the transient characteristics of fluid flow and heat transfer at the heating surface under electricity failure. The flow diagram of numerical calculation is shown in Figure 3.

The program calculation requires the input of the inlet pressure, inlet flow rate, and enthalpy values of the heated surface at a steady state to the steady-state calculation. It is also necessary to enter the variations of inlet flow, inlet enthalpy, outlet pressure, and heat flux of the heating surface with time during the transient state after the electricity failure event, which is entered into the program in the form of a linear fitting equation in this study to calculate the variation of the thermal parameters with time at the heated surface during transient operation.
To validate the flow and heat transfer calculation model at the heating surface, an electricity failure experiment of a supercritical boiler was accomplished at China Coal Group's Pingshuo Power Plant. Due to the very high economic losses associated with plant-wide power failure experiments only the boiler (No. 1) power failure experiment was carried out. At 7:35 a.m. on July 7, 2020, the No. 1 high voltage auxiliary transformer lost electricity and triggered boiler shutdown. At the same time, the main feed pump to the boiler is shut down and the heating surfaces cannot receive make-up water. In addition, the primary and secondary air fans, induced draft fan, and coal feeder will also stop at the same time. Meanwhile, an electric feed pump was connected to supply water to the boiler economizer and the high-pressure bypass valve was manually opened to initiate the discharge pressure relief. At the same time, the plant's DCS collected the variations of boiler economizer inlet flow rate, inlet water temperature, boiler feed water pressure, steam feed pump outlet pressure, electric feed pump outlet pressure, outlet working medium temperature, and inlet pressure of all heating surfaces over time during the electricity failure experiment.

3.1 | Brief introduction of supercritical CFB boiler structure

The structure of the 660 MW supercritical CFB boiler is displayed in Figure 4A,B. The boiler adopts a double air distributor and underpants leg structure. The furnace is equipped with a central partition with double-sided heating and a discontinuous arrangement. Six cyclone separators and six external heat exchangers are provided in the ash circuit of the boiler's external circulation. The medium-temperature superheater (MTSH) and high-temperature reheater (HTR) are arranged on the external bed. The low-temperature superheater (LTSH) and low-temperature reheater (LTR) are arranged in the tail flue and the high-temperature superheater (HTSH) is placed in the
As shown in Figure 5, a high-pressure bypass valve from Germany called the Pentair Sempell valve is installed at the outlet of the supercritical boiler superheater at the Pingshuo Power Plant and can be driven by electricity, steam, or manually. Meanwhile, the structural parameters of the CFB boiler are listed in Table 1. Before the electricity failure experiment, the DCS displays the steady-state thermodynamic parameters of each heating surface, as listed in Table 2, which will be used to calculate the steady-state process.

### 3.2 Inlet parameters measurement

During the electricity failure experiment, we mainly focus on the changes in some parameters at the boiler inlet, such as main feedwater flow, main feedwater temperature, circulating pump flow, and circulating pump outlet temperature. Pingshuo Power Plant adopts SITRANS PDS III differential pressure transmitter from Siemens (Figure 6). The transmitter is arranged at the inlet and outlet of the heating surface. Depending on the

| TABLE 1 Structural parameters of CFB boiler |
|---|
| Project | Unit | Economizer | Water wall | LTSH | MTSH1 | MTSH2 | HTSH | LTR | HTR |
| $d_{\text{out}}$ (mm) | 51 | 33.4 | 51 | 51 | 51 | 51 | 57 | 63.5 |
| $\delta$ (mm) | 7 | 7.1 | 9 | 8 | 7 | 11.5 | 4.5 | 5.5 |
| $d_{\text{in}}$ (mm) | 37 | 19.2 | 33 | 35 | 37 | 28 | 48 | 52.5 |
| $s_{T}$ (mm) | 114.3 | 45 | 114.3 | 115 | 115 | 1485 | 114.3 | 130 |
| $s_{L}$ (mm) | 120 | 107 | 100 | 100 | 63.5 | 97 | 115 |
| $L$ (mm) | 91,100 | 61,000 | 58,320 | 15,350 | 15,350 | 26,380 | 77,760 | 15,250 |
| Number of pipes | 1112 | 2821 | 556 | 380 | 380 | 1100 | 1390 | 560 |

