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STUDIES ON LIQUID FLUIDIZED BED WITH PULSING INLET FLOW

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ABSTRACT

Fluidized beds with pulsing inlet flow are of considerable interest in process engineering. Quantitative understanding of the two-phase flow behaviors in pulsed beds is very important for design and optimum operation of such reactors. The aim of this paper is to understand the mathematical models for pulsed particulate fluidization and its dynamic processes. Two-Fluid Model (TFM) and its simplified version, Local Equilibrium Model (LEM), are solved for pulsed fluidization. LEM is proposed to model pulsed fluidization with acceptable engineering accuracy compared with experimental data, its shortcomings are also discussed at length by analyzing the relaxation processes of two-phase flow due to a jump change of fluidizing velocity and the structure of concentration discontinuity which forms in bed collapse process.

Keywords: Fluidization; Pulsed flow; Two-Fluid model; Local Equilibrium Model.

INTRODUCTION

Fluidized beds are common and important reactors in process engineering because of the high mass or heat transfer rate between the fluid and particles. It is well known that there are non-uniform flow structures such as bubbles and slugs in fluidization which are undesirable for efficient operations, because they can reduce the contact efficiency[1].

As a method of eliminating slugs and gas channeling, reducing the size of bubbles, thus improving the fluidization quality, pulsed fluidization is an operation in which the fluidizing velocity $U(t)$ pulsates with time as rectangular wave, cosinoidal wave or any other patterns[2-3]. Although many people have studied the behaviors of transient flows in fluidized beds[4-6], however, the flow patterns of unsteady two-phase flows are very complex, the quantitative understanding of the flow in pulsed fluidized beds is far from being complete. Few papers modeled the bed height, especially the distribution of particle concentration along the bed when the pulsation frequency of $U(t)$ is not very low. As an important aspect of the quantitative understanding of the flow behaviors in pulsed beds, the main aim of this paper is to understand the mathematical models for pulsed particulate fluidization and predict the dynamic processes in the beds.

In our liquid pulsed fluidization experiment, the one-dimensional character of the flow, i.e., the distinct planar wave character of particle concentration in the bed, can be obviously seen. The concentration waves (expansion wave and shock wave) travel upwards from the distributor (See Fig.1). Fig. 1 shows the transient distribution of particle concentration along the bed at different times in a period, recorded by a digital camera. The gray scale of the photos represents the particle concentration: the darker the photo, the denser the particle concentration. From Fig. 1, one can know that bed height $h(t)$ oscillates up and down in a cycle, a concentration wave from the distributor travels upward periodically as a result of the periodical change of fluidizing velocity $U(t)$, dilute and dense sections of particle concentration distribute alternately, accompanying concentration discontinuities a, b and c between the dilute and dense sections. The above facts show that the axial movement of two-phase flow prevails in pulsed fluidized bed. As a first approximation, it is appropriate to use the one-dimensional mathematical model to simulate the main character of the flow, i.e., particles moving up and down.

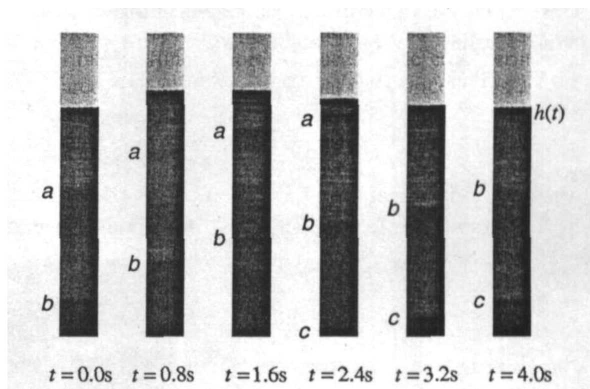

Fig. 1 Transient distribution of particle concentration when $U(t)$ varies with time as a rectangular wave with a period of 4 s (semi-on period 1 s and semi-off period 3 s).

