DEVELOPMENT AND APPLICATION OF THERMAL CALCULATION SOFTWARE FOR BOILER FURNACE

by

Jianwei CHAI [*], ***Xingfang LI, and Meiling YANG***

Langfang Yanjing Vocational Technology College, Hebei, China

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Aiming at the thermal calculation of supercritical boiler furnace check, the article is based on the divisional calculation method in the thermal calculation standard of the Soviet Union in 1973, combined with the 1-D block flow model of pulverized coal combustion, and proposes a new divisional 1-D furnace exchange thermal calculation model, and compiled the corresponding thermal calculation software. The software is easy to use, not only can obtain the average temperature distribution of flue gas along the height of the furnace and the heat load of the section water wall, but also the carbon content of fly ash. The article takes a 600 MW supercritical boiler as an example and uses software to calculate the heat transfer in the furnace.

Key words: *supercritical boiler, furnace heat transfer software, 1-D model, coal combustion model, software development and application*

Introduction

Supercritical coal-fired thermal power plants have a relatively high level of technology, and have the advantages of low coal consumption, low pollutant emissions, and good dynamic characteristics. Critical coal-fired thermal power generation is the mainstream direction of coal-fired thermal power generation technology in the near future. For my country's coal-fired generating units, the development of supercritical coal-fired thermal power plants is conducive to reducing coal consumption, is conducive to the safety and stability of the power grid for flexible peak shaving, is conducive to the improvement of environmental protection, the protection of the ecological environment, and our combustion. The technological leap of coal-fired power generation technology has created a world-class coal-fired thermal power plant. However, so far, in the design and calculation of boiler units in my country, the part related to the heat transfer calculation of the boiler heating surface has been following the Soviet *Standard Method for Thermal Calculation of Boiler Units* (hereinafter referred to as *standard methods*). It is found from many years of domestic operation practice that with the increase of boiler capacity, especially after the unit parameters reach supercritical and supercritical, compared with the actual design value, the furnace outlet flue gas temperature calculated by the *standard method* has a larger deviation. For boilers designed for anthracite, lignite and low quality bituminous coal, the deviation is greater, which will cause the occurrence of superheater overheating and tube bursting in coal-fired boilers, thereby greatly reducing the service life of the boiler.

[*] Corresponding author, e-mail: jianweichai2991@163.com

Some boilers above 600 MW have problems such as low intermediate point temperature and large superheater superheating water volume, causing the unit to automatically fail to be put into operation, poor main steam temperature control, and prone to overheating of the superheater, which seriously endangers the safety of the unit. In addition, some boilers still have the phenomenon that the steam temperature of the final reheater does not meet the standard, which seriously affects the safe and economic operation of the unit [1]. Therefore, the establishment of a set of calculation methods suitable for engineering boiler furnace heat transfer is the primary problem to be solved in the current development of large-scale power generation boilers.

This paper adopts an improved furnace zone thermal calculation method, which is improved on the basis of the section heat transfer method in the Soviet 73 standard method. We divide it into six sections along the height of the furnace. The burner area is divided into two sections, and a pulverized coal combustion model is added to the corresponding sections. The flue gas temperature of each section is derived using an energy balance equation. Based on the aforementioned principles, the paper adopts Microsoft Visual Basic 6.0 language to develop a software for thermal calculation of supercritical boiler furnace.

Development of software for thermal calculation of furnace zone section

Supercritical boilers have large volume and high working fluid parameters in the tubes, and they are generally once-through boilers. The main differences between supercritical boilers and small-capacity boilers in furnace structure size and heat transfer characteristics are: on the one hand, after the working fluid parameters reach supercritical, the superheated heat absorption share increases, in order to ensure that the flue gas temperature at the furnace outlet does not exceed the slagging of coal temperature, more radiant superheaters need to be arranged in the furnace [2]. On the other hand, the furnace adopts a spiral coil design, which makes the mass-flow rate in the water wall tube higher under various loads, and the water wall uses an internally threaded tube, which has a higher heat transfer coefficient in the tube. Therefore, the furnace volume of supercritical boilers is relatively large, and the furnace form is tall and thin.

