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PREDICTION AND VALIDATION OF EFFECT OF BED LENGTH ON RTD OF COAL IN A BUBBLING FLUIDIZED BED

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ABSTRACT

The residence time distribution (RTD) of coal particles in a bubbling fluidized bed with continuous feeding is calculated with an extended convection-dispersion model, in which segregation of coal is accounted for. The effect of bed length on the RTD of coal is investigated, and the results are validated by experiments.

1. INTRODUCTION

The residence time distribution (RTD) of coal particles has a great impact on the reaction in a bubbling fluidized bed with continuous feeding. It is necessary to predict RTD when a fluidized bed is scaled up for industrial projects. A relatively safe method to enlarge the bed while maintaining performance is to extend the bed length. Experimental and numerical methods can be applied to investigate RTD of the bed. It is very difficult to perform experiments, when the scale is very large. One of the numerical options is the Euler-Euler method (1), which takes the fluid as one phase and regards the particles as another continuous phase. It is difficult to model the interaction between the coal and sand particles correctly in this approach. Another alternative method is the Euler-Lagrange method (2), in which both, sand and coal particles, are treated as individual particles, and each particle is traced. This approach consumes too long computing time for practical applications, even when parallel computers are employed.

In order to investigate the effect of bed length on RTD, a semi-empirical, semi-numerical method is proposed here. First, a phenomenological semi-empirical model, namely an extended convection-dispersion model is developed, which takes segregation of coal into account. Second, the segregation model for binary solids is developed and partial differential equations are deduced. Third, experiments are performed to determine the model parameters in the derived equations, such as segregation index and dispersion coefficient. Then, using the so obtained parameters, predictions of the effect of bed length on RTD are made by solving the partial differential equations numerically. Last, experiments are carried out to validate the predictions.

2. EXTENDED CONVECTION-DIFFUSION MODEL

In this section a phenomenology model is constructed in which segregation is considered. The conceptual diagram of the model is shown in Fig.1. A one-fluid model is employed here, which considers the mixture of solids (sand and coal) and fluid (air) as one fluid. Continuous feeding of sand is expressed as convection, the effect of mixing due to bubbling is expressed as dispersion (3) (4), and the effect of difference in density and size of coal and sand particles is expressed as segregation.

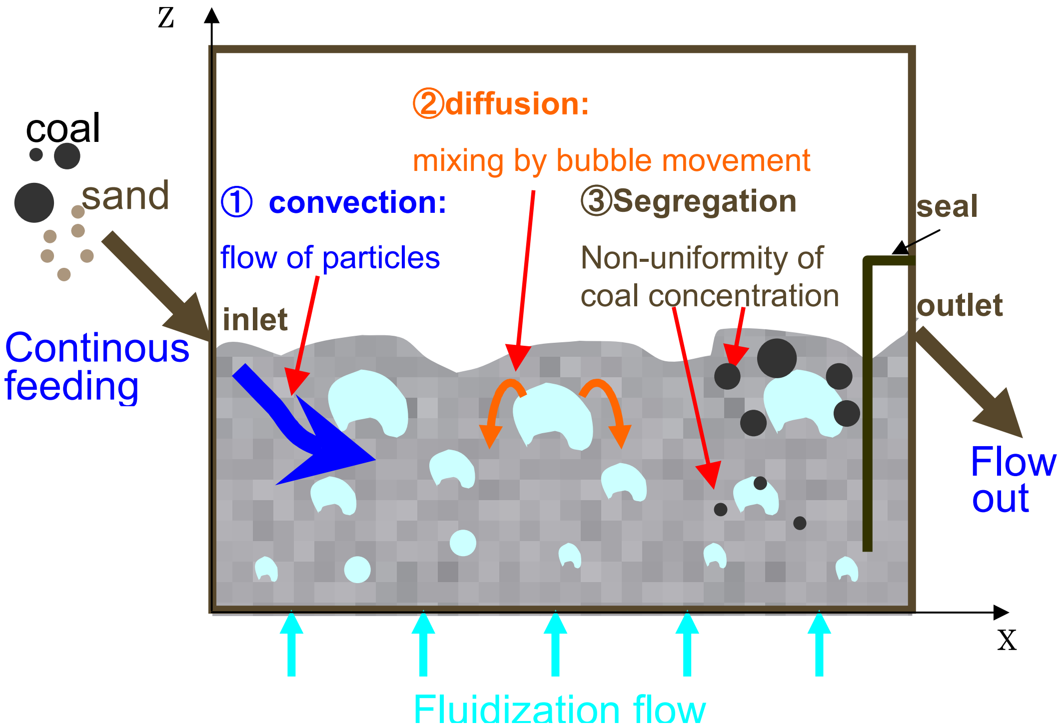


Fig.1 Extended Convection-diffusion Model

2.1 Segregation Model

Segregation occurs when binary solids with different size and density do exist in the fluidized bed (5). In the segregation model proposed here, it is assumed that the dimensionless concentration distribution of coal $C(Z)/C_{average}$ keeps invariant, even if the concentration $C_{average}$ of coal varies with time.

