ISSN 1009－3095 *Journal of Zhejiang University SCIENCE* V.3，No.3，P.251－257，July－Aug.，2002
http：//www.periodicals.com.cn；http：//www.zju.edu.cn/English
http：//www.zjupress.com；http：//lib.zju.edu.cn/eindex.htm；jzu_s@mail.hz.zj.cn

Model prediction of the operating behavior of a circulating fluidized bed boiler*

WANG Qin-hui（王勤辉）[†]，LUO Zhong-yang（骆仲泱），NI Ming-jiang（倪明江）
CEN Ke-fa（岑可法）
（*Clean Energy and Environment Engineering Key Lab，Zhejiang University，Hangzhou 310027，China*）
[†]E-mail：qhwang@cmee.zju.edu.cn

Received May 7，2001；revision accepted Aug.16，2001

Abstract： An improved mathematical model for a circulating fluidized bed（CFB）boiler based on the model developed earlier by the authors was applied to simulate the operation of a 12 MW CFB boiler. The influences of the excess air ratio，primary air ratio，coal particle size distribution，coal properties（ash content and volatile content）and Ca/S ratio on the boiler operation were analyzed. The results showed that the model simulation may be applied to the optimum design and economic operation of the CFB boiler.

Key words： Circulating fluidized bed boiler（CFB），Model，Boiler operation
Document code： A **CLC number：** TK 229.66

INTRODUCTION

The CFB represents an improvement over traditional systems used for coal combustion and is widely applied in industry. Because of the complexity of the processes in the CFB boiler，the influence of the operating control parameters such as coal properties，coal particle size distribution，excess air ratio，primary air ratio and Ca/S ratio on the CFB boiler operation are still not understood fully（Shelton，1996；Seeber et al.，1999）. This is an obstacle for realizing optimum design and economic operation of the CFB boiler. A reasonable way to develop a mathematical model describing the underlying physical and chemical processes occurring in the CFB boiler is to simulate the boiler operation. Previous studies may be found in references（Hannes et al.，1995；Heinbockel et al.，1995；Huilin et al.，2000；Park et al.，1997；Werner et al.，1999）. Although published models have similar structure，significant differences are found in the sub-models.

In this paper，an overall mathematical model for CFB boiler developed earlier by the authors is applied to simulate the operation of a 12 MW CFB boiler and analyze the influences of the boiler operating control parameters on the CFB boiler operation.

MODEL AND PREDICTION

The model for CFB boiler developed earlier by the authors includes the mathematical description for the physical and chemical processes occurring in the boiler and the empirical models for poorly understood processes. Detailed information on the model are given in Wang et al.（1999）. The main characteristics of the model are：（1）The furnace is characterized by two flow regimes：a dense phase turbulent fluidized bed flow regime at the bottom，and a dilute phase core-annulus solids flow structure above the solid entry or secondary air inlet. Particles travel upward in the core and downward in the annulus；（2）Because of the different solid particle and wide size distribution，the particle population is described by particle size and density；（3）The hydrodynamic model takes into account the axial and radial dispersion of gas in the core-

---

* Project（G1999022105）supported by the Special Funds for Major State Basic Research（973）Programme of China

annulus model of the dilute region and couples the process of combustion and particle attrition；（4）Different empirical models for the attrition rate of the individual particle components in the furnace are applied；（5）Volatile，CO_2，O_2，CO，N_2，NH_3，HCN，NO，N_2O，SO_2，H_2，H_2O are considered to be in the furnace；（6）A cluster renewal mechanism is proposed for the calculation of heat transfer coefficients in the furnace on the basis of the special hydrodynamics of CFB；（7）The combustion of char and combustible gases due to rapid mixing of gas solids in the cyclone are considered. The model was applied to the simulation of a 12 MW CFB boiler for the model validation. The model predictions agreed well with the measured results（Wang，1997；Wang et al.，1999）.

