Article

Safety Analysis on the Heating Surfaces in the 660 MW Ultra-Supercritical CFB Boiler under Sudden Electricity Failure

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Abstract: Ultra-supercritical circulating fluidized bed (CFB) boilers are taking up an increasing proportion of the CFB boiler fleet in China, making the safety concern about the heating surfaces in this type of boilers under sudden electricity failure draw more and more attention from the industry. For the time being, however, few studies have made efforts to resolve this concern. Given this, the physical process in a 660 MW ultra-supercritical boiler during the electricity failure accident was precited with a comprehensive model composed of mass and energy conservation equations in this work. The tube temperature of the boiler components with the highest safety risk, i.e., the water wall and a superheater, was obtained to evaluate the safety of the heating surfaces. The results revealed that the tube temperature (about 516 °C and 544 °C) would be obviously lower than the maximum permissible temperature of the tube material (600 °C and 630 °C) even when electricity could be restored at the power plant, indicating that the heating surfaces in the 660 MW ultra-supercritical CFB boilers would generally be recognized to be safe under sudden electricity failure.

Keywords: ultra-supercritical CFB; electricity failure; accident analysis; water wall; superheater

1. Introduction

To achieve its carbon peaking and carbon neutrality goals, great efforts have been paid by China to increase the share of renewables in power generation in the past few years. Even so, out of the consideration of ensuring the security of the energy supply, the share of thermal power generation still stands at 70% in China. Among all types of thermal power plants, circulating fluidized bed (CFB) power plants, especially the ones equipped with boilers of large capacity and high parameters (supercritical or ultra-supercritical), have gained increasing popularity for their higher energy efficiency and lower emission [1–5], and take up approximately 17% of China's total power generation. Currently, over 20% of existing CFB power plants in China are equipped with supercritical or ultra-supercritical boilers. Since supercritical boilers are all once-through boilers, steam separators take the place of boiler drums in these types of boilers, which greatly reduces the water storage and heat capacity of the main steam system. This significantly increases the risk of a safety accident called sudden electricity failure for supercritical boilers.

The electricity failure accident refers to a situation where the electricity supply to a power plant is suddenly cut off. For a CFB power plant, the boiler would immediately shut down, meaning that the primary and secondary air fans, induced draft fan, coal feeders, and feed water pumps would all stop operating. Even though combustion has been basically inhibited at this point, tons of high-temperature bed materials in the furnace would continue to heat the heating surfaces. Contrarily, no fresh working fluid would flow through the heating surfaces to cool them down because of the shutdown of the feed

water pumps, leading to the continuous increase in the tube temperature of the heating surfaces. Given the relatively low heat capacity of the main steam system in supercritical CFB boilers, questions have been posed by the industry on whether the heating surfaces, such as the water wall, would face over-temperature or even tube burst after an electricity failure accident happens.

Unlike most of supercritical CFB boilers, ultra-supercritical CFB boilers are usually equipped with external heat exchangers (EHEs) to provide extra heating surfaces. Therefore, under sudden electricity failure, not only the heating surfaces in the furnace, i.e., the water wall, but also the tube panels in the EHEs, i.e., the superheater, should be paid close attention to (the reason why the reheater could be excluded is that it is heated by the flue gas and thus has a lower heating rate). In this sense, although a couple of studies have been conducted on this topic, there still lacks a convincing conclusion for the safety of the heating surfaces in ultra-supercritical CFB boilers. Deng et al. [6,7] established a zero-dimensional model capable of predicting the tube temperature of the water wall during the electricity failure accident; however, the model was only applicable to supercritical CFB boilers without EHEs. Yao et al. [8] deeply analyzed the three-dimensional temperature field in the furnace of a 170 t/h CFB boiler during the electricity failure accident; however, the physical process in the water side was oversimplified in that work. Li et al. [9–11] carried out an electricity failure experiment in a 660 MW supercritical CFB boiler and established a mathematical model depicting the flow and heat transfer in the heating surface with the aid of the obtained measurement results. The effect of different parameters of the emergency supply pump on the safety of the heating surfaces was carefully investigated; however, in the model, the heat fluxes to the heating surfaces were simply derived from experimental data, making it difficult to be applied to other boilers despite having similar structures. Other studies have also been conducted on the transient process in supercritical boilers [12–20]; however, they are of little referential significance.

In light of this, it is of great importance to conduct research on the physical process in ultra-supercritical CFB boilers, especially the water side of the furnace and EHEs, during the electricity failure accident. In this work, aiming to provide insights into the safety of the heating surfaces under such conditions, the coupling effect between the working fluid in the water wall and superheater was described in detail. Based on this, a mathematic model that consisted of mass and energy conservation equations was developed, and the variation of the tube temperature of the water wall and superheater in a 660 MW ultra-supercritical CFB boiler was simulated. It turned out that even 2 h after the accident happened, the tube temperature of the water wall and superheater still did not reach the permissible value, which means that the heating surfaces in the 660 MW ultra-supercritical CFB boiler could be considered to be safe during the accident.