In order to quantify the segregation effect in the concentration equation, we define two segregation indices S_t,S_b as follows. For simplicity, we only show the one-dimensional model in vertical direction (z-direction).

$$S_t=C_t/C \qquad (1\text{-}1)$$
$$S_b=C_b/C \qquad (1\text{-}2)$$

where C_t denotes the concentration at top surface of the control volume, C_b the concentration at bottom, $C_{average}$ the average concentration in the control volume. According to the assumptions stated above, S_t and S_b are invariant with time.

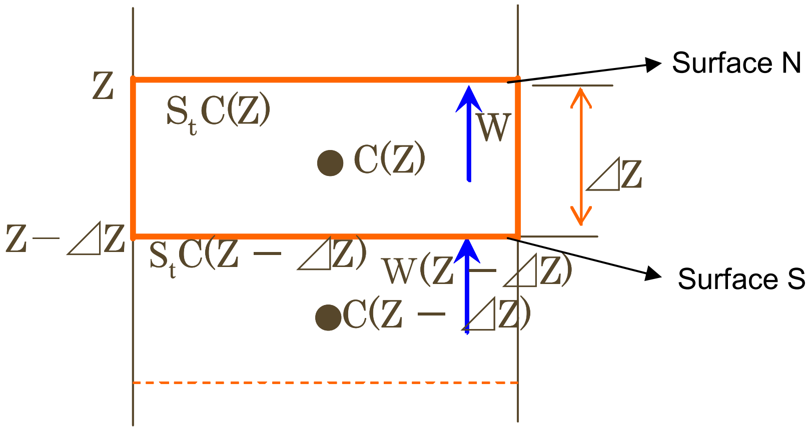


Fig.2 Segregation Model

The control volume (bold square) for concentration equation is shown in Fig.2 for upward flow (W>0). In this case, the concentration at surface S is $S_tC(Z-⊿Z)$, the concentration at surface N is $S_tC(Z)$, so concentration equation can be deduced as

$$\rho A \Delta Z \frac{\partial C}{\partial t} = S_t C(Z-\Delta Z) A \rho W(Z-\Delta Z) - S_t C(Z) A \rho W + D_z \rho A \frac{\partial^2 C}{\partial Z^2} \Delta Z \tag{2}$$

That is, for upward flow we obtain

$$\frac{\partial C}{\partial t} + S_t W \frac{\partial C}{\partial Z} = D_z \frac{\partial^2 C}{\partial Z^2} \tag{3-1}$$

Similarly, the concentration equation for downward flow (W≤0) becomes

$$\frac{\partial C}{\partial t} + S_b W \frac{\partial C}{\partial Z} = D_z \frac{\partial^2 C}{\partial Z^2} \tag{3-2}$$

Note, that in the above equations the convection velocity (second term in equation) is S_tW when the particles move upwards, but S_bW when downwards. One of S_t or S_b is larger than unity and the other smaller. Hence, the segregation phenomenon is described quantitatively.

2.2 Conservation Equations

Conservation equations can be written as:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{4-1}$$

Momentum equations

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu_s}{\rho}\frac{\partial^2 u}{\partial x^2} \tag{4-2}$$

$$u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g+\frac{\mu_s}{\rho}\frac{\partial^2 w}{\partial z^2} \tag{4-3}$$

Concentration equation

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+wS\frac{\partial C}{\partial z}=\frac{\partial}{\partial x}(D_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial z}(D_z\frac{\partial C}{\partial z}) \tag{4-4}$$

where $wS = S_t \max(w,0) + S_b \max(-w,0)$ (4-5)