Abbreviations: CFB, circulating fluidized bed; HTR, high-temperature reheater; HTSH, high-temperature superheater; LTR, low-temperature reheater; LTSH, low-temperature superheater; MTSH, medium-temperature superheater.

| TABLE 2 Steady-state thermodynamic parameters |
|---|
| Parameters | Water wall | LTSH | MTSH1 | MTSH2 | HTSH | LTR | HTR |
| Inlet pressure (MPa) | 19 | 18.3 | 18.2 | 18.1 | 18 | 2.9 | 2.8 |
| Inlet enthalpy (kJ/kg) | 1437.56 | 2722.85 | 3064.06 | 3161.32 | 3253.38 | 3084.73 | 3425.58 |
| Initial steady-state mass flow rate (kg/s) | 0.0988 | 0.539 | 0.864 | 0.889 | 0.314 | 0.205 | 0.509 |

Abbreviations: HTR, high-temperature reheater; HTSH, high-temperature superheater; LTR, low-temperature reheater; LTSH, low-temperature superheater; MTSH, medium-temperature superheater.
relationship between flow and differential pressure \((q \sim \sqrt{\Delta P})\), the changes in flow and pressure are converted and transmitted to the DCS. The variations of some parameters at the boiler inlet after electricity failure are recorded in DCS (Figures 7 and 8).

### 3.3 Outlet parameters measurement

During the electricity failure experiment, the outlet temperature of the boiler heating surfaces at all levels is also important. The safety of the heating surface is judged on the basis of the variations in these temperatures. Thermal sleeve thermocouple (WRN-0301T) is adopted thermoelectric sensor at Pingshuo Power Plant (Figure 9), which transmits the temperature variations after electricity failure to the DCS, and the variations of temperature at the heating surface outlet after electricity failure are recorded in the DCS (Figure 10).

### 3.4 Heat flux calculation of heating surfaces

The heat fluxes were calculated based on the measured data from the actual furnace experiments and the structure of the heating surfaces. On the basis of the measured data of the furnace experiments, the changes of the thermal parameters of the inlet and outlet of each heating surface with time were measured and the
variations in heat flux of the heating surface under electricity failure were calculated as shown in Table 3. The heat flux can be calculated according to Equations (12) and (13). It is worth noting that the heating area varies due to the type of heating surface, which is single-sided and four-sided. For example, the water wall is heated on one side and the economizer is heated on all four sides.

\[
q = \frac{Q(H_{\text{out}} - H_{\text{in}})}{S}, \quad (12)
\]

\[
S = \pi d_n L. \quad (13)
\]

3.5 | Solution method

According to measured data of the heating surface in the experiment, the outlet pressure, inlet flow, and inlet enthalpy (Table 4) fitted to the measured data in different time periods were entered into the program as known conditions.

When calculating the heating surface, a single tube is selected as the calculation loop. In Figure 11, for example, the calculation starts from the inlet of the economizer and ends at the outlet of the water wall. The calculation loop is divided into 419 nodes. Other heating surfaces are calculated in the same way. However, it is important to note that the heating surface may be heated on one side or on all four sides, which is different in the program calculation.

4 | SELECTION OF EMERGENCY WATER SUPPLY PUMP AND SAFETY ANALYSIS OF THE HEATING SURFACE UNDER ELECTRICITY FAILURE

The physical processes within the furnace are complex and many influences emerge in the event of an electricity failure. The amount of water supplied and the operation time of the emergency water supply pump will directly affect the dynamic processes under electricity failure, which is the key factor affecting the safety of boiler heating surfaces after such conditions. Therefore, it is necessary to study the influence of the water supply amount and operation time of the emergency water supply pump on the safety of the boiler heating surface. Meanwhile, the selection of the emergency water supply