2. Physical Process in Typical Ultra-Supercritical CFB Boilers under Sudden Electricity Failure

2.1. Basic Information of the Investigated Ultra-Supercritical CFB Boiler

To ensure the representativeness of the investigated boiler, the 660 MW ultra-supercritical CFB boiler located in the Binchang Power Plant, Shanxi Province, China, is taken as the research object in this work. The boiler is manufactured by Harbin Boiler Company Limited and is mainly composed of a furnace with a single air distribution plate, four steam-cooled cyclones, four EHEs, and a twin tail dust. The schematic diagram of the boiler is shown in Figure 1, whereas the main design parameters of it are listed in Table 1.
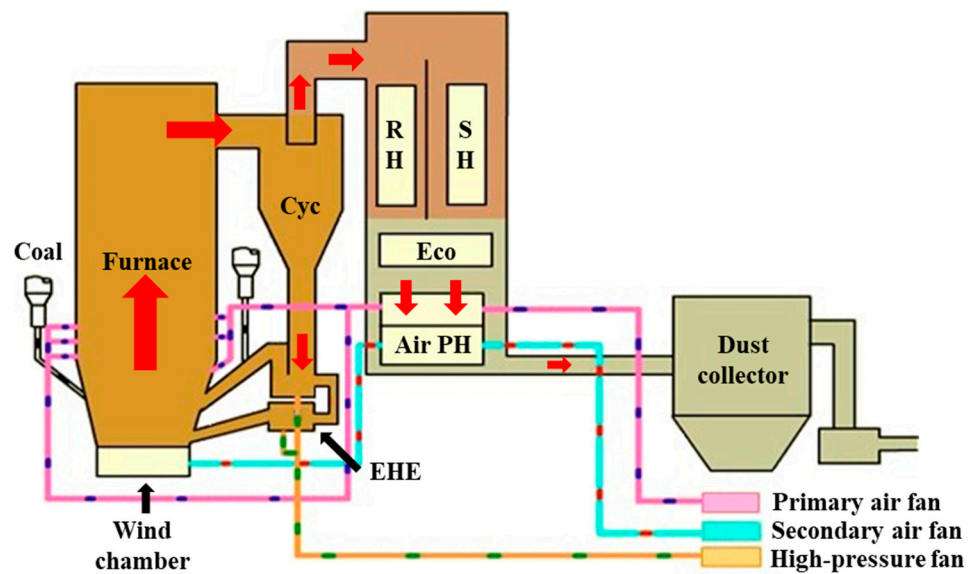
Figure 1. Schematic diagram of 660 MW ultra-supercritical CFB boiler. PH: preheater, SH: superheater, RH: reheater.

Table 1. Main design parameters of boiler.

Parameter	Unit	BMCR	BRL
Main steam flow rate	t/h	1914.3	1858.5
Main steam pressure	MPa	29.4	29.3
Main steam temperature	°C	605.0	605.0
Reheat steam flow rate	t/h	1621.1	1571.7
Reheat steam outlet pressure	MPa	5.96	5.78
Reheat steam outlet temperature	°C	623.0	623.0
Feed-water temperature	°C	302.9	300.9

The design fuel for the boiler is a mixture of coal gangue, slime, and raw coal, and its basic parameters are demonstrated in Table 2.

Table 2. Basic parameters of the design fuel.

Parameter	Abbreviation	Unit	Value
Total moisture on as-received basis	$M_{t,ar}$	%	19.10
Ash on as-received basis	A_{ar}	%	31.34
Fixed carbon on as-received basis	FC_{ar}	%	32.95
Carbon on as-received basis	C_{ar}	%	39.51
Hydrogen on as-received basis	H_{ar}	%	2.21
Nitrogen on as-received basis	N_{ar}	%	0.40
Sulfur on as-received basis	S_{ar}	%	0.63
Oxygen on as-received basis	O_{ar}	%	6.81
Calorific value on as-received basis	$Q_{net,v,ar}$	MJ/kg	14.52

2.2. Steam and Water Flow Circuit of the Investigated Ultra-Supercritical CFB Boiler

To provide fundamental information for the simulation of the physical process in the water side during the electricity failure accident, the steam and water flow circuit of the investigated boiler should be analyzed first. As shown in Figure 2, after being preheated in the economizer located at the tail dust, the feed water would flow through the water wall and directly go into the steam separator. Then the separated steam would enter the low-temperature superheater at the tail dust, the medium-temperature superheater I and II in the EHEs, and the high-temperature superheater in the furnace, in turn, before leaving the main steam system. From the steam and water flow circuit, it can be found out that for all the heating surfaces in the boiler, only the water wall and medium-temperature superheater

I and II are in direct contact with the bed materials and thus have larger heat transfer coefficients. In other words, the water wall and medium-temperature superheater I and II have the highest risk of over-temperature and tube burst among all the heating surfaces. In light of this, only the physical process in the water wall and medium-temperature superheater I and II are considered in this work. In addition, for the sake of convenience, the medium-temperature superheater I and II are assumed to be one entirety (hereinafter, the superheater) in the follow-up simulation.
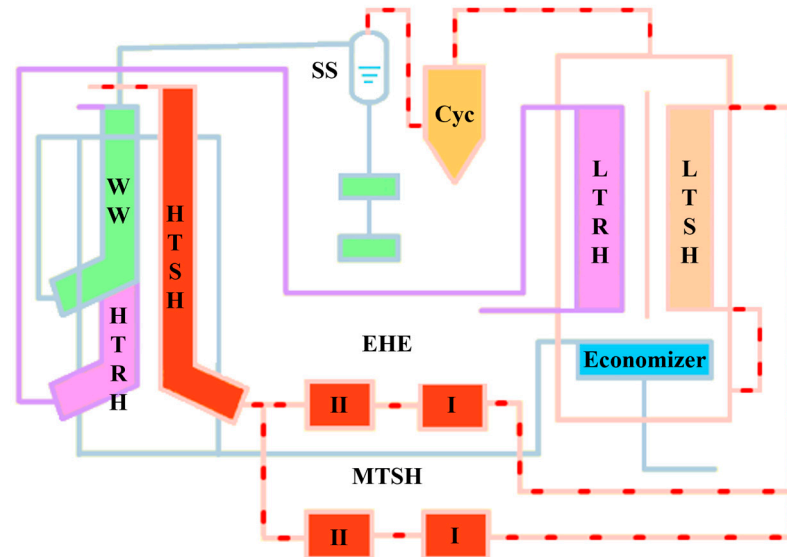
Figure 2. Schematic of steam and water flow circuit of typical ultra-supercritical CFB boiler. LT: low-temperature, MT: medium-temperature, HT: high-temperature, WW: water wall, SS: steam separator, SH: superheater, RH: reheater.

2.3. Physical Process in the Bed Material Side

2.3.1. Physical Process in the Boiler Furnace

Considering that the primary and secondary air fans, induced draft fan, and coal feeders all immediately shut down after the electricity failure accident happens, the vast majority of bed materials would fall and stack on the air distributor because of gravity, forming a stationary bed at the bottom of the furnace. At the same time, combustion would be quickly inhibited due to the rapid reduction of oxygen concentration in the furnace. Therefore, it can be assumed that only the heat transfer process between the stacked bed materials and water wall exists in the furnace during the electricity failure accident, and this process is predominantly achieved by conduction between the fixed bed and bottom heating surfaces as well as surface radiation of the fixed bed.