MATHEMATICAL MODEL

Two-Fluid Model

The model used in this paper is based on the following assumptions: the two phases are incompressible, the fluid density ρ_f and the particle density ρ_p are constants; the diameter of the bed is large enough to ignore the drag force of the sidewall; the gradient of viscous normal stress of fluid phase $\tau_{f,xx}$ is ignored because it is much smaller than that of fluid pressure. Then, the equations used in [7] to describe fluidization can be written as:

$$\frac{\partial \alpha_p}{\partial t}+\frac{\partial (\alpha_p u_p)}{\partial x}=0 \quad (1)$$

$$\alpha_p \rho_p + \alpha_f \rho_f = U(t) \quad (2)$$

$$\rho_p\left(\frac{\partial u_p}{\partial t}+u_p\frac{\partial u_p}{\partial x}\right)-\rho_f\left(\frac{\partial u_f}{\partial t}+u_f\frac{\partial u_f}{\partial x}\right)= \frac{F_p}{\alpha_p\alpha_f}-(\rho_p-\rho_f)g+\frac{1}{\alpha_p}\frac{\partial(-p_p+\tau_{p,xx})}{\partial x} \quad (3)$$

$$\frac{\partial}{\partial t}(\alpha_p\rho_p u_p+\alpha_f\rho_f u_f)+\frac{\partial}{\partial x}(\alpha_p\rho_p u_p^2+\alpha_f\rho_f u_f^2)=$$

$$-\frac{\partial p}{\partial x}+\frac{\partial(-p_p+\tau_{p,xx})}{\partial x}-(\alpha_p\rho_p+\alpha_f\rho_f)g \quad (4)$$

$$\alpha_p+\alpha_f=1. \quad (5)$$

where α_p, α_f, u_p and u_f are volume fraction and velocity of particle phase and fluid phase respectively, F_p is the interphase force per unit volume except for buoyancy, p is fluid phase pressure, p_p, $\tau_{p,xx}$ are particle phase pressure and viscous stress respectively.

The unknowns α_p, α_f, u_p and u_f can be calculated by solving the equation set (1), (2), (3) and (5), then p can be gotten from Eq. (4).

F_p includes drag force F_D and virtual mass force F_{vm}

$$F_p=F_D+F_{vm} \quad (6)$$

One can express the inter-phase drag force F_D as

$$F_D=(\rho_p-\rho_f)g\,\alpha_p\alpha_f^{(2-n)}(u_f-u_p)/u_T\,. \quad (7)$$

where n is the Richardson–Zaki exponent that depends on the particle settling Reynolds number $Re_T=d_p u_T\rho_f/\mu_f$ [7].

Virtual mass force F_{vm} can be expressed as[7]

$$F_{vm}=-C_{vm}\alpha_p\rho_f\left[\frac{\partial u_p}{\partial t}+u_p\frac{\partial u_p}{\partial x}-\frac{\partial u_f}{\partial t}-u_f\frac{\partial u_f}{\partial x}\right] \quad (8)$$

where C_{vm} is virtual mass force coefficient.

The expressions for p_p and $\tau_{p,xx}$ used in this paper are

$$p_p=s\rho_p u_T^2\alpha_p/(\alpha_{p,c}-\alpha_p)\,. \quad (9)$$

$$\tau_{p,xx}=\tfrac{3}{4}\mu_p\frac{\partial u_p}{\partial x}, \quad (10)$$

where s is an adjustable parameter. Duru et al. (2002)[7] obtained the expression of μ_p through experimental method

$$\mu_p=C_\mu\rho_p d_p u_T(\alpha_{p,c}-\alpha_p)^{-1}. \quad (11)$$

where C_μ is 0.18 in their paper.

The above set of equations (1)~(5) including the p_p, F_D, F_{vm} and $\tau_{p,xx}$ terms to close it is named the General Form of Two-Phase Model (GTFM) in this paper.