In addition, the environmental protection requirements are becoming increasingly stringent. When designing supercritical secondary reheat boilers, in order to meet the ultra-low emission standard of NO_x gas pollutants in the flue gas, low nitrogen burners with staged combustion are used. At the same time, to ensure a high pulverized coal combustion efficiency, the burner nozzle of the last layer of the burner along the height direction needs to have a larger distance from the bottom of the screen superheater. These factors have caused great changes in the furnace combustion mode, furnace size and heat exchange in the furnace of the supercritical boiler [3].

The calculation principle and basis of the software

Mathematical model of pulverized coal combustion

According to the mathematical model of the pulverized coal particle group suspension combustion plunger flow established by us, the rate of change of the unburned rate of coke particles u_j with time r of component j is:

$$\frac{\mathrm{d}u_j}{\mathrm{d}\tau} = -\frac{S_j u_j P_0}{\dfrac{1}{K_s} + \dfrac{1}{K_d}} \tag{1}$$

where S_j [m^2] is the component j coke particle surface area, P_0 – the oxygen partial pressure P_a, K_s [kgm^{-2}s^{-1}Pa^{-1}] – the surface reaction rate, and K_d [kgm^{-2}s^{-1}Pa^{-1}] – the diffusion rate. We can get:

$$\frac{\mathrm{d}u_j}{\mathrm{d}\tau} = -\frac{6u_j^{2/3}P_0}{\rho_j d_j \left[\frac{d_j u_j^{2/3}}{1.26} \cdot 10^{\circ} \left(\frac{T_m}{1600} \right)^{-0.75} + \frac{1}{K_s} \right]} \tag{2}$$

where d_j [m] is the component j coke particle diameter, ρ_j [kgm^{-3}] – the density of coke particles of component j, and T_m [K] – the surface temperature of coke particles.

Outlet flue gas temperature of main combustion section and auxiliary combustion section

This area is the burner layer, and its energy balance equation is: section flue gas heat absorption + section water wall heat absorption + heat release to adjacent sections = section coal combustion heat release, the section exits flue gas temperature expression:

$$\vartheta' = \frac{\frac{100}{100 - q_4}\beta_{cr} Q_{ar,net} + Q_{wr} - Q_{hz}}{V_c} - \frac{5.67 \cdot 10^{-8} a_1 T^{n4} \psi F}{B_{j1} V_c} \tag{3}$$

where β_{cr} [kJkg^{-1}] is the pulverized coal burn-out rate, $Q_{ar,net}$ [kJkg^{-1}] – the coal receives base low calorific value, Q_k [kJkg^{-1}] – the air and recirculated flue gas enters the furnace heat, Q_{wr} [kJkg^{-1}] – the external heat source enters the furnace, Q_{hz} [kJkg^{-1}] – the slag removes heat, a_1 – the exits furnace blackness of the section, T^n – the flue gas outlet temperature k, B_{j1} [kgh^{-1}] – the amount of fuel fed into the section, V_c [kJkg^{-1}°C^{-1}] – the specific heat capacity of the flue gas, ψF – the product of the thermal efficiency coefficient and the area of the water wall section, $\psi F = \psi_{PJ} F_{PJ} + \psi_{C1} + \psi_{C2} F_{C2}$, where ψ_{PJ}, ψ_{C1}, and ψ_{C2} are the effective coefficient of heat of the water wall and the effective coefficient of heat of the upper and lower sections of the section, respectively, F_{PJ}, F_{C1}, and F_{C2} [m^2] are the area of the water wall of the section and the upper and lower section area, respectively.

