

Modeling on Char Combustion Characteristics in Fly-ash and Its Countermeasure Improved for Circulating Fluidized Bed Boilers

Abstract. A mathematical model of single char particle combustion in circulating fluidized bed (CFB) boiler is developed in this paper. Its numerical solution in operating conditions of CFB boiler verifies the nature of a phenomenon that the distribution of carbon content of char particles in fly-ash has a peak value versus their diameters. When the temperature of the fine char particle is close to the bed temperature, there also exists a peak value for its burn-out time. The fly-ash recirculation and the hot cyclone are presented to improve combustion of char particles.

Streszczenie. W artykule przedstawiono model matematyczny zapłonu zwęglonych cząstek (sadzy) w kotle z cyrkulacją warstwową fluidalną (ang. Circulating Fluidized Bed – CFB). Wyjaśniono w ten sposób charakterystykę rozkładu zawartego w cząstce węgla oraz wpływu temperatury cząstki na szybkość wypalania. Dla poprawy sprawności procesu, zaproponowano zastosowanie recyrkulacji lotnych popiołów oraz wiru gorącego powietrza. (Modelowanie poprawa charakterystyki zapłonu zwęglonych cząstek (sadzy) w lotnych popiołach w piecach CFB).

Keywords: circulating fluidized bed; char; fly-ash; combustion

Słowa kluczowe: CFB, zwęglacz, popiół lotny, zapłon.

Introduction

Circulating fluidized bed (CFB) combustion techniques have been widely used in China due to its numerous merits, for example, burning various low-grade fuels. However, the universal problem in operation is that the carbon content of fly-ash is much higher than generally expected [1, 2]. In analyzing fly-ash sampling from a number of CFB boilers, a special interesting phenomenon is observed that the distribution of carbon content of char particles in fly-ash has a peak value versus their diameters (Fig.1). It indicates that there are some char particles with definite diameters which are not easy to burn out in CFB boiler. This universal phenomenon becomes a key point concerned by CFB boiler designers. Thus a thorough study on burning processes of char particles in CFB boiler is needed in order to improve CFB boiler performance. So far, many papers concerning CFB combustion have been published. Lee et al. set up a one-dimensional mathematical model to predict the coal combustion behavior in CFB boilers [3]. By experiments Xiao researched carbon content in fly ash from circulating fluidized bed boilers [4]. Remiarova et al. [5] also developed a model for the combustion of a single porous char particle under the pseudo steady state assumption. By fragmentation Carlos et al. [6] and Zhang et al. [7] studied char particle characteristics during fluidized bed combustion. However none of these studies explained the phenomenon above. Therefore, modeling of combustion characteristics of char particles in fly-ash is carried out so as to find out the physical nature of the universal phenomenon mentioned above and to take measures to improve combustion of char particles.

Mathematical models for char particle combustion

Several kinds of combustion models can be set up according to intrinsic porosity reaction mechanism of char particle combustion [8, 9]. Model 1-Single particle, constant density core-shrinking model: This model only considers the

primary reaction on the surface of a char particle, i.e., direct reaction of carbon and oxygen. This model is suitable for low-grade fuels with high ash content. Model 2-Single particle, constant diameter core-shrinking model considering radiation heat transfer: On the basis of Model 1, this model takes into account radiation heat exchange between the particle and the furnace wall. Thus this model approaches further real char particle combustion. In the following analysis, single particle, constant diameter core-shrinking model considering radiation heat transfer, that is Model 3, is adopted on the basis of the operating conditions of CFB boilers, burning low-grade fuels with high ash content. Following assumptions are adopted: (1) Combustion reaction occurs on the surface of a char particle. The reaction interface continuously moves to the core of the particle during its combustion, an ash shell is being formed outside the core, and its diameter is the same as the original char particle. (2) The particle is flowing in furnace entrained by gas with certain slip velocity. (3) The combustion reaction is first-order reaction process. There is no temperature gradient inside the particle. The combustion reaction is ignored that occurs inside the intrinsic porosity of the particle. (4) Equation (1) indicates that the internal diffusion-resistance of oxygen embodies the resistance of the ash shell. (5) Enthalpy of the char particle is determined by the balance of the released heat of the chemical reaction, convection heat transfer between the particle and the gas, and radiation heat exchange between the particle and the furnace wall.

$$(1) \quad D_e = f_n D$$

where: D_e —diffusion coefficient considering resistance of ash shell, f_n —coefficient.

$$(2) \quad f_n = 0.59 - 0.12 \times 10^{-3} \delta$$

where: δ —thickness of ash shell, D —diffusion coefficient.

$$(3) \quad D = D_0 \left(\frac{T_g}{273} \right)^{1.81}$$

where: D_0 –mass-diffusion rate of oxygen at 273K in gas.

$$(4) \quad D_0 = 0.1482 \times 10^{-4}$$

where: T_g –gas temperature.