The model was improved for simulating the operation of CFB boiler with changing control parameters. Then the improved model was applied to study the influence of the operating control parameters on the operating behavior of the 12MW CFB boiler. Fig. 1（see next page）shows the scheme of this 12 MW bituminous coal fired CFB boiler developed by Zhejiang University. It is the first in China of the type with an external heat exchanger（EHE）. The furnace was 21m high and had a 5.45×2.45m section in the water-wall region and a 5.45×1.5m refractory tile lined section at the bottom. The upper section of the furnace was water-cooled using standard membrane wall construction. It was equipped with two cyclones. Part of the solid particles separated by two cyclones was cooled by the EHE，and the rest was recycled into the furnace by a pair of recycling devices. The flue gas from the two cyclones flowed through the superheater，economizer and air preheater in the backpass. Three rows of secondary air inlets located in two sidewalls at 1.5m，2.0m and 2.5m above the distributor respectively（Wang，1997；Wang et al.，1999）.

For studying the influence of each control parameter on the boiler operating behavior，all operating parameters were kept unchanged except the selected one. The influences on furnace temperature，heat transfer，combustion efficiency and emissions were considered as the main topics. The model input data are shown in Table 1，Table 2 and Table 3 show the ultimate analysis，the proximate analysis and the size distribution of the coal respectively.

Table 1 The model input data

Item	Parameter	Item	Parameter
Rated capacity	75 t/h	Feed water temperature	105 ℃
Main steam pressure	3.82 MPa	Air temperature	25 ℃
Main steam temperature	450 ℃	Combustion air flow rate	70500 Nm^3/h

Table 2 Analysis of the coal

Analysis of the coal，Air dry	Value	Analysis of the coal，Air dry	Value
$M_{t,ar}$，Total moisture（wt%）	5.72	S_{ad}，Sulfur（wt%）	0.85
C_{ad}，Carbon（wt%）	63.01	A_{ad}，Ash（wt%）	23.74
H_{ad}，Hydrogen（wt%）	3.59	M_{ad}，Moisture（wt%）	1.43
O_{ad}，Oxygen（wt%）	6.23	V_{ad}，Volatile（wt%）	24.035
N_{ad}，Nitrogen（wt%）	1.15	Q_{ad}，Heating value（MJ/kg）	24.45

Table 3 The coal particle size distribution

Diameter（mm）	0－0.1	0.1－0.3	0.3－0.5	0.5－1	1－1.5	1.5－2	2－3.5	3.5－5	5－6.5	6.5－8
Mass fraction（%）	0.5	2	6	16	9	10	13	18	12	13.5

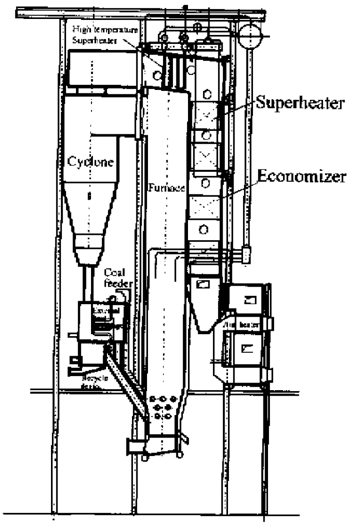

Fig. 1 The scheme of the 12 MW CFB boiler

RESULT AND DISCUSSION

Influence of excess air ratio α

In Fig. 2, although the average temperature in the furnace decreases with increasing excess air ratio, the shape of the temperature profiles along the furnace height is different. Here H is the height of the furnace and h is the height above the distributor. The average furnace temperature at an excess air ratio of 1.1 is the highest but the furnace exit temperature is low. The temperature in the low part of the furnace at an excess air ratio of 1.2 is higher than that at an excess air ratio of 1.15. However, the furnace temperature at an excess air ratio of 1.3 is lower and more uniform along the furnace height. The temperature profiles in the furnace at different excess air ratio are explained in the following sections.

