MODELING STUDY ON NON-UNIFORM DISTRIBUTION IN THE LATERAL DIRECTION IN LARGE SCALE CFB BOILERS

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Abstract–With the development of large scale circulating fluidized bed (CFB) boilers, the section area of the furnace increases, and the lateral non-uniform distribution of the furnace become prominent, especially, which causes a serious threat to the boiler efficiency and safety. To guarantee the high performance of CFB boilers, the lateral non-uniform distribution of solid concentration should be studied with experiments and simulation. A 2-D CFB mass balance model, based on 1-D cell model developed at Tsinghua University, was proposed in this paper, which consisted of the coal ash formation, solid attrition and size reduction, fast bed flow model and segregation model. The lateral dispersion coefficient D_{sr} and D_{gr} were used to describe the dispersion between the lateral neighbor cells in dense bed and dilute zone, so the gas-solid flow both in lateral and vertical directions could be predicted by this 2-D model, and the effect of coal feed, primary air distributing, cyclone efficiency and dispersion coefficient on lateral non-uniform distribution were studied via modeling. Compared to the coal feeding, the primary air distributing has a greater influence to the lateral non-uniform distribution. The uniform boundary conditions will alleviate the lateral non-uniform distribution in large scale CFB boilers.

Keywords: CFB boiler, 2-D Model, Non-uniform distribution, Lateral direction

1. INTRODUCTION

With the advantages of fuel flexibility and low cost of emission control, circulating fluidized bed (CFB) boilers have been developed rapidly in the past three decades (Liu et al, 2015), especially for large scale CFB boilers. The world's largest 600 MW supercritical circulating fluidized bed (SCCFB) boiler has been successfully in commercial operation since the beginning of 2013 in Baima Power Plant in Sichuan, China (Yue et al, 2015). Besides, there are 10 units of 350 MW SCCFB boilers and more than 100 units of 300 MW CFB boilers in operation. The boiler efficiency increases with the higher steam parameters for the larger capacity.

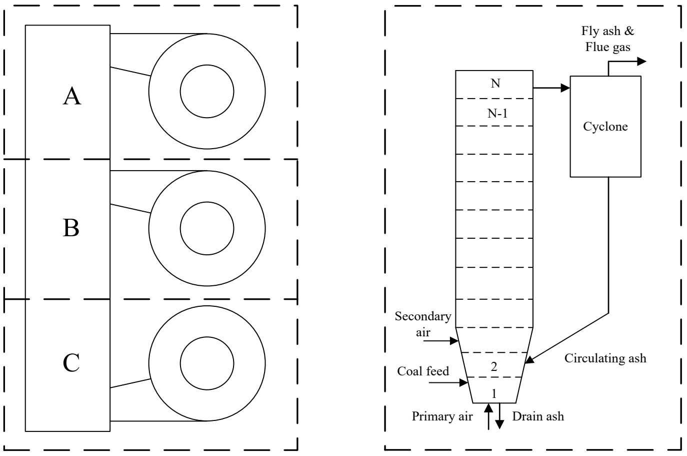
However, with the larger furnace volume of the CFB boiler, the section area of the furnace increases, and the heterogeneity problems in the width direction (or the lateral direction) of the furnace of CFB boilers become prominent. The lateral non-uniform of solid concentration, and the lateral temperature and heat flux distribution deviation are the main heterogeneity problems of the single-furnace CFB boilers (Hu, 2013), which cause a serious threat not only to the combustion efficiency and pollutant control, but also to the boiler stability and hydrodynamic safety. The field tests show the temperature and heat flux distribution deviation in the lateral direction both in dense bed and dilute zone in different 300 MW CFB boilers (Zhang, 2009; Li et al, 2012). The temperature and heat flux distribution are mainly affected by the gas-solid flow and the structure of the furnace, like heat transfer surface arrangement etc. So, the gas-solid flow is the main influence of the temperature distribution in a specific furnace structure, and the solid concentration distribution is determined by the gas-solid flow as well. To guarantee the high efficiency of CFB boilers, the lateral non-uniform distribution of solid particles in the furnace should be studied.