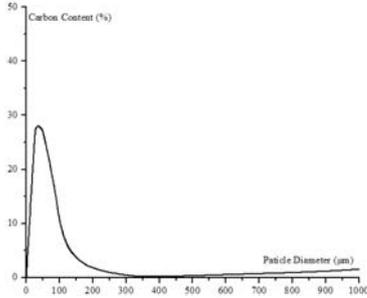


Fig.1. Carbon content distribution in fly-ash

This model is described mathematically as follows:

1) Heat-balance equation

$$(5) \quad \frac{C_p}{S} \frac{dT_p}{dt} = Q_L \beta C_{O_2} \frac{273}{T_g} K_e - \alpha_p (T_p - T_g) - \sigma_0 \varepsilon_p \varphi_p (T_p^4 - T_g^4)$$

$$(6) \quad K_e = \frac{1}{K_0 e^{-\frac{E}{RT}} + \frac{d_p}{Nu D_e}}$$

where: C_{O_2} –oxygen concentration at 273K and 760mmHg, C_p –specific heat capacity of char particle, K_e –effective value of reaction rate constant which depends on kinetic and diffusion component, d_p –particle diameter, E –activation energy, K_0 –reaction frequency factor, Nu –Nusselt number, R –universal gas constant, Q_L –heat generation, S –specific surface of char particle, T_p –particle temperature, t –time, α_p –convective heat transfer coefficient, β –chemical equivalent coefficient, ε_p –char particle emissivity, σ_0 –Stefan-Boltzmann constant, φ_p –radiation coefficient. The left term in Equation (5) represents the enthalpy change of the char particle, and the three terms in right represent respectively the heat released of chemical reaction, convective heat transfer between the particle and the gas, and radiation heat exchange between the particle and the furnace wall.

2) Mass-conservation equation

$$(7) \quad \frac{\rho_p}{2} \frac{d(d_p)}{dt} = -\beta C_{O_2} \frac{273}{T_g} K_e$$

where: ρ_p –particle density.

3) Flowing equation

In order to simplify analysis, the agglomeration of char particle is ignored. Therefore the terminal velocity of the single particle represents the slip velocity between the gas and the char particle.

$$(8) \quad V_t = \left[\frac{4(\rho_p - \rho_g) g^2}{225 \rho_g \mu} \right]^{\frac{1}{3}} d_p$$

$$(9) \quad V_t = \left[\frac{3.1(\rho_p - \rho_g) g}{\rho_g} d_p \right]^{\frac{1}{2}}$$

where: V_t –terminal velocity, ρ_g –gas density, μ –dynamic viscosity. Equations (8) and (9) are separately used for Reynolds Number $Re < 500$ and $Re > 500$. Correspondingly,

$$(10) \quad Nu = \frac{2}{1 - 0.1 Re^{0.4}}$$

$$(11) \quad Nu = 0.54 Re^{\frac{1}{2}}$$

Then the residence time of the char particle in furnace is:

$$(12) \quad t = \frac{H_{bed}}{V_f - V_t}$$

where: V_f –superficial gas velocity, H_{bed} –bed height. On the operating conditions of CFB boilers (improved by a recycle separator), the residence time t^s of the char particle is:

$$(13) \quad t^s = \frac{1}{1 - \eta} t$$

where: η –separation efficiency of the recycle separator.

$$(14) \quad \eta = 1 - \exp \left[-0.693 \left(\frac{d_p}{d_{50}} \right)^m \right]$$

where: d_{50} –cut size, m –coefficient depending on the cyclone.

The initial conditions are:

$$(15) \quad t=0 \quad T_p = T_{p0} \quad \text{and} \quad d_p = d_{p0}$$

Thus Equations (1)-(14), together with the initial conditions Equation (15), form a complete analytical model for the combustion of a single particle in CFB boilers. In this paper, the model calculations have been carried out for coal types used in Power Plant of Tsinghua University. The compositional data for the coal is shown in Table 1. The input operating parameters (Table 2) also come from Power Plant of Tsinghua University, which include combustor description (H_{bed} , d_{50} , etc.), operating conditions (V_f , T , etc.) and fuel properties (K_0 , E , etc.). It should be pointed out that the fuel properties are obtained from the fuel analysis made by Analysis Center of Tsinghua University.

Table 1. Compositional data for the coal

C(%)	H(%)	O(%)	N(%)	S(%)
47.15	3.36	8.64	0.76	0.66
A(%)	W(%)	V ^r (%)	Q _L (J/kg)	
26.29	13.14	39.79	17.6×10 ⁶	

Table 2. Operating parameters

H _{bed} (m)	d ₅₀ (m)	m	V _f (m/s)
13.8	40×10 ⁻⁶	1.06	4.1
T _g (°C)	K ₀ (m/s)	E(J/mol)	
850	41600	117000	

Results and discussion

1) Effects of char particle diameters on their surface temperatures

In CFB operating conditions the bed temperature is not very high, therefore the reaction rate of a char particle depends on the kinetics of chemical reaction. Based on the numerical analysis of the model, particle surface temperatures as a function of burning time for two char particle diameters 40μm and 400μm separately are shown in Fig.2.