The boundary conditions and the initial conditions are

$$x=0:\ u_p(t,0)=0,\ \alpha_p(t,0)=1-\left(U(t)/u_T\right)^{1/n}; \quad (12)$$

$$x=h(t):\ u_p(t,h)=\mathrm{d}h(t)/\mathrm{d}t; \quad (13)$$

$$t=0:\ \alpha_p(0,x)=\alpha_{p,0},\ u_p(0,x)=0,\ h(0)=h_0\,. \quad (14)$$

where a uniform fluidized state is assumed at $t=0$, $\alpha_{p,0}$ and h_0 are initial particle concentration and bed height respectively, $h(t)$ is the instantaneous bed height, $u_p(t,h)$ is the instantaneous particle velocity at the bed surface.

Although the inclusion of p_p and F_{vm} in GTFM can make it well-posed, the understanding of the constitutive relation of p_p, F_{vm} and $\tau_{p,xx}$ are not complete now, and the adjustable parameters in these expressions cannot be accurately determined and are chosen at will to some extent. In order to grasp the main effects of the pulsed flow in the bed, we intend to propose a simplified model of TFM, in which there are no adjustable parameters.

Local Equilibrium Model (LEM)

If both terms on the left hand side of Eq. (3) are neglected, as well as the particle stress terms on its right hand side, the first order partial differential equation degenerates into an algebraic relation

$$0=F_D-(\rho_p-\rho_f)\alpha_p\alpha_f g \quad (15)$$

Introducing Eqs. (7) into Eq. (15) yields,

$$U(t)-u_p(t,x)=u_T(1-\alpha_p(t,x))^n \quad (16)$$

There are no partial derivatives of the variables to time t and space coordinate x in the above equation, it is the local equilibrium equation among the fluidizing velocity U, particle velocity u_p and particle volume fraction α_p, thus it can be named Local Equilibrium Model (LEM).

Introducing Eq. (16) into Eq. (1) and eliminating particle velocity u_p yields the hyperbolic concentration wave equation

$$\frac{\partial\alpha_p}{\partial t}+V\frac{\partial\alpha_p}{\partial x}=0 \quad (17)$$

where V is the concentration wave

$$V=\frac{\partial(\alpha_p u_p)}{\partial\alpha_p}=u_p+\alpha_p\frac{\partial u_p}{\partial\alpha_p}=$$

$$U(t)+[n\alpha_p(1-\alpha_p)^{n-1}-(1-\alpha_p)^n]u_T \quad (18)$$

For a given fluidizing velocity U, V has a maximum at $\alpha_p=\alpha_{p,cr}=2/(n+1)$. Under our experimental conditions $n=2.414$, and $a_{p,cr}=0.5858\approx a_{p,c}$, so V usually increases with the increasing of α_p.

Let V_s be the speed of concentration shock, integrating the solid phase mass conservation Eq. (1) yields

$$V_s=\frac{\alpha_{p,B}u_{p,B}-\alpha_{p,F}u_{p,F}}{\alpha_{p,B}-\alpha_{p,F}}=$$

$$U(t)-\frac{\alpha_{p,B}(1-\alpha_{p,B})^n-\alpha_{p,F}(1-\alpha_{p,F})^n}{\alpha_{p,B}-\alpha_{p,F}}u_T \quad (19)$$

where $\alpha_{p,B}$, $\alpha_{p,F}$ are particle volume fraction at the back and front of the shock respectively and $u_{p,B}$, $u_{p,F}$ are particle velocity at the back and front of the shock respectively.

NUMERICAL RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

In this section, we show the numerical results from GTFM and LEM. The method of characteristics and a five order WENO (Weighted Essentially Non-Oscillatory) scheme [8] are used to solve LEM and GTFM respectively.

We also give the experimental results to check the numerical results. Details about the experiments please refer to [9]. The summaries of the physical properties of materials and test case are listed in Table 1 and Table 2 respectively.

Table 1 Physical Properties of the Particles and Fluid

Particles	d_p (mm)	ρ_p (kg/m^3)	u_T (m/s)	n	τ_p (s)	ρ_f (kg/m^3)
Glass beads	1.8	2600.0	0.1937	2.412	0.032	1000.0

Table 2 Summary of the Test Case

U_1 (m/s)	U_2 (m/s)	T_1 (s)	T_2 (s)	h_0 (m)
0.055	0.1482	3.0	1.0	1.950

Fig.2 shows the bed height variation vs. time responding to a pulsed fluidizing velocity from GTFM, LEM and the experimental data when the state is fully developed and periodical. Fig. 3a-3c shows the distribution of particle concentration at different times in a period. The dynamic behaviors are depicted photographically in Fig.1.