Simulation is one of the most feasible methods to study the gas-solid flow in the CFB furnace. So far, the CFB models can be distinguished as computational fluid dynamics (CFD) models and semi-empirical models (Hu et al, 2013). CFD models can offer more detailed hydrodynamics description in the CFB furnace and help researchers to understand the mechanisms of gas-solid flow. Comparing with CFD models, the equations in semi-empirical models normally are derived from experiments or field test data, and the empirical models are relatively simple, so the semi-empirical models take less time to calculate and also offer key parameters of the CFB boilers.

In this paper, based on the 1-D mass balance model (Yang et al, 2005), the applicable 2-D mass balance model of CFB boiler will be developed. The main target of this 2-D semi-empirical model is to study the lateral non-uniform distribution of solid particles in the CFB furnace. The field test data of a 300 MW single-furnace CFB boiler were used to determine the model input data. The effects of the coal feeding, air distribution, cyclone efficiency and lateral dispersion on the lateral gas-solid flow were studied with the 2-D model. The calculation results showed obvious differences of solid concentration in paralleling cells along the height direction.

2. MODEL DESCRIPTION

The 2-D mass balance model is developed based on the 1-D mass balance model. The 1-D model has been developed and validated by many researchers (Yang et al, 2005; Hu et al, 2012; Liu et al, 2015) in different studies. So far, the 2-D mass balance model only considers the mass balance, and the combustion process, desulfurization and energy balance are not taken into account. The cell model is employed to set up the mass balance of solid flow, which includes the coal ash formation, solid attrition and size reduction, fast bed flow model and segregation model, and more details can be found in the previous work (Yang et al, 2005).



(a) Cell in width direction (b) Cell in height direction

Fig. 1. 2-D mass balance model cell structure

A 300 MW single-furnace CFB boiler was simulated with the 2-D model. The CFB furnace is 47.6m high, and has a cross section of 31.9m in width and 9.6m in depth. Three thermal insulated cyclones are employed. To study the gas-solid flow in width and height direction, there are 3 same cells in width direction, shown in Fig. 1(a), and N cells in height direction, shown in Fig. 1(b) (in this study, N = 15). For the cell (i, j) and ash particle size group k, age group l, the solid mass balance can be showed in Fig. 2 and described by Eq. (1) (cell number i in height direction, and j in width direction).

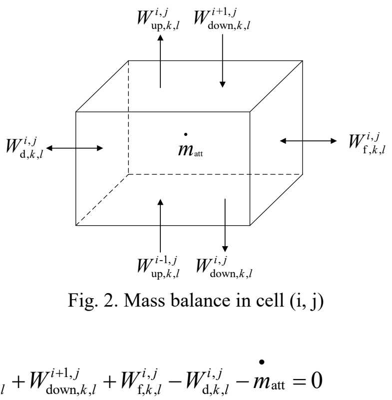


Fig. 2. Mass balance in cell (i, j)

$$W^{i-1,j}_{\mathrm{up},k,l} - W^{i,j}_{\mathrm{up},k,l} - W^{i,j}_{\mathrm{down},k,l} + W^{i+1,j}_{\mathrm{down},k,l} + W^{i,j}_{\mathrm{f},k,l} - W^{i,j}_{\mathrm{d},k,l} - \dot{m}_{\mathrm{att}} = 0 \qquad (1)$$

How to describe the lateral solid dispersion is the key point in modeling work. According to precious study (Hu et al, 2013, 2016), though the mechanism of lateral dispersion in dense bed is different to that in dilute zone, the values of lateral dispersion coefficient are similar in dense bed and dilute zone, which is about 0.001~0.01 m^2/s. The 2-D model used D_{sr} and D_{gr} to calculate the lateral dispersion in dense bed and dilute zone separately, and assumed that $D_{sr}= D_{gr}=$ 0.001~0.004 m^2/s. The lateral dispersion can be calculated by Eq. (2).

$$W_{\mathrm{d},k,l}^{i,j}=D_{\mathrm{sr(gr)}}\frac{\partial C_{k,l}^{i,j}}{\partial x}\times A_{\mathrm{sec}}^{i} \tag{2}$$