D_x, D_z are the horizontal and vertical dispersion coefficients of coal, respectively; μ_s is the viscosity, given by (5)

$$\frac{\mu_s}{d_p{}^2\rho_p}=\begin{cases} 657 & \varepsilon_{\min}<\varepsilon<\varepsilon_{\min}+0.01 \\ 164+4.9\dfrac{1-\varepsilon}{\varepsilon-\varepsilon_{\min}} & \varepsilon_{\min}+0.01<\varepsilon<\dfrac{1}{3}(1+2\varepsilon_{\min}) \\ 87.2\dfrac{1-\varepsilon}{\varepsilon-\varepsilon_{\min}} & \dfrac{1}{3}(1+2\varepsilon_{\min})\le\varepsilon<1 \end{cases} \tag{5}$$

where d_p, ρ_p are diameter and density of sand, respectively. ε is the void fraction of sand (coal may be neglected here) and ε_{min} is the void fraction when the sand is closely packed (quiescent bed). ε can be determined when the pressure gradient dp/dz is measured.

Segregation indices S_b and S_t as well as dispersion coefficients D_x and D_z are to be determined in experiments.

3. EXPERIMENT AND DETERMINATION OF PARAMETERS

3.1 Experimental Conditions

Table1: Operating Conditions

Bed length	1 m	Diameter of sand	0.294mm	Superficial Velocity U0	0.322m/s
Bed height	1 m	Density of sand	2610 kg/m3		
Bed depth	0.037m	Diameter of coal	0.95mm	U0/Umf_sand	4
Height of free board	1 m	Density of coal	1120 kg/m3		

*) U_{mf}_sand denotes minimum fluidization velocity of sand.

A quasi two-dimensional bubbling fluidized bed is used in the experiments (refer to Fig1.) The bed material is sand, and tracer is coal. A sintered plate is used as distributor for the fluidizing flow. Experiments are carried out under atmospheric pressure at room temperature. Further operation conditions are listed in Table1.

3.2 Segregation Experiment

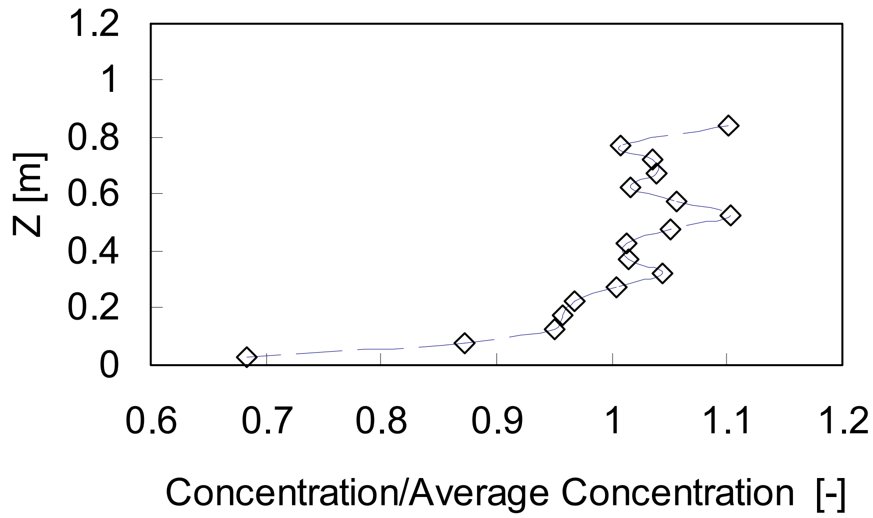


Fig.3 Measurement of Coal Segregation in Sand

In order to determine the segregation indices S_t and S_b, we measure the concentration distribution of coal along the vertical direction. Under fixed superficial velocity (0.322m/s), a certain amount of coal (about 2%) is injected into the bed (no continuous feeding). After a certain time long enough to obtain steady conditions, the fluidized bed is quickly shut-down (superficial velocity reduced to zero) in a very short time. Then, samples are taken from the bed, layer by layer with a vacuum cleaner. Coal and sand are separated by a sieve. In this way the coal concentration at each layer is measured. Fig.3 shows a typical result of the coal distribution. We can see that the concentration is higher in the higher part of the bed. From this distribution, the segregation indices S_t and S_b can be determined.

3.3 Measurement Of RTD And Determination of Diffusion Coefficients

In order to determine the dispersion coefficients D_x and D_z, we measure the residence time distribution (RTD) of coal in a fluidized bed. Sand is fed continuously into the bed at the inlet at a certain rate. For steady conditions, sand will leave the bed at the outlet at the same rate. For the RTD measurements, pulse experiments have been performed: coal (2% weight of bed material) is injected into bed at a very short time (less than 1% of plug-flow time τ). At the outlet, the amount of coal exiting the bed is sampled at fixed time intervals. By measuring the weights of exited coal and sand for each sample, the RTD function (E-curve) can be obtained.