**TABLE 3** Heat flux variations under accident

| Time (min) | Heat flux (kW/m²) |
|------------|------------------|
|            | Water wall       |
|            | LTSH             |
|            | MTSH1            |
|            | MTSH2            |
|            | HTSH             |
|            | LTR              |
|            | HTR              |
| 0          | 47.49            |
| 2          | 21.48            |
| 8          | 7.52             |
| 12         | 4.57             |
| 15         | 3.68             |
| 20         | 3.61             |

**TABLE 4** Input parameters of the calculation model under accident

| Time (min) | Inlet mass flow rate (t/h) | Inlet enthalpy of water wall (kJ/kg) | Outlet pressure of superheaters (MPa) | Inlet enthalpy of reheaters (kJ/kg) | Outlet pressure of reheaters (MPa) |
|------------|---------------------------|-------------------------------------|-------------------------------------|-----------------------------------|-----------------------------------|
| 0          | 1079                      | 1437.555                            | 18                                  | 3084.729                          | 2.8                               |
| 2          | 560.748                   | 1545.077                            | 21                                  | 3056.321                          | 2.7                               |
| 8          | 235                       | 1512.649                            | 20.9                                | 3014.054                          | 3.3                               |
| 12         | 130                       | 1467.742                            | 19.1                                | 3027.451                          | 1.0                               |
| 15         | 98.13                     | 1461.754                            | 17.8                                | 3014.131                          | 1.2                               |
| 20         | 90                        | 1418.723                            | 15.4                                | 2997.805                          | 1.1                               |
pump is also of great importance. It is worth mentioning that the safety analysis should be for the most dangerous operating conditions, therefore the calculation is based on the heat absorption ratio (0.64) converted to the heat load at full load. In the safety calculation analysis, there are some parameters that need to be entered into the calculation program, as shown in Table 5. However, the effect of heat storage in the metal tube wall and thermal inertia of the working mass under electricity failure is not considered for the time being, which may cause a certain prediction error, and the variation of these factors should be considered in the actual project.

TABLE 5  Safety analysis input parameters

| Time (min) | Outlet pressure of superheaters (MPa) | Outlet pressure of the reheaters (MPa) | Inlet mass flow rate (t/h) | Inlet temperature (°C) |
|------------|---------------------------------------|----------------------------------------|---------------------------|------------------------|
| 0          | 18                                     | 2.8                                    | 1079                      | 265                    |
| 2          | 21                                     | 2.7                                    | Linear reduction to 200 t/h before 120 s and emergency supply pump flow rate after operating |                        |
| 8          | 20.9                                   | 3.3                                    |                           | Temperature is steady-state inlet temperature of 265°C before operating and 30°C afterwards |
| 12         | 19.1                                   | 1                                      |                           |                        |
| 15         | 17.8                                   | 1.2                                    |                           |                        |
| 20         | 15.4                                   | 1.1                                    |                           |                        |
4.1 Effects of water supply amount on the safety of heating surfaces

In the verification section of the calculation model mentioned above, all the heating surfaces of the boiler can be adequately cooled. In fact, the water supply in the validation section is an approximately linear decrease due to the boiler being equipped with a circulation pump. On the whole, the water supply is large and the working medium temperature generally tends to decrease. At this time, the heating surfaces are safe. However, due to the diversity of projects, many units will not be equipped with circulating pumps or the pump will not be started after electricity failure occurs throughout the plant, and only under electricity failure conditions the emergency water supply pumps can be put into operation. If a relatively small water supply can meet the cooling conditions and ensure the safety of the heating surfaces after an electricity failure, the boiler can be equipped with a small flow rate emergency water supply pump. The construction costs of the power station must be saved.

Figure 12 shows the effect of water supply amount on the outlet temperature of the water wall after an electricity failure. The outlet temperature of the water wall increases with time when the water supply amount is small. The trend in outlet temperature is the result of the effects of working fluid flow, heat flux, and system pressure. When the water supply amount is small, the outlet temperature of the water wall initially rises considerably. This phenomenon occurs because cooling is less effective when the working fluid is stored in the water wall in smaller quantities. If the water supply amount does not match the heat flux to the heating surface, then the temperature of the working medium in the water wall will rise rapidly, which will greatly affect the safety of the water wall. In addition, the outlet temperature of the water wall increases first when the water supply amount is 150 t/h, reaching 598.3°C at 455 s, which is higher than the allowable temperature of 12CrMoV. When the water supply amount is 200 t/h, the outlet temperature does not more than 500°C and the tube-burst will not occur.