2.3.2. Physical Process in the EHEs

Similar to the situation in the furnace, only heat transfer process exists in the EHEs during the electricity failure accident. Owing to the cutoff of fluidizing air, a fixed bed is formed at the bottom of the EHEs as well. Therefore, the heat transfer between the bed materials in the EHEs and superheater is achieved through two mechanisms: particulate phase convection and radiation between the bed materials and immersed heating surfaces as well as surface radiation between the fixed bed and exposed heating surfaces.

2.4. Physical Process in the Water Side

Under the condition of no manual intervention, the physical process in the water side would heavily depend on the dynamic response characteristic of a solenoid valve called the pressure control valve (PCV). The PCV is a type of overpressure protection device and is usually installed at the outlet of the superheater [7]. When the main steam pressure exceeds a preset value, i.e., the set pressure, the PCV would jump up to exhaust extra steam to

the environment at a rate proportional to its certified capacity to lower the pressure in the steam–water system. On the other hand, when the main steam pressure falls below another preset value, i.e., the re-seating pressure, the PCV would shut again to avoid wasting the working fluid. Based on the aforementioned response characteristic of the PCV and the assumption that the main steam valve remains closed during the electricity failure accident, it can be inferred that the physical process in the water side would alternate between the following two steps:

(1)   Step 1: the gradual increase in the temperature and pressure in the main steam system. During this step, the PCV remains closed as the main steam pressure is still below the set pressure of the PCV. In this process, although there is no working fluid flowing out of the main steam system as the main steam valve is also closed (which is often the case), the pressure in the water wall is not always equal to that in the superheater, which leads to a non-negligible working fluid mass flow rate between these two devices. In the meantime, the working fluid in the main steam system is continuously heated by the bed materials in the furnace and EHEs, causing the incessant increase in the temperature and pressure in the system.

(2)   Step 2: the exhaust of the working fluid through the PCV. During this step, since the main steam pressure is higher than the set pressure of the PCV, the PCV would jump up and the working fluid in the main steam system would be exhausted to the environment, bringing about the decrease in pressure in the superheater. The PCV would shut again when the main steam pressure is reduced to the re-seating pressure of the PCV, making the physical process in the water side reenter step one. The physical process in the water side would continue to switch between these two steps until the boiler reaches thermal equilibrium.

3. Model Description

3.1. Modeling Approach and Hypothesis

To give an accurate description of the physical process in the furnace and EHEs during the electricity failure accident, the following modeling approach and hypotheses are adopted:

(1)   The physical process in the furnace and EHEs are considered, and both include three components: bed materials, tube wall, and working fluid.

(2)   The working fluid in the water wall and superheater as regarded as two entireties.

(3)   Mass and energy conservation are both taken into account.

(4)   The heat transfer between the furnace (EHEs) and environment is ignored.

The interactions between different components are demonstrated in the below figure (Figure 3).
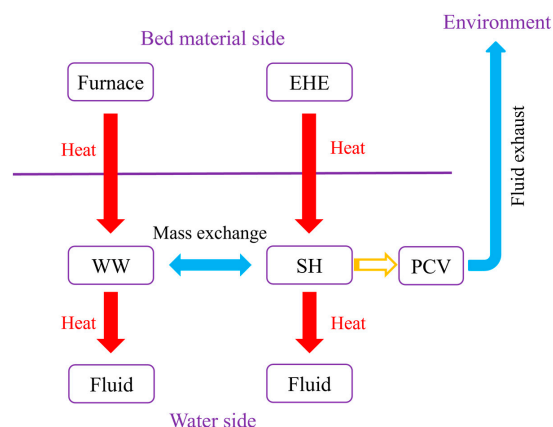
Figure 3. Schematic of interactions between different components.

3.2. Governing Equations for the BED Materials

3.2.1. Governing Equations for the Bed Materials in the Furnace

Given that the primary and secondary air fans and induced draft fan all stop operating at the start of the physical process, the mass of the bed materials in the furnace can be assumed to remain unchanged during the process. Thus, there is no need to set up the mass conservation equation for the bed materials in the furnace.

As for the energy conservation equation, based on the first law of thermodynamics for closed systems, it is formulated as follows [7]:

$$Q_{bt,fur} = -m_{b,fur}C_{b,fur}\frac{dT_{b,fur}}{dt} \tag{1}$$

where $Q_{bt,fur}$ is the heat flux between the bed materials and tube wall in the furnace, $m_{b,fur}$ is the mass of the bed materials in the furnace, $C_{b,fur}$ is the specific heat capacity of the bed materials in the furnace, $T_{b,fur}$ is the temperature of the bed materials in the furnace, while t refers to time.

$Q_{bt,fur}$ is composed of two parts, namely the conduction and radiation heat flux, and can be determined as

$$Q_{bt,fur} = (h_{bt,c,fur}A_{bt,c,fur} + h_{bt,r,fur}A_{bt,r,fur})(T_{b,fur} - T_{t,fur}) \tag{2}$$

where $h_{bt,c,fur}$ and $h_{bt,r,fur}$ are the convective and radiative heat transfer coefficients between the bed materials and tube wall in the furnace, respectively, $A_{bt,c,fur}$ and $A_{bt,r,fur}$ are the convective and radiative heat transfer area between the bed materials and tube wall in the furnace, respectively, and $T_{t,fur}$ is the tube temperature of the water wall.

According to previous literature [21], $h_{bt,c,fur}$ and $h_{bt,r,fur}$ can be given by

$$h_{bt,c,fur} = \frac{1}{\frac{1}{h_{re}} + \frac{\delta_{re}}{\lambda_{re}}} \tag{3}$$

where h_{re} is the heat transfer coefficient between the bed materials and refectory in the furnace, and δ_{re} and λ_{re} are the thickness and thermal conductivity of the refractory in the furnace, respectively.