3. NUMERICAL EXPERIMENTS

To study the lateral non-uniform distribution of the CFB furnace, numerical experiments were carried out with the 2-D model. The model used A, B, and C, shown in Fig. 1(a), to describe the paralleling three beds and cells, A and C represented the left and right bed and cells, B represented the middle bed and cells. The calculating cases were listed in Tab. 1. The model assumed that the total primary air and total coal feed are 3, the value of A, B and C in Tab. 1 showed the primary air distributing and coal feeding in the paralleling three beds and the bigger value meant more coal feed or primary air in this bed. Total coal feed is 221.5 t/h in three beds, and 1 means 73.8 t/h in each bed. Total primary air is 130.47 Nm^3/s, and 1 means 43.49 Nm^3/s in each bed. The d_{99} of three cyclones were 120 μm, while the d_{50} of three cyclones were different, listed in Tab. 1. Case 1 was the basic condition. Case 2-4, case 5-7, case 8-11 and case 12-15 studied the effect of coal feeding, primary air distributing, cyclone collection efficiency and dispersion coefficient respectively.

Tab. 1. Key input parameters of calculating cases

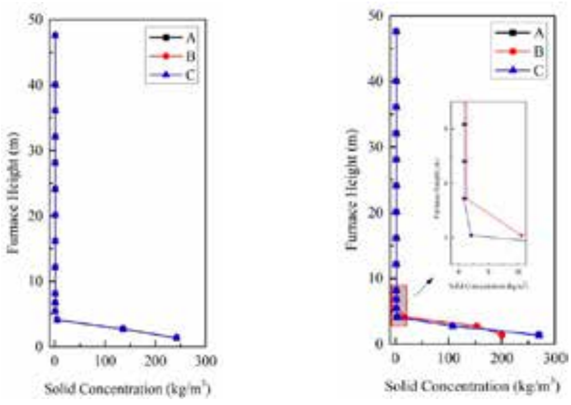
Case	D_{sr} or D_{gr} (m^2/s)	Coal feed value (-)			Primary air distributing value (-)			d(50) of 3 cyclones (μm)		
		A	B	C	A	B	C	A	B	C
1	0.001	1	1	1	1	1	1	34	34	34
2	0.001	0.95	1.1	0.95	1	1	1	34	34	34
3		0.9	1.2	0.9						
4		0.85	1.3	0.85						
5	0.001	1	1	1	0.95	1.1	0.95	34	34	34
6					0.9	1.2	0.9			
7					0.85	1.3	0.85			
8	0.001	1	1	1	1	1	1	34	41	34
9								34	37	34
10								34	31	34
11								34	27	34
12	0.000	0.9	1.2	0.9	1	1	1	34	34	34
13	0.002									
14	0.003									
15	0.004									

4. RESULTS AND DISCUSSION

4.1 CALCULATING RESULTS

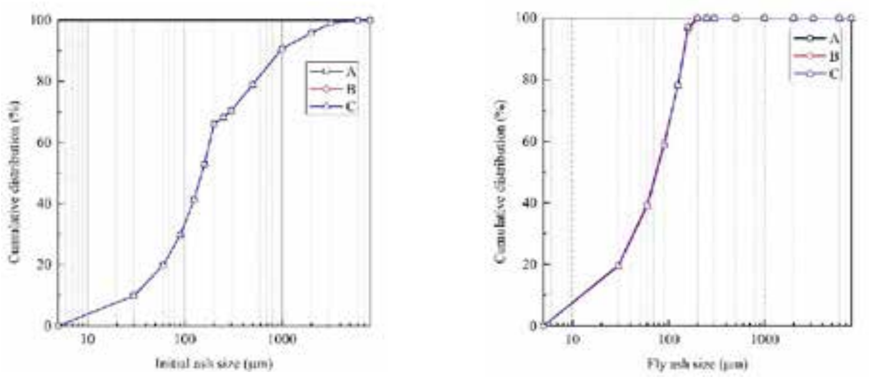
The solid concentration distribution in the furnace and the ash size distributions were calculated. The influences of coal feeding, primary air distributing and cyclone collection efficiency were also studied.