Figure 13 shows the effect of different water supply amounts on the outlet temperature of each superheater stage in the event of an electricity failure. At this point, the supply pumps run for the same time, 120 s. The temperature change of each superheater stage is separately calculated when the water supply amount is

![Figure 12](image12.png)

**FIGURE 12** Outlet temperature variations of water wall for different water supply amounts under electricity failure

![Figure 13](image13.png)

**FIGURE 13** Outlet temperature variations of superheaters for different water supply amounts under electricity failure (pump operation time, 120 s). Water supply amount: (A) 200 t/h and (B) 250 t/h. HTSH, high-temperature superheater; LTSH, low-temperature superheater; MTSH, medium-temperature superheater
200 and 250 t/h. In general, the outlet temperature of the superheater will increase for a period of time, and then decrease. This is because there is no working fluid entering the heating surface after an electricity failure accident occurred, so cooling is not possible. When the cooling water enters the heating surface, the temperature of the working fluid at the heating surface does not drop instantly because the heat flux of the heating surfaces is relatively high. At this point, the water supply amount is not sufficient to cool the heating surface. When the water supply amount is relatively larger than the heat flux of the heating surface, the heating surfaces will be cooled. Finally, the outlet temperature of each heating surface approaches the inlet temperature of LTSH. At the same time, the trend of the outlet temperature of the superheater at each level shows that the time to reach the maximum temperature is different and there is a certain lag in the direction of flow working fluid. When the water supply amount is 200 t/h, the outlet temperature of LTSH reaches 546.4°C at 167 s, which is the highest. Thereafter, the temperature tends to decrease, indicating that the water supply has a cooling effect on the heating surface. Meanwhile, the outlet temperature of MTS1 reaches 599.6°C at 188 s, MTS2 reaches 654.2°C at 218 s, and HTSH reaches 727.9°C at 239 s. When the water supply amount is 250 t/h, the outlet temperature of LTSH reaches 509.8°C at 150 s, which is the highest. Meanwhile, the outlet temperature of MTS1 reaches 599.6°C at 188 s, MTS2 reaches 654.2°C at 177 s, and HTSH reaches 659.1°C at 206 s. The calculations show that when the water supply amount is 250 t/h, the working fluid temperature at all levels superheater does not exceed the allowable temperature of the corresponding material. At the same time, the results show that the outlet temperature of each level of superheater reaches the highest point at different times for the same water supply. The time for the same heating surface to reach its maximum point also varies for different supplement amounts. The larger the water supply, the shorter the time for the heating surface to reach its maximum point. Therefore, the larger the water supply, the better the cooling effect of the heating surface.

The water supply needs to be selected to meet the safety requirements of all heating surfaces. In the calculation of reheater, delays in flow changes and other factors are taken into account. Therefore, the reheater is kept in a steady state for the first 10 s and the transient process after 10 s.

Figure 14 shows the effect of water supply amount on the outlet temperature of LTR and HTR in the event of an electricity failure. The inlet flow rate of the reheater remains constant for the first 10 s and therefore it will cool the outlet temperature of the LTR. The outlet temperature of LTR and HTR first rises when the water supply amount is relatively small and then falls as the heat flux of the reheater decreases. When the water supply amount is relatively large, the outlet temperature of the reheater decrease with time. The calculations show that when the water supply amount is relatively large, the outlet temperature of the reheater rises considerably. This phenomenon occurs because cooling is less effective when the working medium is stored in the reheater in small quantities. This situation indicates that if the water supply amount does not match the heat flux to the heating surface, the temperature of the working medium in the reheater will rise rapidly, which will significantly affect the safety of the reheater. In addition, the outlet temperatures of LTR and HTR always increase continuously, reaching 594.1°C at 148 s.