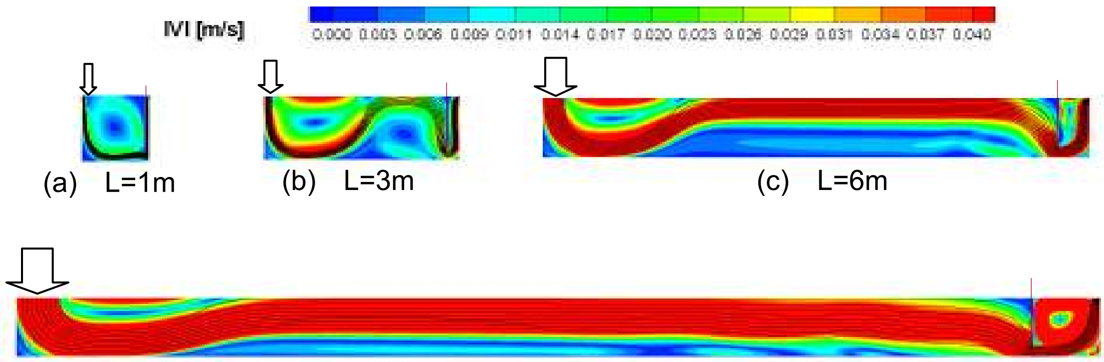


Fig.4 Flow in Beds of Various Lengths (Color by Solid Particle Velocity)

The flow in the bed has been computed by solving equations (4-1) ~ (4-3). The result for a bed length of 1m is shown in Fig.4(a). By solution of equation (4-4), RTD can be calculated, if S_t,S_b,D_x and D_z are given. By curve fitting, we can fix the dispersion coefficients D_x and D_z. Fig. 5 shows the RTD for the 1m bed.

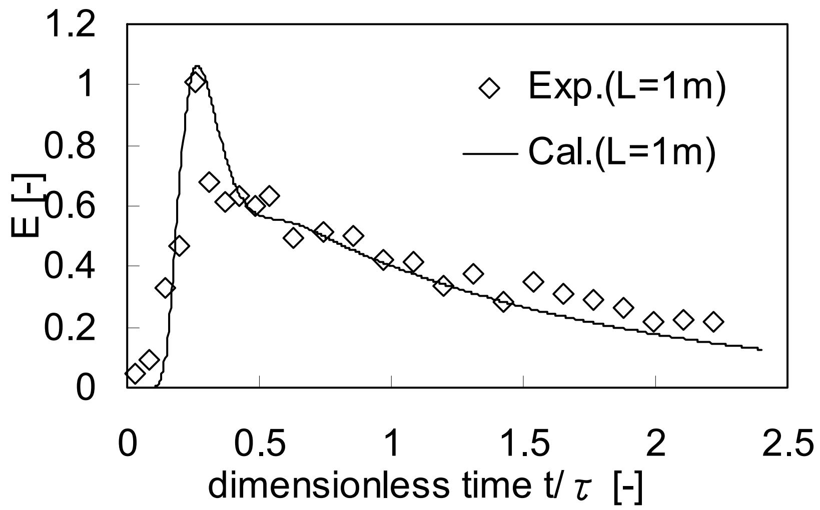


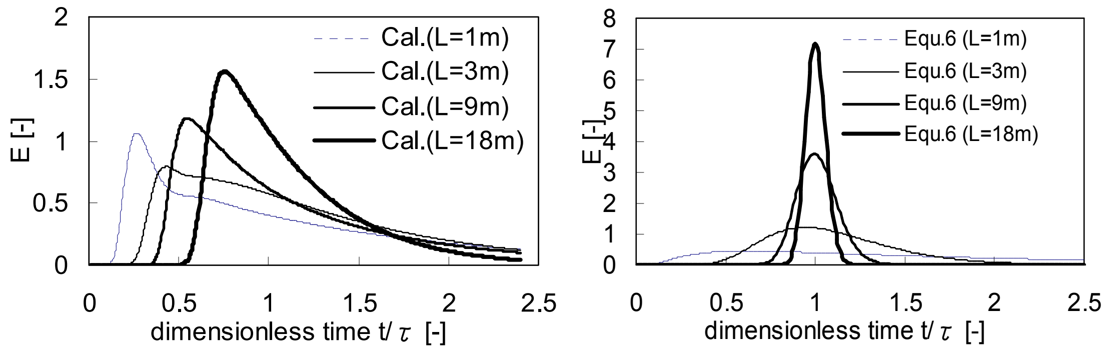
Fig.5 Determine Diffusion Coefficients by Curve Fitting (L=1m)

The normalized residence time distribution function E is defined as the ratio of exited coal per unit dimensionless time to total injected coal. In the figure, τ denotes plug-flow time (τ = Wt/Q), where Wt [kg] is the total weight of particles present in the bed at a certain time, and Q [kg/s] is the rate of sand supply.