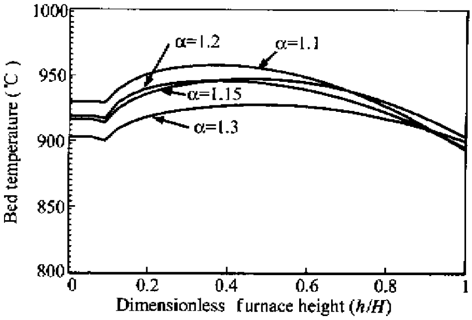

Fig. 2 Effect of excess air ratio on the furnace temperature profile

As we know, the temperature along the CFB furnace height is determined by the heat release fraction of fuel combustion, cooling medium (such as air) and heat transfer to the heat surface when it was arranged. The fuel combustion rate in the furnace is determined by temperature, oxygen concentration and fuel concentration. With increasing excess air ratio, the gas velocity in the furnace increases and the entrainment of particles from the dense bed increases. It means that the solid particle concentration (including the char particles) in the upper section increases with increasing excess air ratio and that the solid concentration profile is more uniform. The heat release fraction will increase with increasing char concentration. On the other hand, the air as the cooling medium in the furnace increases with the increase in excess air ratio. It is easy to understand that the temperature in the low section of the furnace was higher at an excess air ratio of 1.1 for the higher heat release fraction and less cooling medium and that the furnace temperature dropped rapidly in the upper section for less combustible char and less oxygen. In contrast, the furnace temperature was lower and more uniform at an excess air ratio of 1.3 for the uniform heat release fraction distribution along the furnace height and more cooling medium. As seen in Fig. 2, there exists a reversed temperature distribution in that the temperature in the lower section at an excess air ratio of 1.2 is higher than that at 1.15. This may be caused by the effect of the oxygen concentration at different excess air ratio. With increasing excess air ratio, the oxygen concentration increases and the effect of the cooling medium increases at the same time. The effect of the oxygen concentration on the combustion rate is in contrast with the effect of the air as the cooling medium. There exists a competition between the effect of the oxygen concentration increase and the effect of the cooling medium increases with increasing excess air ratio. The oxygen concentration profiles are given in Fig. 3. The oxygen concentration in the dense bed at a excess air ratio of 1.2 was higher than that at 1.15 but the oxygen concentration in the section above the dense bed was lower than that at 1.15. It implies that the effect of the increasing oxygen concentration on the combustion rate was greater than the increasing effect of the cooling medium with increasing excess air ratio from 1.15 to 1.2. Because of the higher temperature, the combustion rate in the section above the dense bed was higher and more oxygen was consumed. It induced a lower oxygen concentration in this region. In the upper part of the furnace, the temperature dropped faster for less combustible char with similar heat transfer at an excess air ratio of 1.2.

Another important influence of excess air ratio is on the fuel combustion efficiency. Fig. 4 shows the effect of excess air ratio on the carbon content in the fly ash does not vary monotonously. The carbon content in the fly ash was higher at an excess air ratio of 1.1 for lower oxygen concentration in the furnace. For an excess air ratio of 1.3, the effect of lower furnace temperature and shorter residence time on the char combustion rate was stronger than the effect of higher oxygen concentration. This was why the carbon content in the fly ash was slightly high at an excess air ratio of 1.3.

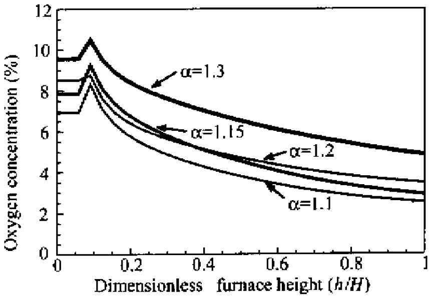

Fig. 3 Profiles of the oxygen concentration in the furnace with different excess air ratio

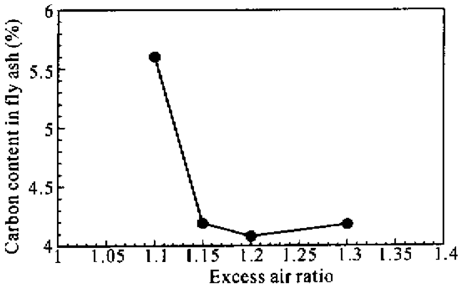

Fig. 4 Effect of excess air ratio on carbon content in the fly ash

Apparently, there exists an optimal selection for excess air ratio. For the 12 MW CFB boiler, excess air ratio of 1.2 may be a proper selection.

Influence of air stage

As can be seen in Fig. 5, the temperature in the upper section of the furnace decreases with increasing primary air ratio from 50% to 70%; but the temperature in the lower section at a primary air ratio of 60% is the lowest. It may be explained as follows.