![Figure 14](image-url)
and 681°C at 128 s, exceeding the allowable temperature of the reheater material. When the water supply amount is 250 t/h, the maximum temperatures of the LTR and HTR reach 558°C and 655.5°C at 130 and 125 s, respectively. The maximum temperature difference in the superheater is very small, which is due to the cooling effect at a constant flow rate is unchanged in the initial stage. Therefore, for the safety of the reheater, the water supply amount should not be less than 250 t/h.

The above safety calculations and analysis of the different water supply amounts for all boiler heating surfaces illustrate that the flow rate of the emergency water supply pump needs at least 250 t/h to meet the conditions for adequate cooling of the heating surfaces to ensure the safety of all heating surfaces. This condition provides an important basis for the selection of an emergency supply pump. It is worth noting that such calculations are made without taking into account the heat storage in the metal tube wall and the thermal inertia of the working mass. This may lead to some errors in the calculation results. Therefore, future studies on the electricity failure accident process should couple the flue gas side heat transfer, the metal wall heat storage, and the mass side heat transfer, and consider the influence of each factor on the change of the mass parameters under electricity failure.

Figure 15 shows the inlet pressure variation of the water wall under different water supply conditions in the event of an electricity failure. The inlet pressure difference of the water wall under different water supply conditions is very small. A high-pressure bypass valve exists at the outlet of HTSH, the opening of which is the decisive factor in the variation of system pressure during pressure relief. In this paper, it is assumed that the opening of the high-pressure bypass valve is the same for different water supplies. Therefore, the inlet pressure difference of the water wall is small under varying conditions. The effect of pressure on the system may appear in future studies. In this project, the working fluid state is different for different water supplies, therefore, the opening of the high-pressure bypass valve can be adjusted to achieve system pressure relief. In the safety analysis and calculation of the heating surface, the opening of the high-pressure bypass valve is determined by the actual operation of the high-pressure bypass valve in the power station. The valve operation process and the combination of different conditions can be calculated when selecting the type of emergency water supply pump in the actual project.

### 4.2 Effects of operation time of the emergency water supply pump on the safety of heating surfaces

The operation time of the emergency water supply pump is another key factor affecting the safety of the heating surface. If the emergency water supply pump is not put into operation in time in the event of an electricity failure, the heating surface of the boiler will be exposed to a high temperature for a long time without being cooled. Therefore, it is important to study the temperature variations of the heating surfaces when the emergency water supply pump is in operation for different periods of time under electricity failure.

In the section, the working conditions for different operation times when the water supply amount is 200 and 250 t/h are calculated. Before utilizing the pump in the operation, the change rate of the feed water is the same as that when the emergency water supply pump is used in the operation at 2 min after an electricity failure. Figure 16 shows the outlet temperature variation of the water wall with time for different pump operation times under electricity failure. As can be seen in Figure 16A, the outlet temperature of the water wall will rise rapidly when the water supply amount is 200 t/h and the operation time of the water supply pump is 180 and 210 s. When the water supply time is 210 s, the outlet temperature of the water wall rises rapidly, reaching 797.3°C at 246 s, much higher than the allowable temperature of water wall material 12CrMoV. At this point, the program calculation stops. When the water supply time is 180 s, the outlet temperature of the water wall reaches 686.5°C at 246 s. The allowable temperature of water wall material 12CrMoV is 580°C, so for the water wall when the water supply amount is 200 t/h, the water supply pump needs to be put into operation within
150 s. The earlier it is put into operation, the better the cooling effect. As shown in Figure 16B, the outlet temperature of the water wall reaches 798.3°C at 246 s when the operation time is 210 s and reaches 640.9°C at 240 s when the operation time is 180 s. Meanwhile, Figure 16A,B shows that the materials are safe when the emergency water supply pump is operated within 120 and 150 s. The slight temperature fluctuation in the figure is related to the pressure changes. Therefore, in general, when the flow rate of the emergency water supply pump is 200 and 250 t/h, and the operation time is within the limits of 150 s, the safety of the water wall can be ensured.