$$h_{bt,r,fur} = \frac{\sigma}{\frac{1}{\varepsilon_{b,fur}} + \frac{A_{b,fur}}{A_{t,fur}}\left(\frac{1}{\varepsilon_{t,fur}} - 1\right)}\frac{(T_{b,eff,fur}^{4} - T_{t,fur}^{4})}{T_{b,fur} - T_{t,fur}} \tag{4}$$

where σ is the Stefan–Boltzmann constant, $\varepsilon_{b,fur}$ and $\varepsilon_{t,fur}$ are the emissivity of the bed materials and tube wall in the furnace, respectively, whereas $A_{b,fur}$ and $A_{t,fur}$ are the surface area of the bed materials and tube wall in the furnace (the former is equal to $A_{bt,r,fur}$). $T_{b,eff,fur}$ is the effective temperature of the bed materials in the furnace and is defined as

$$T_{b,eff,fur} = \frac{T_{b,fur} + T_{t,fur}}{2} \tag{5}$$

3.2.2. Governing Equations for the Bed Materials in the EHEs

Similarly, owing to the cutoff of the fluidizing air, only energy conservation needs to be considered for the bed materials in the EHE. Based on the first law of thermodynamics for closed systems, the energy conservation equation for the bed materials in the EHE can be formulated as follows:

$$Q_{bt,EHE} = -m_{b,EHE}C_{b,EHE}\frac{dT_{b,EHE}}{dt} \tag{6}$$

where $Q_{bt,EHE}$ is the heat flux between the bed materials and tube wall in the EHE, $m_{b,EHE}$ is the mass of the bed materials in the EHE, $C_{b,EHE}$ is the specific heat capacity of the bed materials in the EHE, and $T_{b,EHE}$ is the temperature of the bed materials in the EHE.

$Q_{bt,EHE}$ consists of two parts as well, i.e., the heat flux between the bed materials and immersed and exposed tube wall in the EHE, and can be determined as

$$Q_{bt,EHE} = (h_{bt,i,EHE} A_{bt,i,EHE} + h_{bt,e,EHE} A_{bt,e,EHE})(T_{b,EHE} - T_{t,EHE}) \tag{7}$$

where $h_{bt,i,EHE}$ and $h_{bt,e,EHE}$ are the heat transfer coefficients between the bed materials and immersed and exposed tube wall in the EHE, $A_{bt,i,EHE}$ and $A_{bt,e,EHE}$ are the heat transfer areas between the bed materials and immersed and exposed tube wall in the EHE, respectively, and $T_{t,EHE}$ is the tube temperature of the superheater.

According to the heat transfer model developed by Zhang [22], $h_{bt,i,EHE}$ can be calculated as

$$h_{bt,i,EHE} = h_{bt,p,cv} + h_{bt,g,cv} + h_{bt,p,r} \tag{8}$$

where $h_{bt,p,cv}$, $h_{bt,g,cv}$, and $h_{bt,p,r}$ are the heat transfer coefficients for particulate phase convection, gas phase convection, and particulate phase radiation, respectively. It should be noted that $h_{bt,g,cv}$ can be assumed to be zero as there is no macro flow in the EHE.

Moreover, $h_{bt,p,cv}$ and $h_{bt,p,r}$ can be given by [22]

$$h_{bt,p,cv} = \frac{1}{\frac{1}{h_{bt}} + \frac{1}{h_{bc}}} \tag{9}$$

where $1/h_{bt}$ and $1/h_{bc}$ represent the interface and internal thermal resistance of the bed materials in the EHE.

$$h_{bt,p,r} = \frac{\sigma}{\frac{1}{\varepsilon_{b,EHE}} + \frac{1}{\varepsilon_{t,EHE}} - 1} \frac{(T_{b,eff,EHE}^4 - T_{t,EHE}^4)}{T_{b,EHE} - T_{t,EHE}} \tag{10}$$

where $\varepsilon_{b,EHE}$ and $\varepsilon_{t,EHE}$ are the emissivity of the bed materials and tube wall in the EHE, respectively. $T_{b,eff,EHE}$ is the effective temperature of the bed materials in the EHE and is defined as

$$T_{b,eff,EHE} = \frac{T_{b,EHE} + T_{t,EHE}}{2} \tag{11}$$

As regard $h_{bt,e,EHE}$, it has a similar form as $h_{bt,r,fur}$:

$$h_{bt,e,EHE} = \frac{\sigma}{\frac{1}{\varepsilon_{b,EHE}} + \frac{A_{b,EHE}}{A_{t,EHE}}\left(\frac{1}{\varepsilon_{t,EHE}} - 1\right)} \frac{(T_{b,eff,EHE}^4 - T_{t,EHE}^4)}{T_{b,EHE} - T_{t,EHE}} \tag{12}$$

where $A_{b,EHE}$ and $A_{t,EHE}$ are the surface area of the bed materials and tube wall in the EHE (the former is equal to $A_{bt,e,EHE}$).

3.3. Governing Equations for the Tube Wall

During the process, unless tube burst occurs, the mass of the tube wall can be assumed to remain unchanged. Therefore, only the energy conservation equation needs to be set up for the tube wall.

3.3.1. Governing Equations for the Tube Wall in the Furnace (Water Wall)

By analogy to the derivation of the energy conservation equation for the bed materials, the equation for the water wall is obtained as follows:

$$Q_{bt,fur} - Q_{tw,fur} = m_{t,fur} C_{t,fur} \frac{dT_{t,fur}}{dt} \tag{13}$$

where $Q_{tw,fur}$ is the heat flux between the water wall and the working fluid inside it, $m_{t,fur}$ is the mass of the water wall, and $C_{t,fur}$ is the specific heat capacity of the water wall.

$$Q_{tw,fur} = h_{tw,fur} A_{tw,fur} (T_{t,fur} - T_{w,fur}) \tag{14}$$

where $h_{tw,fur}$ is the heat transfer coefficient between the tube wall and the working fluid in the water wall, $A_{tw,fur}$ is the heat transfer area between the tube wall and the working fluid in the water wall, and $T_{w,fur}$ is the temperature of the working fluid in the water wall.

The Mokry correlation [23] is adopted to determine $h_{tw,fur}$:

$$\frac{h_{tw,fur} d_{t,fur}}{\lambda_{w,fur}} = 0.0061 \text{Re}_t^{0.904} \text{Pr}_t^{0.684} \left(\frac{\rho_{w,t}}{\rho_{w,w}} \right)^{0.564} \tag{15}$$

where $d_{t,fur}$ is the diameter of the water wall, $\lambda_{t,fur}$ is the thermal conductivity of the water wall, Re_t and Pr_t are the Reynolds number and Prandtl number at reference temperature $T_{t,fur}$, respectively, while $\rho_{w,t}$ and $\rho_{w,w}$ are the density of the working fluid at reference temperature $T_{t,fur}$ and $T_{w,fur}$, respectively.