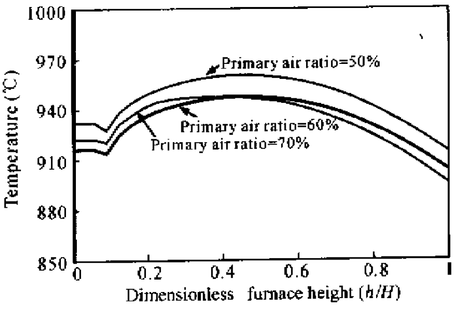

Fig. 5 Effect of primary air ratio on furnace temperature profiles

As mentioned in above, the air introduced into the furnace supplied oxygen and cools the furnace. As seen in Fig. 6, the increment of the heat release fraction in the dense bed for increasing primary air ratio from 60% to 70% was much higher than that from 50% to 60%. This was why the temperature in the low part of the furnace at a primary air ratio of 70% was higher than that at primary air ratio of 60%. For primary air ratio of 50%, less cooling medium caused a higher temperature in the dense bed and maintained the high temperature above the dense bed for the higher heat release fraction and lower solid concentration which induced lower heat transfer.

The solid concentration in the furnace increased with increasing primary air ratio due to increasing bed gas velocity (Fig. 7). In contrast, the temperature in the upper part of the furnace above the dense bed at a primary air ratio of 70% was lower due to the low heat release fraction and the high solid concentration.

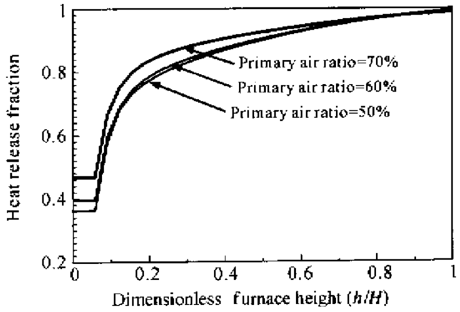

Fig. 6 Profiles of the heat release fraction along the furnace height

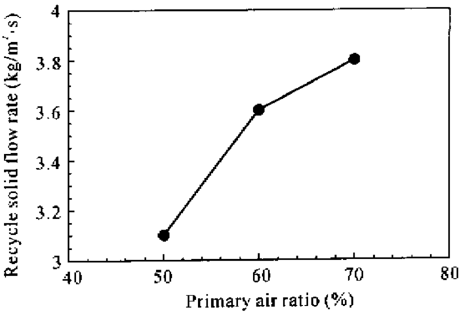

Fig. 7 Effect of primary air ratio on solid flow rate at furnace exit

Air staging is often used in CFB boilers as the control technique for lower NO_x emission. The profiles of NO and N_2O concentration along the furnace height with different primary air ratio are given in Fig. 8 and Fig. 9 showing that NO_x emission decreases obviously with decreasing primary air ratio and that N_2O emission decreases slightly with decreasing primary air ratio. This may be achieved by reducing the availability of oxygen in the lower part of the furnace to control NO_x and N_2O formation. In addition, Fig. 8 shows that the NO_x emission at a primary air ratio of 60% is only slightly higher than that at a primary air ratio of 50%. It seemed that the decrement of the NO_x emission by the air staging is not proportional to the decrement of the primary air ratio.

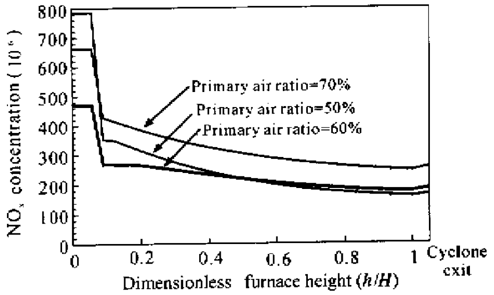

Fig. 8 Effect of air staging on NO_x emission

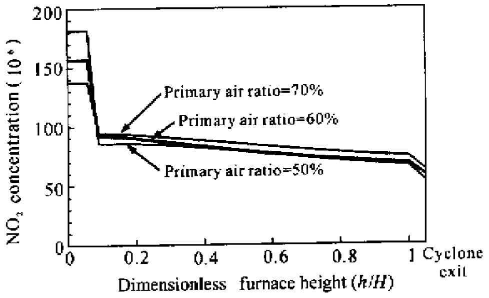

Fig. 9 Effect of air staging on N_2O emission

Influence of coal particle size

As we know, char particles comprise the main composition of the bed material in the furnace when it is fired with coal of high ash content. This means the size distribution of bed material in the furnace is determined definitely by the coal particle size. Three different coal particle sizes were used for studying their influences on the boiler operation. As seen in Fig. 10, for finer coal particle size, the temperature along the furnace height is lower and more uniform, probably because (1) The coarse char particles can't be eluted into the upper furnace and burn in the lower part of the furnace, where the heat release fraction in the lower part of the furnace is higher; (2) The higher solid concentration in the furnace burning fine coal particles enhances the heat transfer to the membrane wall. As shown in Fig. 11, the heat transfer coefficient along the furnace height is higher when fine coal particles were used because of the greater convective heat transfer.