Figure 17 shows the outlet temperature variations of the superheater at each stage for different operation time conditions of the emergency water supply pump. When the water supply amount is 200 or 250 t/h and the water supply pump operating time is 180 s, the outlet temperature of the LTSH reaches 797°C at 183 s, which is not allowed by the allowable temperature of the material. This is because the heat flux is relatively large for a short time after the electricity failure and the heating surface are not cooled in time. The heating up of the heating surface is a rapid process. When the water supply pump is used in operation at 150 s after the electricity failure, the outlet temperature of superheaters at all levels reaches 630.2°C at 246 s, 783.7°C at 149 s, 799°C at 146 s, and 797°C at 146 s, respectively, when the water supply amount is 200 t/h, And the temperature reaches 603.9°C at 166 s, 674.5°C at 149 s, 716.5°C at 153 s, and 742.7°C at 172 s, respectively, when the water supply amount is 250 t/h. As can be seen from the calculations for the superheater at all levels, the emergency supply pumps used at 150 s operation are not permitted. Although the water supply amount is increased as soon as possible, the rapid rise in temperature after the electricity failure can cause the outlet temperature to exceed the allowable temperature of the material. At the same time, when the emergency water supply pump used in operation at 120 s with a water supply amount of 200 t/h, the temperature of the HTSH already exceeds the permissible temperature of the material, which is also not allowed.

Figure 18 shows the outlet temperature variations of reheaters for different operating time conditions of the emergency water supply pump. Figure 18A shows that when the water supply pump is operating at 150 s after the electricity failure, the outlet temperature of LTR reaches 776.9°C at 160 s when the water supply amount is 200 t/h and 759.4°C at 154 s when the water supply amount is 250 t/h. Meanwhile, when the water supply pump is operating at 120 s, the water supply amount of 200 t/h cannot meet the cooling requirements of the LTR material. Figure 18B shows that when the water supply pump is operating at 150 s after the electricity failure, the outlet temperature of HTR reaches 798.2°C at 128 s regardless of the amount of water added. When operating with the supply pump for 120 s after a power failure the outlet temperature of the HTR does not exceed the allowable temperature of the material which is typically SA-213S30432, a very high allowable temperature. However, the material allowable temperature of the LTR is very low, so generally the inlet of the reheater needs to be spray cooled. Perhaps this will appear in future research. The calculations for the reheater show that due to the low allowable temperature of the LTR material, a relatively large water supply is required and the operation time of the emergency water supply pump needs to be operated within 120 s.

On the basis of the above calculation and analysis on the safety of the heating surface at all levels under...
FIGURE 17  Outlet temperature variations of superheaters for different pump operation times under electricity failure. Outlet temperature variations of (A) LTSH, (B) MTSH1, (C) MTSH2, and (D) HTSH. HTSH, high-temperature superheater; LTSH, low-temperature superheater; MTSH, medium-temperature superheater

FIGURE 18  Outlet temperature variations of reheaters for different pump operation times under electricity failure. HTR, high-temperature reheater; LTR, low-temperature reheater
different operation time conditions of the water supply pump, the emergency water supply pump with a delivery capacity of 250 t/h needs to be started in time within 120 s to ensure the safety of the heating surface at all levels after a boiler electricity failure.

5 CONCLUSION

In this study, a transient calculation model of the flow and heat transfer at the heating surface was established by analyzing the characteristics of the physical processes at the heating surface of a supercritical CFB boiler under electricity failure. An electricity failure experiment of the boiler was accomplished at the Pingshuo Power Plant. The variation pattern of the thermal parameters under electricity failure at the Pingshuo power station was calculated and analyzed. The calculation results were compared with the measured data from the actual furnace. On this basis, the influence of the flow rate and operation time of emergency water supply pump on the safety of heating surfaces was calculated and analyzed. The following conclusions were obtained.