Smoke temperature at the exit of burnout zone

This area is the burn-out area on the upper part of the burner layer. The energy balance equation is: section flue gas heat absorption + section water wall heat absorption + section upward section radiant heat = section pulverized coal combustion heat release + burner the section radiates heat to this section, and the expression of the flue gas temperature at the mouth of the section:

$$\vartheta'' = \frac{\Delta\beta_{cr} Q_{ar,net}}{VC''} + \frac{VC}{VC''}\vartheta' + \frac{5.67 \cdot 10^{8} a_1 T'^4 \psi A_1}{B_j VC''} - \frac{5.67 \cdot 10^{8} a_1 T^4 \psi F}{B_j VC''} \tag{4}$$

where $\Delta\beta_{cr}$ is the combustion rate of pulverized coal in the section, VC' and VC'' [kJkg^{-1}°C^{-1}] are the average specific heat capacity of the flue gas at temperatures ϑ' and ϑ'', respectively, B_{j2} [kgh^{-1}] – the amount of fuel fed into section III, and T_{PJ} – the flue gas temperature in the burnout zone arithmetic mean:

$$T_{PJ}{}^4 = \frac{T'^4 + T''^4}{2} \tag{5}$$

The flue gas temperature of each section in the burnout zone

The pulverized coal in the section has been basically burned out, and there is no obvious heat release from pulverized coal combustion [4]. The heat is mainly given to the water wall by the flue gas. The outlet flue gas temperature expression of this section:

$$\vartheta' = \frac{\Delta\beta_{cr}Q_{ar,net}}{VC'} + \frac{VC'}{VC''}\vartheta' - \left\{1+\left(\frac{T'}{T''}\right)^4 \frac{5.67\cdot 10^8 a_1 T^4\left[A_{PJ}\left(\psi''-\psi'\right)+\psi_{PJ}F_{CT}\right]}{2B_j VC'}\right\} \tag{6}$$

where A_{PJ} [m^2] is the average cross-sectional area of the furnace in this section:

$$A_{PJ} = \frac{A_1 + A_2}{1}$$

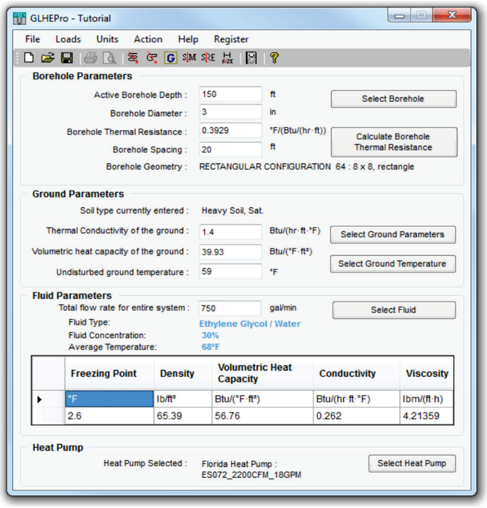

Figure 1. The main interface of the boiler furnace thermal calculation software

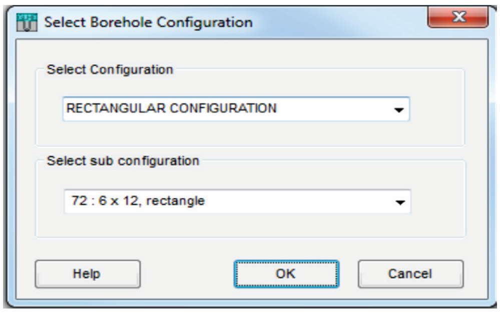

Figure 2. Coal quality parameter input interface

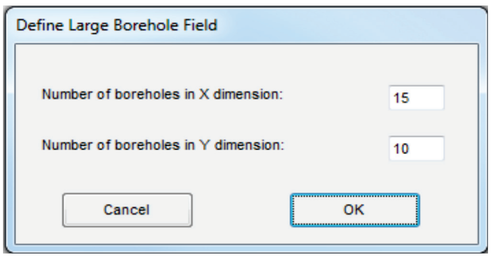

Figure 3. Thermal parameter input interface

Software compilation and use method

Based on the aforementioned calculation principles, this paper has compiled a supercritical boiler furnace thermal calculation software [5]. This software needs the support of the Microsoft Visual Basic 6.0 language environment. It first enters the main interface when running. The main interface of the software is shown in fig. 1.