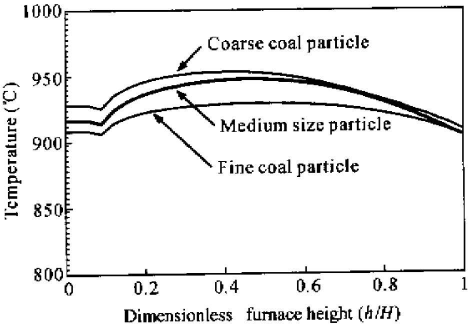

Fig. 10 Effect of size of feed coal particle on furnace temperature

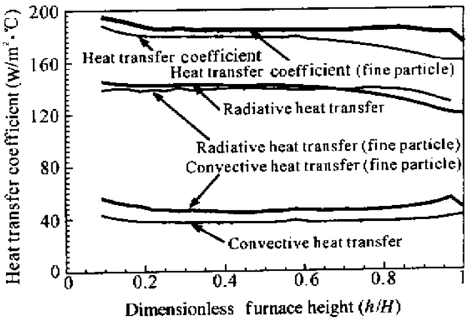

Fig. 11 Heat transfer coefficient for two different sizes of coal particle

Effect of coal properties

1. Effect of ash content in the coal

Fig. 12 shows the profiles of the furnace temperature for 23% and 33% ash content in the coal. As shown in Fig. 12, the furnace temperature with higher ash content is lower.

The reasons for this may be explained as follows: The solid concentration in the furnace increases with increasing ash content in the coal. The higher solid concentration enhances the heat transfer to the wall membrane in the furnace.

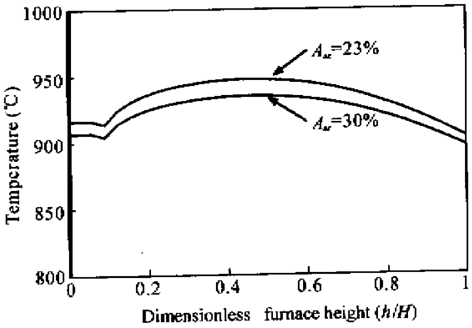

Fig. 12 Effect of ash content in the coal on the profile of furnace temperature

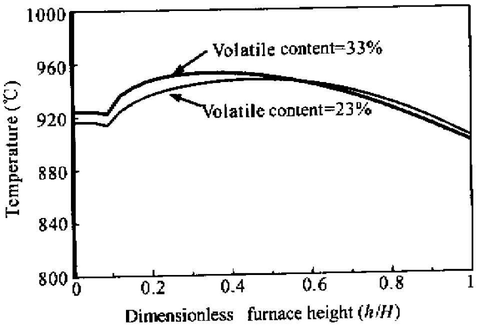

Fig. 13 Effect of volatile content in the coal on the profile of furnace temperature

2. Effect of volatile content

The profiles of the furnace temperature for 23% and 33% volatile content in the coal are given in Fig. 13. For higher volatile content in the coal, the furnace temperature was higher in the lower part of the furnace and lower in the upper part of the furnace. It is easy to understand that the heat release fraction for higher volatile content in the coal was higher in the lower part of the furnace and lower in the upper part because the major part of the volatile content burns in the lower part of the furnace.

Influences of Ca/S ratio

Fig. 14 shows the SO_2 concentration profiles for different Ca/S molar ratios. The SO_2 concentration along the gas flow with limestone addition was lower than that without limestone addition. Moreover, it decreased with increase in the Ca/S molar ratio. Because our model assumed that all SO_2 released in the dense bed, the SO_2 concentration varied slightly along the furnace height above the dense bed, i. e. , the dilute zone, and in the cyclone before limestone addition after it decreased rapidly in the secondary air inlet region (about 2 m) owing to the secondary air injection. On the contrary, with limestone addition, the SO_2 concentration decreased obviously along the furnace height in the dilute region and in the cyclone.