(1) The transient calculation model of flow and heat transfer at the heating surface of a supercritical CFB boiler was established on the basis of the conservation equations of mass, momentum, and energy. The thermal parameters variation laws of the heating surface of a 660 MW supercritical CFB boiler at the China Coal Group's Pingshuo Power Station were calculated and analyzed. The transient calculation model was validated by means of an electricity failure experiment accomplished on an actual furnace at the Pingshuo Power Plant. These conclusions indicate that the calculation model under electricity failure established in this study is reasonable and accurate for the selection of an emergency water supply pump and for the safety analysis and calculation of the heating surface under these conditions.

(2) After an electricity failure, although the combustion process in the furnace basically stops, there is still a large amount of heat accumulation in the high-temperature bed material. At this point, the emergency feed pump is activated and optimized for operation in conjunction with the high-pressure bypass valve, which not only enables the boiler to relieve pressure but also cools each heating surface and can ensure safe operation. If the emergency water supply pump is not equipped or used in operation later after an electricity failure, then the heating surface may overheat and burst.

(3) The calculations indicate that when the water supply amount is small, the outlet temperature of the heating surface rises considerably. This phenomenon occurs because the cooling effect is less effective when the working fluid is stored in the heating surface in smaller quantities. The results show that the outlet temperature of the water wall does not exceed 500°C when the water supplement amount is 200 t/h. When the water supply amount is 250 t/h, the outlet temperatures of the superheater at all levels reach the maximum value of 509.8°C, 550.9°C, 599.2°C, and 659.1°C, respectively, and the emergency water supply pump is used in operation at 120 s after an electricity failure to meet the allowed requirements of the material. Meanwhile, the outlet temperatures of the reheaters at all levels reach the maximum values of 558°C and 655.5°C, meeting the allowable requirements of the material. If the emergency water supply pump is used late in the operation, then the outlet temperature of the heating surface will rise rapidly. Only when the emergency water supply pump is used to operate within 120 s after an electricity failure, the outlet temperature of the heating surface will decrease with time to ensure the safety of the heating surface.

(4) The calculation and analysis on the safety of the heating surface under different water supply amounts and operation times of the emergency water supply pump after electricity failure indicate that the water supply amount of the boiler should be at least 250 t/h. The emergency water supply pump with a flow rate of 250 t/h should be started within 120 s after an electricity failure to meet the cooling conditions of the heating surface so that the safety of the heating surface can be ensured. The safety study should also take into account the heat storage in the metal wall of the heating surface and the thermal inertia of the mass in future studies so that the calculation results will be more accurate. This aspect is of great significance to the selection of an emergency water supply pump and the determination of flow rate and pressure head for supercritical CFB boilers with external beds.

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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

NOMENCLATURE
\( A \)  inner cross-section area, m\(^2\)
\( d_n \)  inner diameter, m
\( \Delta \)  difference between calculated and actual pressure values, Pa
\( f \)  friction factor
\( g \)  gravity, m/s\(^2\)
\( h \)  specific enthalpy, J/kg
\( H \)  enthalpy, kJ/kg
\( i \)  space index
\( j \)  time index
\( K \)  pressure drop coefficient
\( L \)  total length of channel, m
\( m \)  inlet mass flow rate, kg/s
\( M \)  mass flow rate, kg/s
\( n \)  total number of control volume
\( P \)  pressure, Pa
\( q \)  heat flux, kW/m\(^2\)
\( Q \)  single tube mass flow, kg/s
\( q_l \)  linear power density, W/m
\( s \)  pitch, mm
\( S \)  Heating area of tube, m\(^2\)
\( t \)  time, s
\( \Delta t \)  time step, s
\( z \)  axial length, m
\( \Delta z \)  space step, m

GREEK SYMBOLS
\( \delta \)  pipe wall thickness
\( \delta_d \)  dimensional Dirac delta function, m\(^{-1}\)
\( \vartheta \)  angle of flow direction with respect to horizontal plane, radian
\( \rho \)  density, kg/m\(^3\)

SUBSCRIPTS
\( \text{in} \)  inlet
\( \text{out} \)  outlet
\( \text{jb} \)  local
\( \text{n} \)  inner
\( \text{T} \)  transverse
\( \text{L} \)  longitudinal

SUPERSCRIPTS
\( 0 \)  initial steady value
\( j \)  old time value
\( j+1 \)  new time value

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