4. PREDICTION AND VERIFICATION

4.1 Prediction the Effect of Bed Length

Assuming that the dispersion coefficients and the segregation indices are constant, if only the length of bed is extended, predictions for RTD of coal particles for various bed lengths can be made by solving equations (4). RTD functions have been calculated for 3m, 9m and 18m long beds. The flow fields for each bed length is shown in Fig.4; RTDs for various bed length are presented in Fig. 6(a)



(a) 2D with segregation (2DS) (b) 1D without segregation (1DN)

Fig.6 Prediction of The Effect of Bed Length On RTD

4.2 Validation by Experiment

A validation experiment has been performed for a 3m long bed. With exception of bed length, all other conditions are the same as for the 1m bed. The plug flow time τ is also kept the same. The comparison between calculation and experiment (Fig.7) shows good agreement for RTD.

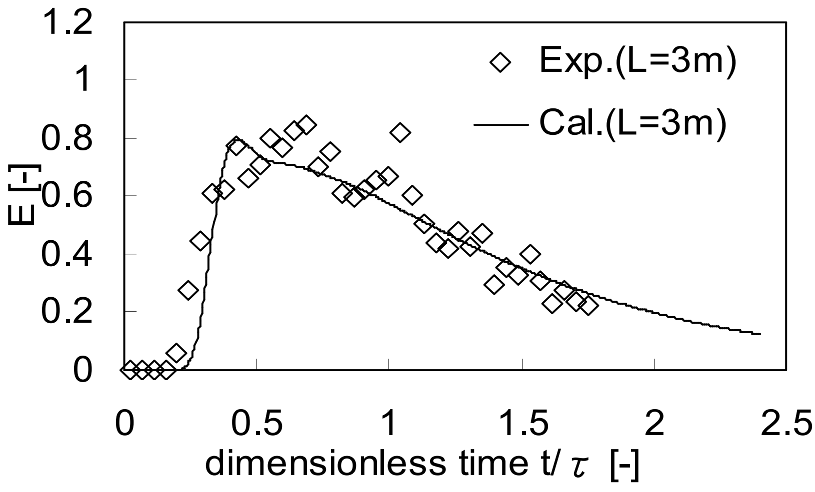


Fig.7 Comparison of Experiment and Prediction (L=3m)

5. DISCUSSIONS

We compare predictions of a two-dimensional model with segregation (2DS) with a one-dimensional model without segregation (1DN). For horizontal (x-direction) one-dimensional flow, the normalized RTD function E is given by (6)

$$E = \frac{1}{\sqrt{4\pi(D_x / uL)(t/\tau)}} \exp\left[-\frac{(1-t/\tau)^2}{4(D_x / uL)(t/\tau)}\right] \quad (6)$$

This solution is plotted for various bed lengths in Fig.6 (b). We can see that the predictions for 2DS and 1DN are much different. The peak of 1DN is higher and appears later. Eq.(6) cannot predict RDT of coal correctly for the beds considered here. For 1DN, we can see that the peak of RTD curve becomes higher, and the initial exiting time delays to later times, when the bed length becomes longer (Fig.6(b)). This is caused by the dimensionless dispersion coefficient D_x/uL, which becomes smaller when bed length is longer. The same trend can be found in 2DS. However, the 1m long bed is an exception: the peak of RTD is higher than that of the 3m long bed. With recourse to Fig.4 it can be assumed that the different behavior of the short bed is caused by the different flow pattern.

6. CONCLUSIONS

We summarize our results as follows.

1) Segregation is accounted for in the extended convection-dispersion model. We measured necessary parameters for this model. Predictions on the effect of bed length on the residence time distribution of coal in a bubbling fluidized bed can be made by the model presented here. The predictions have been validated by experiments. It has been shown, that the one-dimensional model cannot give correct predictions for the beds considered here.

2) When the bed length becomes longer, the initial exiting time of coal becomes later, and the peak of RTD curve becomes higher and are delayed. It has been shown, that for similar flow patterns, the RTDs also look similar.

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