Re_t in Equation (15) is defined as

$$\text{Re}_t = \frac{4 \cdot 0.5 \dot{m}_f}{\pi \mu_{w,t} d_{t,fur}} \tag{16}$$

where $\dot{m}_f$ is the working fluid mass flow rate between the water wall and superheater, and $\mu_{w,t}$ is the viscosity of the working fluid at reference temperature $T_{t,fur}$. In view of the fact that the average fluid mass flow in the water wall is actually $0.5 \dot{m}_f$, the numerator in Equation (16) should be multiplied by a factor of 0.5.

3.3.2. Governing Equations for the Tube Wall in the EHEs (Superheater)

Using the same derivation method as in Section 3.3.1, the energy conservation equation for the superheater can be formulated as follows:

$$Q_{bt,EHE} - Q_{tw,EHE} = m_{t,EHE} C_{t,EHE} \frac{dT_{t,EHE}}{dt} \tag{17}$$

where $Q_{tw,EHE}$ is the heat flux between the superheater and the working fluid inside it, $m_{t,EHE}$ is the mass of the superheater, and $C_{t,EHE}$ is the specific heat capacity of the superheater.

$$Q_{tw,EHE} = h_{tw,EHE} A_{tw,EHE} (T_{t,EHE} - T_{w,EHE}) \tag{18}$$

where $h_{tw,EHE}$ is the heat transfer coefficient between the tube wall and the working fluid in the superheater, $A_{tw,EHE}$ is the heat transfer area between the tube wall and the working fluid in the superheater, and $T_{w,EHE}$ is the temperature of the working fluid in the superheater.

$h_{tw,EHE}$ can also be calculated by the Mokry correlation [23]; however, it should be noted that the Re_t here should be defined as

$$\text{Re}_t = \frac{4 \cdot 0.5 (\dot{m}_f + \dot{m}_{exh})}{\pi \mu_{w,t} d_{t,EHE}} \tag{19}$$

where $\dot{m}_{exh}$ is the exhaust mass flow rate through the PCV and is calculated as

$$\dot{m}_{exh} = \begin{cases} 0 & \text{Step one} \\ w_{cer} \sqrt{\frac{P_{w,EHE}}{P_{w,cer}} \frac{v_{w,cer}}{v_{w,EHE}}} & \text{Step two} \end{cases} \tag{20}$$

where w_{cer} is the certified capacity of the PCV, $P_{w,EHE}$ is the pressure in the superheater, $P_{w,cer}$ is the rated pressure of the PCV, while $v_{w,EHE}$ and $v_{w,cer}$ are the specific volume of the working fluid at reference pressure $P_{w,EHE}$ and $P_{w,cer}$, respectively.

3.4. Governing Equations for the Working Fluid

3.4.1. Governing Equations for the Working Fluid in the Water Wall

(1) Mass Conservation Equation

The change of the mass of the working fluid in the water wall originates from the mass exchange between the water wall and superheater, and thus the mass conservation equation can be given by

$$\frac{dm_{w,fur}}{dt} = -\dot{m}_f \tag{21}$$

where $m_{w,fur}$ is the mass of the working fluid in the water wall.

(2) Energy Conservation Equation

Based on the first law of thermodynamics for open systems, the energy conservation equation for the working fluid in the water wall can be formulated as follows:

$$Q_{tw,fur} = m_{w,fur}\frac{dU_{w,fur}}{dt} + \dot{m}_f(H_{w,fur} - U_{w,fur}) \tag{22}$$

where $U_{w,fur}$ is the specific internal energy of the working fluid in the water wall, and $H_{w,fur}$ is the specific enthalpy of the working fluid in the water wall.

3.4.2. Governing Equations for the Working Fluid in the Superheater

(1) Mass Conservation Equation

Unlike the working fluid in the water wall, the variation of the mass of the working fluid in the superheater is the result of the mass exchange between the two devices and the exhaust of the working fluid, and thus the mass conservation equation can be given by

$$\frac{dm_{w,EHE}}{dt} = \dot{m}_f - \dot{m}_{exh} \tag{23}$$

where $m_{w,EHE}$ is the mass of the working fluid in the superheater.

(2) Energy Conservation Equation

Based on the first law of thermodynamics for open systems, the energy conservation equation for the working fluid in the superheater can be formulated in the same way:

$$Q_{tw,EHE} = m_{w,EHE}\frac{dU_{w,EHE}}{dt} - \dot{m}_f H_{w,fur} + \dot{m}_{exh}H_{w,EHE} + (\dot{m}_f - \dot{m}_{exh})U_{w,EHE} \tag{24}$$

where $U_{w,EHE}$ is the specific internal energy of the working fluid in the superheater, and $H_{w,EHE}$ is the specific enthalpy of the working fluid in the superheater.

3.5. Determination of Working Fluid Mass Flow Rate between Water Wall and Superheater

The working fluid mass flow rate between the water wall and superheater $\dot{m}_f$ has a significant impact on the physical process during the electricity failure accident as it largely determines the heat transfer coefficient between the tube wall and the working fluid inside it. Therefore, it is of great importance to accurately predict this parameter. To obtain $\dot{m}_f$, the following hypothesis and approach is adopted in this work:

(1)　For the sake of simplicity, among the three categories of pressure drop, only frictional pressure drop (accounts for the majority) is considered in this work.

(2)　The frictional pressure drop between the water wall and superheater $\Delta P_{fur,EHE}$ is assumed to be directly proportional to $\dot{m}_f^2$, and thus $\Delta P_{fur,EHE}$ can be calculated as

$$\Delta P_{fur,EHE} = \frac{\dot{m}_f^2 \overline{v}_{fur,EHE}}{\dot{m}_{f,BMCR}^2 v_{BMCR}}\Delta P_{fur,EHE,BMCR} \tag{25}$$

where $\overline{v}_{fur,EHE}$ is the average specific volume of the working fluid in the water wall and superheater, v_{BMCR} is the specific volume of the working fluid under the boiler

maximum continuous rate (BMCR) condition, $\dot{m}_{f,BMCR}$ is the working fluid mass flow rate between the water wall and superheater under the BMCR condition, and $\Delta P_{fur,EHE,BMCR}$ is the frictional pressure drop between the water wall and superheater under the BMCR condition.