Fig. 3(a) shows the solid concentration in the furnace of case 1. The solid concentrations are same in three beds, proving that the lateral solid concentration distribution are uniform in the furnace when the boundary conditions are same in three beds. Fig. 3(b) shows the solid concentrations in the furnace of case 7. The solid concentration in dense bed of the middle bed is lower than that of left and right bed, instead in dilute zone, the solid concentration of the middle bed is higher, showing the typical lateral solid concentration non-uniform distribution along the furnace. Fig. 4 shows the particle size distributions in three beds of initial coal ash, fly ash, bottom ash and circulating ash of case 7. The initial feeding coal ash size of three beds are same, while the fly ash size, bottom ash size and circulating ash size are different in three beds, and the middle bed ash size is coarser than other two beds. The ash size distribution can also show the heterogeneity problems in the width direction.

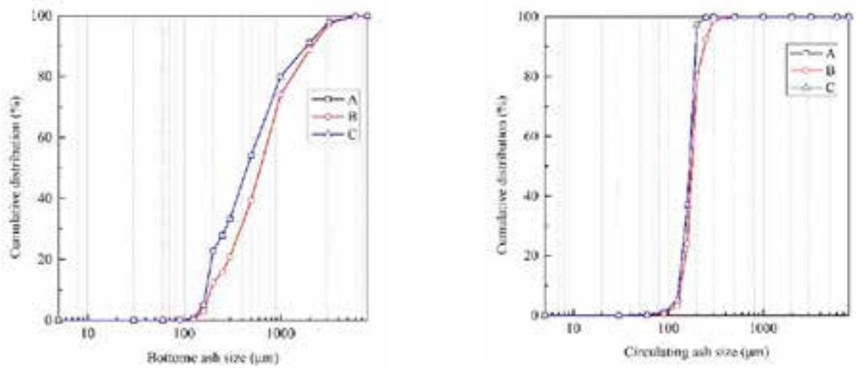


(a) Case 1 (b) Case 7

Fig. 3. Solid Concentration of the furnace



(a) Initial ash size distribution (b) Fly ash size distribution



(c) Bottom ash size distribution (d) Circulating ash size distribution

Fig. 4. Ash particle size distribution of case 7

To compare the ash flow rate and size distribution of 15 cases, the ash flow rates and mass averaged ash size were calculated and listed in Tab. 2. To evaluate the lateral solid concentration non-uniform distribution, Eq. (3) and (4) were used to calculate the mean square error of solid concentration of lateral cells along the height of furnace. The mean square error $\sigma_C(h)$ and σ_C can represent the lateral non-uniform distribution in the height of h and the whole furnace.

Tab. 2. Calculating results of ash flow rate and average size

Case	Flow rate (kg/s)						Mass averaged particle size (μm)					
	Fly ash		Bottom ash		Circulating ash		Fly ash		Bottom ash		Circulating ash	
	A (C)	B	A (C)	B	A (C)	B	A (C)	B	A (C)	B	A (C)	B
1	1.52	1.52	0.83	0.83	355.57	355.57	42.77	42.77	387.13	387.13	161.08	161.08
2	1.46	1.64	0.77	0.94	349.97	366.27	42.79	42.71	390.60	380.68	161.51	160.29
3	1.40	1.75	0.71	1.06	344.19	376.32	42.81	42.63	394.22	374.79	161.98	159.57
4	1.34	1.87	0.65	1.18	338.29	385.69	42.82	42.55	397.99	369.44	162.49	158.91
5	1.51	1.54	0.84	0.80	350.85	364.63	42.87	42.54	379.15	402.83	160.72	162.01
6	1.50	1.56	0.86	0.77	345.12	371.71	42.93	42.30	371.55	419.28	160.40	162.99
7	1.49	1.62	0.88	0.69	340.89	551.37	43.00	42.59	362.72	465.97	160.16	174.64
8	1.51	1.72	0.82	0.65	349.33	230.61	42.63	46.92	391.07	481.47	160.93	178.13
9	1.52	1.62	0.83	0.73	352.45	290.82	42.71	44.98	389.12	430.93	160.97	169.22
10	1.53	1.40	0.83	0.93	358.68	435.56	42.85	40.25	385.06	343.06	161.21	152.59
11	1.53	1.27	0.83	1.06	361.54	525.38	42.96	37.31	383.15	302.62	161.38	144.81
12	1.40	1.76	0.71	1.06	342.99	378.62	42.77	42.69	394.98	373.46	162.01	159.58
13	1.40	1.75	0.71	1.06	345.17	374.46	42.85	42.58	393.60	375.87	161.96	159.57
14	1.41	1.75	0.71	1.06	345.99	372.92	42.88	42.55	393.08	376.78	161.94	159.58
15	1.41	1.74	0.71	1.06	346.63	371.49	42.90	42.51	392.54	377.63	161.91	159.58