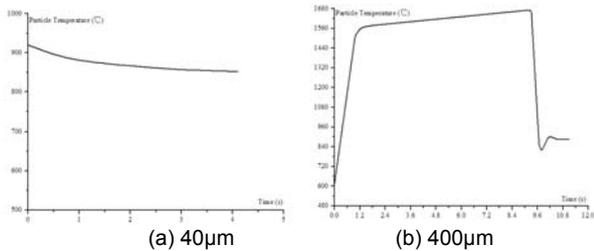


Fig.2. Influence of char particle diameters

Fig.2 (a) shows that the surface temperature of the smaller particle rises rapidly due to its less thermal inertia. Then the temperature stays in a low level, close to the bed temperature, because of its less ash shell resistance, larger specific surface and higher heat loss to surrounding gas. Fig.2 (b) indicates that the larger one is contrary to the smaller one. Surface temperature rises gradually and stays in a high level for a quite long time, then falls down abruptly because of high radiation heat loss by the higher surface temperature and low heat release rate of chemical reaction.

2) Burn-out time of char particles as a function of initial char particle diameters

Keeping the main data of coal properties and operating conditions unchanged and using the model, the burn-out time of char particles as a function of initial char particle diameters is shown as Curve 1 on Fig.3. It indicates that the char particles having the initial particle diameters about 40 to 50 μm need the longest burn-out time. The curve shows a peak value of the burn-out time for such particles. This is different from conclusion that the burn-out time of char particles is directly proportional to square of particle diameters. The main reasons of existence of the peak value are as follows: (1) The reaction rate of a char particle in CFB boiler conditions depends on the kinetics of chemical reaction, so the particle temperature is the key factor influencing combustion reaction rate. (2) In the light of char particle flow characteristics in CFB boiler (Equation (12)), the mean residence time of smaller char particles is shorter than that of larger char particles (Curve 2 on Fig.3). (3) Effects of separator performance on char combustion. From (13), a recycle separator of CFB boiler can make fly-ash recirculate in the combustor and prolong their residence time greatly (Curve 3 on Fig.3). It is evident that the burn-out time is longer than the residence time in the region where Curve 1 intersects Curve 3. Thus the particles in this region are not easy to burn out. It is the distribution of carbon content that Fig.1 shows. The above various reasons result in this phenomenon that it is difficult for certain smaller char particles to burn out in CFBC. Understanding this combustion feature is important for the selection of optimum combustion conditions.

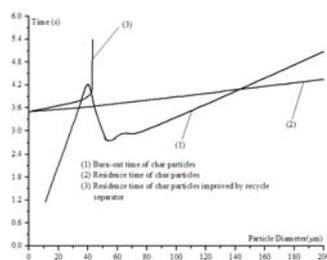


Fig.3. Burnout time and residence time of char

Countermeasures to improve combustion of fine particle

Since the reaction rate of a char particle depends upon the kinetics of chemical reaction in CFB boiler operating

conditions, the particle temperature is the key factor influencing combustion reaction rate. From the above discussions, it is known that the residence time of fine particles is also the key factor influencing. Raising the bed temperature will increase NO_x emission. Therefore an acceptable way is to prolong the residence time of fine particles.

1) Increase of the furnace height

The furnace height should ensure that the particles burn out which are not recovered by a recycle separator and pass through the combustor only once. To get enough residence time, the furnace height of CFB boiler is 3 to 4 times as high as a general fluidized bed because of its higher fluidizing velocity.

2) Reduction of the fluidizing velocity

The reduction of the fluidizing velocity may prolong the residence time of fine particles. However, it makes the furnace area large and the convection coefficient low.

3) Use of the fly-ash recirculation

It is known that coarse coal particles are fed into the commercial CFB boilers in practice. As a result there exists a dense phase zone in the bottom of the combustor, which is mainly composed of coarse particles.

4) Use of the hot cyclone

Most of the particles are concentrated near the wall of the cyclone due to the centrifugal force, leaving few fine particles in the central volume of the cyclone.

Conclusions

In CFB boiler operating conditions, the fine char particles possess the lower surface temperatures, close to the bed temperature. The curve of burn-out time of char particles versus their diameters has a peak value. The char particles of 40 to 50 μm in diameters are the most difficult to burn out. Some measures should be taken to improve the combustion of fine particles, such as the uses of the fly-ash recirculation, and the hot cyclone.

Acknowledgments: This work was financially supported by Doctor Foundation from Ministry of Education of P. R. China (20101402110011).

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