(3)　Suppose a possible working fluid mass flow rate $\dot{m}'_f$, use Equations (1)–(24) and the two below equations to determine the pressure in the water wall and superheater ($P_{w,fur}$ and $P_{w,EHE}$) under the given $\dot{m}'_f$.

$$P_{w,fur} = f(U_{w,fur}, v_{w,fur}) \tag{26}$$

$$P_{w,EHE} = f(U_{w,EHE}, v_{w,EHE}) \tag{27}$$

where $v_{w,fur}$ is the specific volume of the working fluid in the water wall.

(4)　Compare $P_{w,fur} - P_{w,EHE}$ and $\Delta P_{fur,EHE}$ (calculated from $\dot{m}'_f$ through Equation (25)). If the difference between these two values is lower than a preset threshold ε, then $\dot{m}'_f$ can be seen as $\dot{m}_f$. Otherwise, repeat (3) and (4) until $|P_{w,fur} - P_{w,EHE} - \Delta P_{fur,EHE}| < \varepsilon$.

4. Results and Discussion

4.1. Initial Values of the Simulation

Based on the design value of this 660 MW ultra-supercritical CFB boiler, the initial values of the simulation are listed in Table 3.

Table 3. Initial values of simulation.

Parameter	Value	Parameter	Value
Fluid temperature in water wall/°C	368	Fluid pressure in water wall/MPa	32.4
Fluid temperature in superheater/°C	500	Fluid pressure in superheater/MPa	30.6
Tube temperature of water wall/°C	387	Volume of water wall volume/m^3	50
Diameter of water wall/mm	6.5	Mass of water wall/t	630
Tube temperature of superheater/°C	546	Volume of superheater/m^3	14
Diameter of superheater/mm	8.0	Mass of superheater/t	190
Furnace bed temperature/°C	860	Mass of bed materials in furnace/t	238
Refractory temperature/°C	860	Mass of refractory in furnace/t	245
Thickness of refractory/mm	120	/	/
EHE bed temperature/°C	735	Mass of bed materials in EHE/t	400
Set pressure of PCV (MPa)	30.73	Re-seating pressure of PCV (MPa)	29.81
Certified capacity of PCV (t/h)	392		

4.2. Physical Process under Sudden Electricity Failure

With the aid of the built-in ode113 solver in Matlab, the equation system composed of Equations (1)–(24) can be solved, and the total simulation time is set as 8000 s as electricity should able to be restored after this period of time.

4.2.1. Physical Process in the Bed Material Side

As demonstrated in Figure 4, during the electricity failure accident, the furnace and EHE bed temperature both gradually drop but at a decreasing speed. This phenomenon is more obvious for the EHE bed temperature as the heat flux between the bed materials and tube wall in the EHE declines much faster throughout the process. This is partly due to the larger percentage reduction in the temperature difference between the bed materials and tube wall in the EHE (58.6%) than that in the furnace (51.8%) from start to finish.
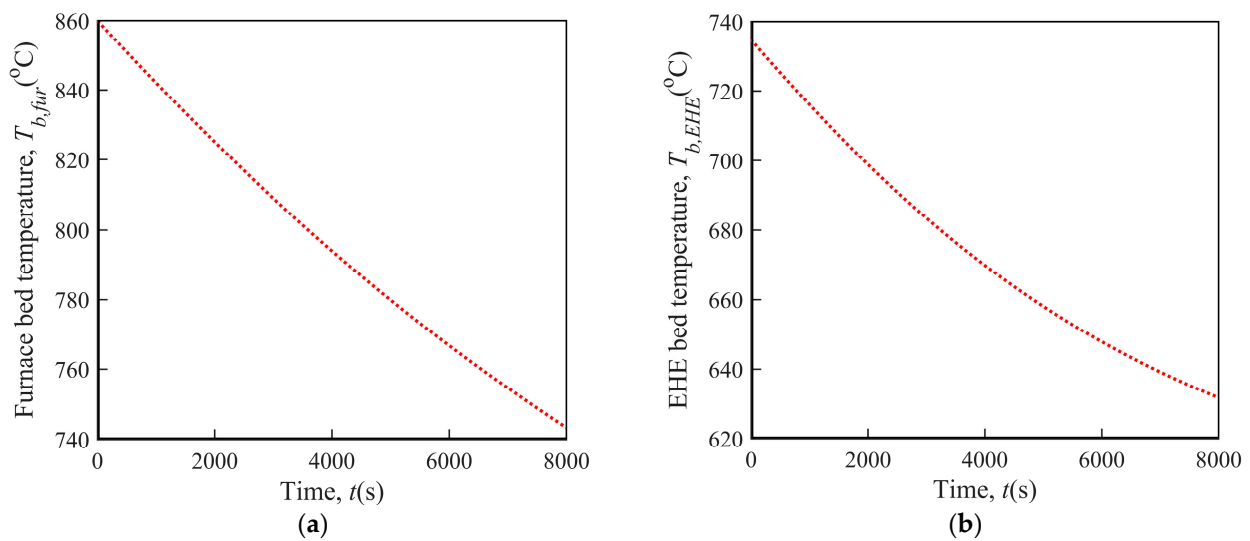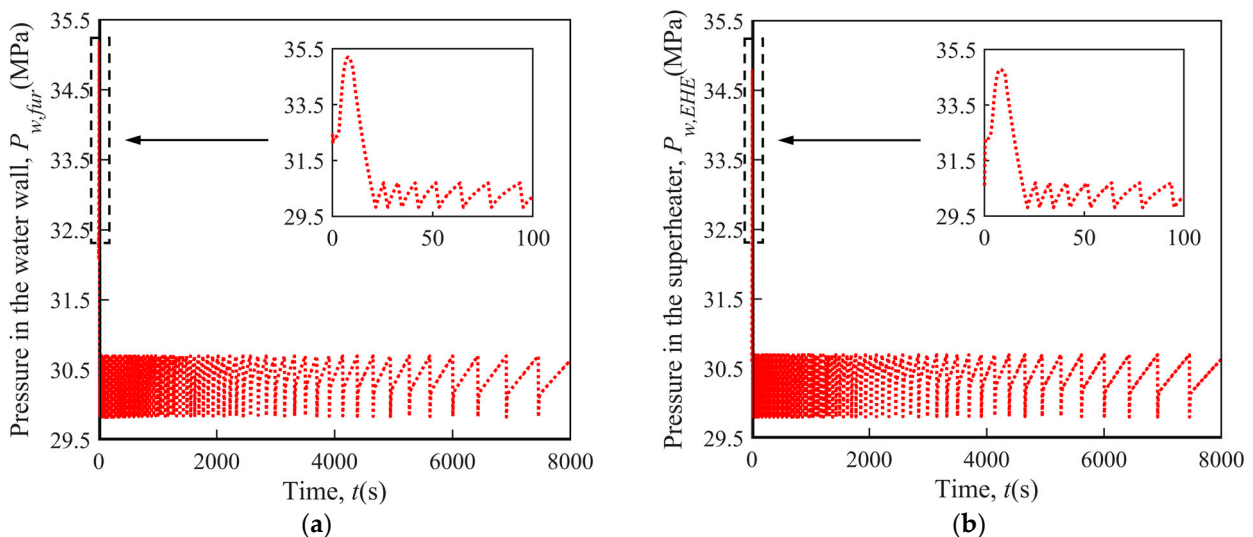
Figure 4. Variation of bed temperature under sudden electricity failure. (**a**) Furnace bed temperature; (**b**) EHE bed temperature.