$$\sigma_C(h)=\sqrt{\left[\sum_j\left(C^j(h)-\overline{C}(h)\right)^2\right]\Big/(N-1)} \tag{3}$$

$$\sigma_C=\frac{1}{H_\mathrm{b}}\int_0^{H_\mathrm{b}}\sigma_C(h)\,\mathrm{d}h \tag{4}$$

4.2 THE EFFECT OF COAL FEEDING

Case 1-4 studied the effect of coal feeding to the lateral non-uniform distribution. With the coal feed value in the middle bed increase, the lateral solid concentration deviation increase, shown in the Fig. 5. For more coal feed in the middle bed, the ash flow rate in the middle bed increase, and more fine particle size ash in the middle bed, so the ash mean size in the middle bed decrease, while in the A or C bed, the ash flow rate decrease and the mean ash size increase, shown in the Tab. 2.

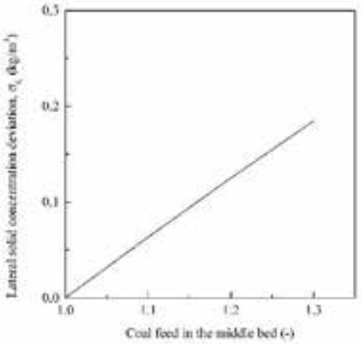


Fig. 5. The influence of coal feeding to σ_C

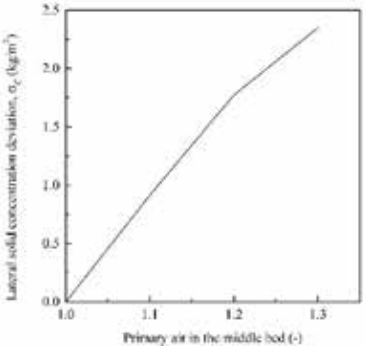


Fig. 6. The influence of primary air distributing to σ_C

4.3 THE EFFECT OF PRIMARY AIR DISTRIBUTING

Case 1 and case 5-7 studied the effect of primary air distributing to the lateral non-uniform distribution. With the primary air in the middle bed increase, the lateral solid concentration deviation increase, shown in the Fig. 6. Compared to the effect of coal feed, when the boundary condition changes in a same percent, σ_C of air distributing is bigger than that of coal feed, so the primary air distributing has a greater influence to the lateral non-uniform distribution. In the industrial CFB boilers, the uniform air distributing is really hard, especially when the air distributor has larger section area, and this may be a main reason causing the lateral non-uniform distribution in the furnace.

With more primary air in the middle bed, the fly ash and circulating ash flow rate in the middle bed increases, and the bottom ash flow rate decreases. For the higher air speed, more ash, whose size is larger than the circulating ash while smaller than the bottom ash, participates the circulation, so the circulating ash size and bottom ash size in the middle bed both increase. The influence trend in the A or C bed is opposite, shown in the Tab. 2.