Because most of the sorbent particles were in the size range of 0 – 1 mm after calcination, and particles in this size range comprised the main composition of the solid particles in the upper part of the furnace, the solid concentration and the solid recycle ratio increased with limestone addition. Then the heat transfer coefficient in the furnace and the heat load of the external heat exchanger increased. For this reason, the furnace temperature decreased with increasing Ca/S ratio as seen in Fig. 15.

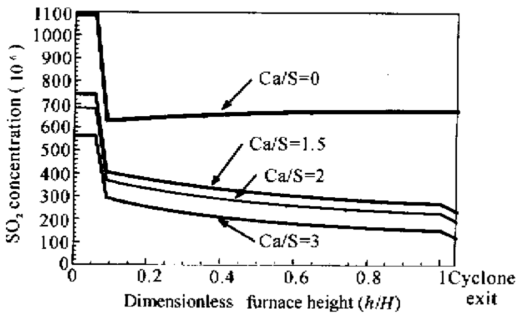

Fig. 14 Effect of Ca/S ratio on SO_2 emission

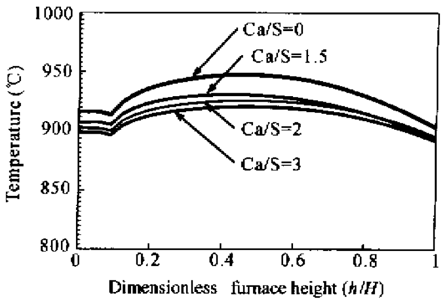

Fig. 15 Effect of Ca/S ratio on furnace temperature

CONCLUSIONS

An improved mathematical model for a Circulating Fluidized Bed (CFB) boiler was applied to simulate the operation of a 12 MW CFB boiler with different operating control parameters. The influences of the excess air ratio, primary air ratio, coal particle size distribution, coal properties (ash content and volatile content) and Ca/S ratio on the boiler operation parameters such as furnace temperature, combustion efficiency, heat transfer in the furnace, emission were analyzed. The results showed the model simulation may be applied to optimum design and economic operation of CFB boilers.

References

Hannes, J. , Renz, U. , Van den Bleek, C. M. , 1995, The IEA Model for Circulating Fluidized Bed Combustion. *In*: Proceeding of the 13th International Conference on FBC. Ed. by Heinschel. ASME, Orlando, p. 287 – 296.

Heinbockel, I. , Fett, F. N. , 1995, A mathematical model for pressurized circulating fluidized bed Combustion. *In*: Proceeding of the 13th International Conference on FBC, Ed. by Heinschel. ASME, Orlando, p. 1283 – 1301.

Huilin, L. , Guangbo, Z. , Rushan, B. , et al. , 2000, A coal combustion model for circulating fluidized bed boilers. *Fuel*, 79: 165 – 172.

Park, C. K. , Basu, P. , 1997, A model for prediction of transient response to the change of fuel feed rate to a circulating fluidized bed boiler furnace. *Chemical Engineering Science*, **52**(20): 3499 – 3509.

Seeber J. , Scheffknecht, G. , 1999, Boiler design concept for standardized medium size CFB plants, *In*: Circulating Fluidized Bed Technology VI. Ed. by J. Werther. DECHEMA, p. 933 – 948.

Shelton, E. , 1996, How We Got Here From There: Steps and Missteps on the Path to Utility Scale CFBs, *In*: Circulating Fluidized Bed Technology V. Ed. by Mooson Kwauk and Li Jinghai. Science Press, Beijing, p. 313 – 320.

Wang Qinhui, 1997, Mathematical Modeling and Performance Testing of Circulating Fluidized Bed Boiler, Ph. D. thesis of Zhejiang University, Hangzhou, China(in Chinese).

Wang Qinhui, Luo Zhongyang, Li Xuantian et al. , 1999, A mathematical model for a circulating fluidized bed. *Energy*, **24**, 633 – 653.

Werner, A. , Grausam, M. , Linzer, W. , et al. , 1999, Overall modelling of circulating fluidized bed boilers, *In*: Circulating Fluidized Bed Technology VI, Ed. by J. Werther. DECHEMA, p. 425 – 436.