Steps of software for thermal calculation

Generate coal quality parameters, thermal parameters and structural parameters; import coal quality parameters; import thermal parameters; import structural parameters; start calcula-

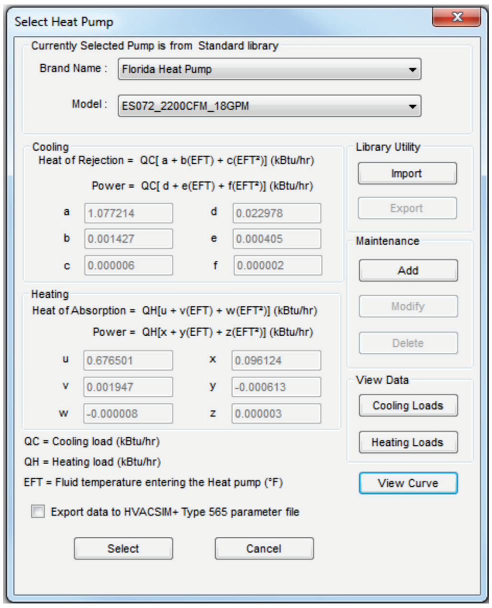

Figure 4. Structure parameter input interface

tion; display calculation results; save calculation results [6]. Before the software performs calculations, the interfaces for inputting various parameters are shown in figs. 2-4.

Run the main program

According to the interface prompts, we click on the *Import Coal Type Parameters*, *Import Thermal parameters,* and *Import Structural Parameters* buttons to import various parameters required for calculation from the data directory [7]. After importing the parameters, you can click the *Start calculation* button perform furnace thermal calculation.

Display and save of calculation results

After the thermal calculation is completed, the result is displayed in the output interface in the form of graphics by the output subroutine. After the programmed calculation is completed, the output subroutine in the program displays the results in different forms of graphics in the output interface. The output interface is shown in fig. 5. The output interface includes histograms and graphs of the flue gas temperature at the exit of each section of the furnace, and histograms of the heat load on the radiant heating surface of each section of the furnace [8]. In order to facilitate the user to analyze the calculation results, a schematic diagram of the furnace zone is also given in the interface.

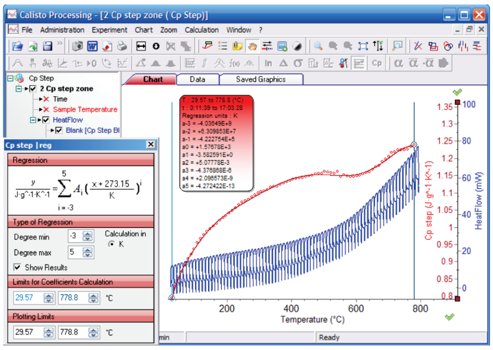

Figure 5. Calculation result output interface

Analysis of calculation results

In order to better reflect the heat load distribution in the furnace and the temperature changes of combustion products, the paper adopts the divisional thermal calculation method. Sectional calculation according to the lay-out of the burners of each layer, the furnace is divided into several sections along the furnace height, and the flue gas temperature along the furnace height is calculated according to the energy equation of each section. In the steady-state, the energy equation determines each furnace. The relationship between heat release and heat transfer in a zone [9]. The flue gas temperature of each section is calculated based on the heat release in the section, the change in the enthalpy of the combustion products and the heat transfer in the section.