4.4 THE EFFECT OF CYCLONE EFFICIENCY

Case 1 and case 8-11 studied the influence of cyclone collection efficiency to the lateral non-uniform distribution. Case 1 is the uniform boundary condition, and the efficiency of 3 cyclones are same, so $\sigma_C = 0$. When the efficiency of the middle cyclone decreases, like case 8-9, the circulating ash flow rate decreases, the fly ash flow rate increases, and the mean sizes of fly ash and circulating ash increase. On the contrary, when the efficiency of the middle cyclone increases, the circulating ash flow rate increases, the fly ash flow rate decrease, and the mean sizes of fly ash and circulating ash decrease. Both increasing and decreasing the middle cyclone efficiency will cause the boundary condition non-uniform, so the lateral solid concentration deviation increase, shown in the Fig. 7.

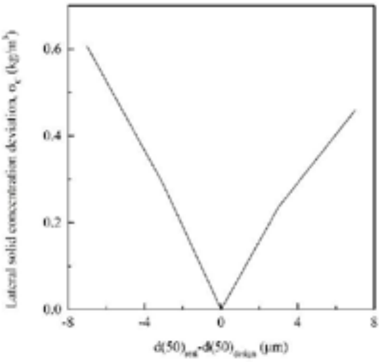


Fig. 7. The influence of cyclone efficiency to σ_C

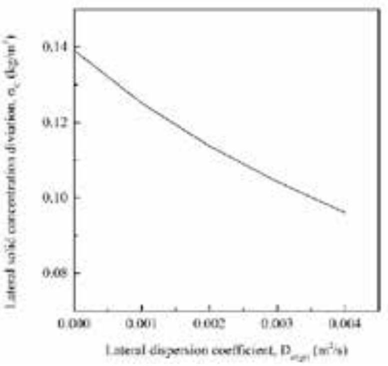


Fig. 8. The influence of dispersion coefficient to σ_C

4.5 THE EFFECT OF DISPERSION COEFFICIENT

Case 3 and case 12-15 studied the influence of lateral dispersion coefficient to the lateral non-uniform. With the dispersion coefficient increases, the lateral solid concentration deviation decreases, shown in the Fig. 8, and the differences of flow rate, ash mean size of A(C) bed and B bed decrease, listed in the Tab. 2. So the lateral dispersion will weaken the non-uniform distribution. For the equation solution method limitation, the program will run-error time when the $D_{sr(gr)}$ is larger 0.005m^2/s. In future work, the cases of the $D_{sr(gr)}$ larger than 0.005m^2/s will be studied.

5. CONCLUSIONS

A 2-D CFB boiler mass balance model is proposed in this paper, which consists of the coal ash formation, solid attrition and size reduction, fast bed flow model and segregation model. The ash flow rate and particle size, solid concentration along the furnace can be calculated by the model. This model can predict the gas-solid flow not only in the height direction but also in the width direction, which can be used to study the lateral non-uniform distribution in large scale CFB boilers.

The influences of coal feeding, primary air distributing, cyclone efficiency and lateral dispersion coefficient to the lateral non-uniform distribution have been discussed via the 2-D model. Non-uniform boundary conditions will cause the lateral non-uniform distribution in the furnace, and the lateral dispersion will weaken the lateral non-uniform distribution to some extent. Compared to the coal feeding, the primary air distributing has a greater influence to the lateral non-uniform distribution. The uniform boundary conditions will alleviate the lateral non-uniform distribution in large scale CFB boilers.

NOTATIONS

W_{up}	Upward flow rate, kg/s	D_{gr}	Dispersion coefficient in dilute phase, m^2/s
W_{down}	Downward flow rate, kg/s	C	Solid concentration, $\mathrm{kg/m}^3$
W_{f}	Coal feed, slagging flow rate, kg/s	A_{sec}	Section area between lateral cells, m^2
W_{d}	Lateral dispersion flow rate, kg/s	σ_C	Solid concentration deviation, $\mathrm{kg/m}^3$
$\dot{m}$	Mass flux rate, kg/s	N	Number of lateral cells
D_{sr}	Dispersion coefficient in dense phase, m^2/s	H_{b}	Furnace height, m

Subscripts

i	Cell number in height direction	l	Age group
j	Cell number in width direction	att	Attrition
k	Particle size group		

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