4.2.2. Physical Process in the Water Side

(1) Fluid Pressure

As illustrated in Figure 5, the fluid pressure in the water wall has a similar variation trend to that in the superheater. After reaching their maximum values (close to 35.2 MPa) at the start of the process, these two parameters enter a period of approximately equal-amplitude oscillation due to the intermittent exhaust of the working fluid. The upper and lower bound of the oscillation value are about 30.7 Mpa and 29.8 Mpa, which corresponds to the set and re-seating pressure of the PCV. Based on the premise that the main steam valve is closed during the electricity failure accident, the rapid increase in the fluid pressure in the water wall and superheater at the beginning of the process is caused by the sudden decrease in the fluid outflow rate from the main steam system as the PCV has a much lower certified capacity than the main steam valve (392 t/h vs. 1914 t/h).
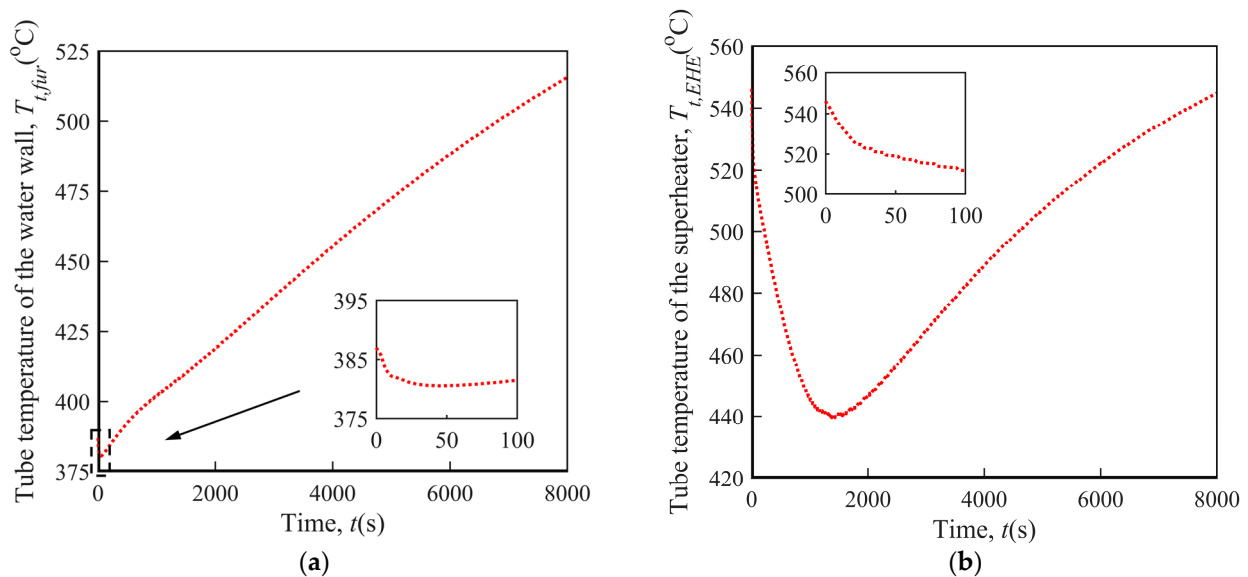

Figure 5. Variation of fluid pressure under sudden electricity failure. (**a**) Water wall; (**b**) Superheater.

(2) Tube Temperature

Different from the furnace and EHE bed temperature, as shown in Figure 6, the tube temperature of the water wall and superheater takes on a first falling then rising trend. The reason why the tube temperature drops at first is that after the electricity failure accident

happens, the heat flux between the bed materials and tube wall would rapidly decrease owing to the cutoff of the fluidizing air. Meanwhile, however, as a result of the exhaust of working fluid, the heat flux between the tube wall and working fluid would basically remain unchanged as before the accident occurs (heat transfer still occurs by forced convection). Therefore, the heat flux between the tube wall and working fluid would be larger than that between the bed materials and tube wall, making the tube wall lose some of its heat. Shortly afterward, with the gradual decrease in the temperature difference between the tube wall and working fluid inside it, the heat flux between the bed materials and tube wall would be higher than that between the tube wall and working fluid again, bringing about the simultaneous rise in the temperature of the tube wall and the working fluid inside.

Figure 6. Variation of tube temperature under sudden electricity failure. (**a**) Water wall; (**b**) superheater.

Moreover, for the tube temperature of the water wall, the length of the downward phase is relatively short as the initial temperature difference between the tube wall and the working fluid inside it is already quite small (<20 °C), meaning that there is not much room for a reduction in the tube temperature. Contrarily, the temperature difference between the superheater and the working fluid flowing through it is much larger as a portion of the working fluid is from the water wall and thus has a relatively low temperature. The larger temperature difference results in a longer downward phase for the tube temperature of the superheater.