The thesis is based on a 600 MW supercritical boiler. The boiler is a Bunsen once-through boiler with an intermediate reheating, supercritical pressure variable pressure operation and a built-in re-circulation pump starting system, with a single furnace mouth lay-out and solid slag discharge. The boiler burns bituminous coal. The width of the boiler furnace is 22.187 m, the depth is 15.632 m, the ceiling tube elevation is 63.844 m, and the furnace volume is 18010 m^3. Table 1 shows the comparison between the calculated value of the furnace outlet flue gas temperature and the actual measured value under the load of BMCR, THA, 75% THA, and 50% BMCR. The measurement results in the table are the average temperature of eight test points at the manhole at the exit of the furnace using an infrared thermometer during the performance test [10]. From the results in tab. 1, it can be seen that under BMCR conditions, the furnace outlet flue gas temperature of 1120 °C obtained by the calculation method in this paper differs from the measured value by 18 °C; while the 1005 °C calculated by the standard method differs from the measured value by 133 °C. Under THA conditions, the furnace outlet flue gas tem-

Table 1. Comparison of flue gas temperature at furnace outlet

Working condition	Temperature of flue gas at furnace outlet [°C]		
	Infrared test data	Gulwich method calculation results	Improved calculation result of partition method
Maximum load (BMCR)	1138	1005	1120
Rated load (THA)	1081	987	1107
75% THA	1017	875	975
50% BMCR	997	784	878

perature obtained by the calculation method in this paper differs from the measured value by 26 °C, while the standard method is 94 °C. Under 75% and 50% THA conditions, the difference between the calculated results of the proposed method and the measured value is smaller than that of the standard method. The thesis uses a double-inlet and double-outlet steel ball mill direct-blowing pulverizing system, front and back walls are opposed for combustion, four layers of primary air outlets are arranged, and a total of 32 burners are used. The paper uses this software to calculate the maximum load condition (BMCR) furnace heat transfer.

Figure 6 shows the flue gas temperature distribution along the furnace height under different loads obtained by the calculation method in this paper.

Figure 7 shows the distribution of radiant heat load in each section. The abscissa is the radiant heat load of the water wall in each section, and the ordinate is the section along the height of the furnace.

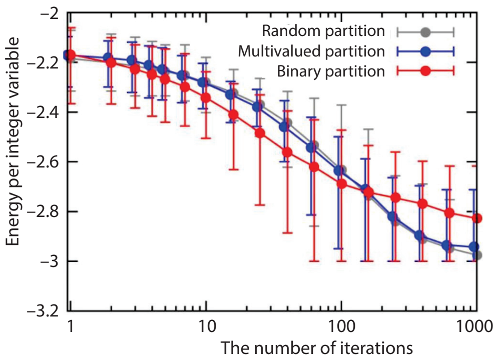

Figure 6. Calculation results of the improved segmentation method

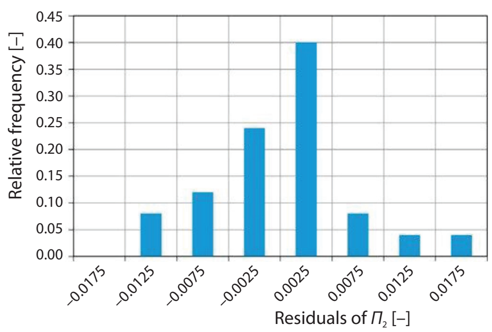

Figure 7. Histogram of heat load on the radiant heating surface of each section of the furnace

Conclusion

The boiler furnace thermal calculation method proposed in this paper can be applied to boilers that generally use low nitrogen burners. Using this method, the flue gas temperature and thermal load along the height of the furnace can be calculated. Based on the calculation method of the furnace section heat transfer in the Soviet Union 73 *Standard Method*, the paper proposes that the furnace is divided into three sections along the height direction, and pulverized coal combustion models are added to two sections, thereby establishing three. The energy balance equation of the section is derived, the expression of the outlet flue gas temperature of each section is derived, and the corresponding boiler thermal calculation software is compiled. The calculation results show that the results obtained by the boiler furnace thermal calculation software can better reflect the average flue gas temperature and heat load distribution along the furnace height. Therefore, using the boiler furnace thermal calculation software compiled in this paper can be a more important reference for improving the thermal calculation of supercritical boiler furnace verification using staged combustion.

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