In light of the facts that the tube temperature of the water wall and superheater is still well below the corresponding maximum permissible temperature (600 °C and 630 °C) when electricity can be restored and the maximum pressure in the main steam system during the accident is less than 9% higher than the normal operating pressure, the heating surfaces in the 660 MW ultra-supercritical CFB boilers can be considered to remain safe under sudden electricity failure.

(3) Fluid Mass

Surprisingly, the mass of the working fluid in the water wall shows a completely different variation trend to that in the superheater. As demonstrated in Figure 7, the fluid mass in the water wall presents an overall descending trend, while on the whole, the fluid mass in the superheater increases first and then decreases. The initial increase in the fluid mass in the superheater is caused by the reduction in the fluid temperature during this period, which is the result of the influx of lower-temperature working fluid from the water wall (the cooling effect of the influx fluid still plays a bigger role than the heating effect of the tube wall because of the relatively large temperature difference between the fluid in the water wall and superheater at this point). However, along with the decrease in the mass in the water wall, the working fluid mass flow rate between the water wall and superheater drops as well, the fluid mass in the superheater then progressively decreases due to the

subsequent rise in the fluid temperature. In addition, it turns out that the interval between two adjacent drops in the fluid mass in the superheater becomes longer, indicating that the fluid exhaust frequency would decrease with time during the electricity failure accident.
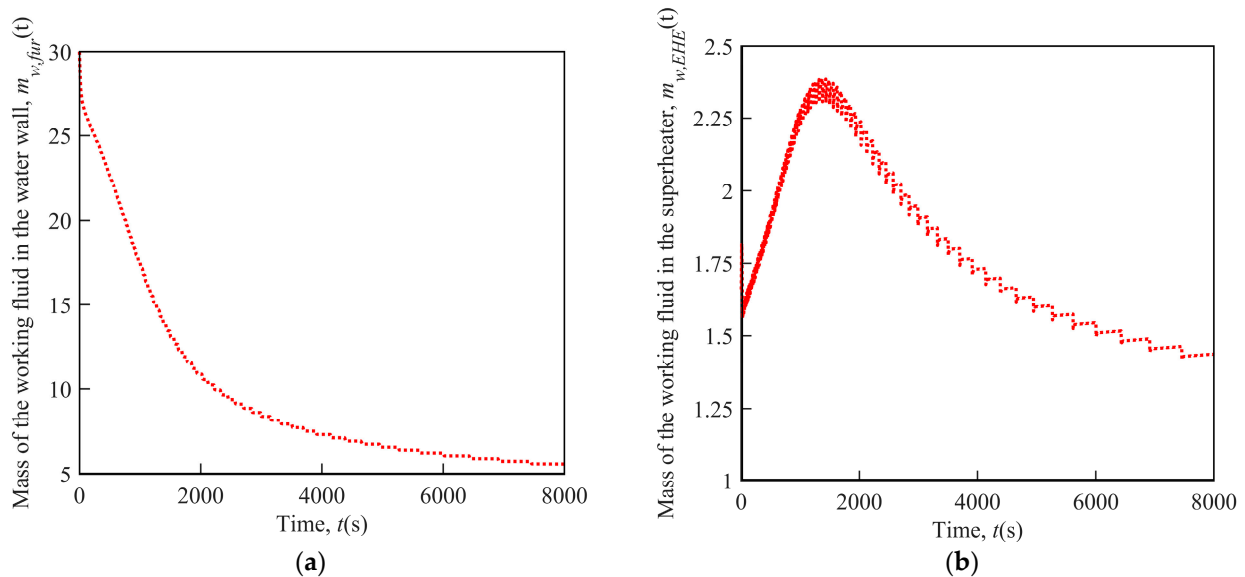
Figure 7. Variation of fluid mass under sudden electricity failure: (**a**) Water wall; (**b**) superheater.

5. Conclusions

The safety of the heating surfaces in ultra-supercritical CFB boilers under sudden electricity failure has remained to be an unresolved question in the industry. Nevertheless, existing studies cannot fully address this issue. Therefore, in this work, based on the in-depth analysis on the physical process in both the bed material and water side during the electricity failure accident, a mathematical model that consisted of mass and energy conservation equations was set up. Using this model, the variation of a few key parameters in a 660 MW ultra-supercritical CFB boiler during the accident was predicted, and a preliminary conclusion on the safety of the heating surfaces under sudden electricity failure can be made.

To sum up, the main conclusions of this work are shown as follows:

- During the electricity failure accident, the bed temperature gradually dropped but at a decreasing speed, whereas the tube temperature took on a first falling then rising trend. In contrast, after reaching the maximum value, the fluid pressure in the heating surfaces went through a process of approximately equal-amplitude oscillation.
- Under the steam and water flow circuit design reported in this work, the safety of the heating surfaces in the 660 MW ultra-supercritical CFB boiler could be guaranteed for there is enough time for electricity to be restored.

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Nomenclature

A	Area (m^2)
C	Specific heat capacity (J/kg·K)
d	Diameter (m)
H	Specific enthalpy (J/kg)
h	Heat transfer coefficient (W/m^2·K)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
Pr	Prandtl number (-)
Q	Heat flux (W)
Re	Reynolds number (-)
T	Temperature (K)
t	Time (s)
U	Specific internal energy (J/kg)
v	Specific volume (m^3/kg)
w	Capacity (kg/s)

Greek letters

δ	Thickness (m)
ε	Emissivity (-)
λ	Thermal conductivity (W/m·K)
μ	Viscosity (kg/m·s)
ρ	Density (kg/m^3)

Subscripts and superscripts

b	Bed materials
BMCR	Boiler maximum continuous rate
bt	Bed materials to tube wall
c	Conduction
cer	Certified
cv	Convection
e	Exposed
eff	Effective
EHE	External heat exchanger
exh	Exhaust
f	Flow
fur	Furnace
g	Gas phase
i	Immersed
p	Particulate phase
r	Radiation
re	Refractory
t	Tube wall
tw	Tube wall to working fluid
w	Working fluid

Abbreviations

BMCR	Boiler maximum continuous rate
BRL	Boiler rated load
CFB	Circulating fluidized bed
EHE	External heat exchanger
PCV	Pressure control valve
PH	Preheater
RH	Reheater
SH	Superheater
SS	Steam separator
WW	Water wall

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