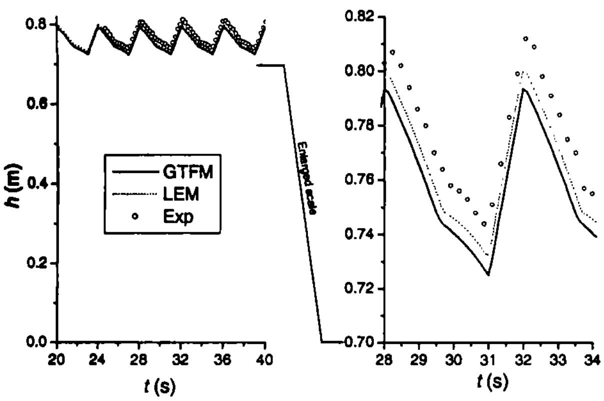

Fig. 2 Bed height variations vs. time responding to a periodically pulsed fluidizing velocity.

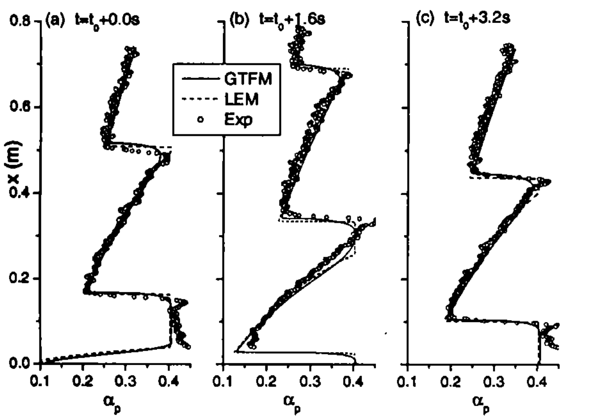

Fig. 3 Distribution of particle concentration at different times in a period, where s=0.07, $C_\mu=0, C_{vm}=0.5$

From Figs. 2 and 3, one can know that the numerical results of GTFM and LEM also fit the experimental well.

However, several undetermined constitutive relationships are included in GTFM, the adjustable parameters of which are always chosen at will to some extent. Although LEM, a further simplification of TFM, is very simple, it is highly capable of simulating complex processes in pulsed fluidization over a broad range of operating parameters, and its numerical results well fit experimental results in both the variation of bed height and the distribution of particle concentration as fluidizing velocity varies.

According to the experimental data, it is not true that the concentration discontinuity from LEM is a plane without thickness as shown in Fig. 3. The limitations of LEM will be discussed at length in the following section.

LIMITATIONS OF LEM

In this section, we will discuss the time scale that errors exist after a sudden change of fluidizing velocity and the spatial region where errors exist when sharp gradient of particle concentration exists in the flow field.

Relaxation Processes of the Two-Phase System After a Sudden Change of Fluidizing Velocity

The uniform flow field in the bed is assumed in this subsection, i.e., $\partial/\partial x=0$. If the fluidizing velocity U gets a sudden increment ΔU at $t=t_0$, according to LEM, the corresponding increments of u_p, u_f, α_p and α_f can be obtained from the Eqs. (1), (2), (5) and (16): $(\Delta\alpha_p)_{LEM}=(\Delta\alpha_f)_{LEM}=0$, $(\Delta u_p)_{LEM}=(\Delta u_f)_{LEM}=\Delta U$,

where, $\Delta\varphi=\varphi(t_{0+})-\varphi(t_{0-})$, $\varphi=\alpha_p,\alpha_f,u_p,u_f,U,\cdots\cdots$. In fact, the inertia of the two phases is different and it becomes very important when fluidizing velocity U gets a jump change, so the difference of the inertial forces between the two phases has considerable influence. The effect of inertia on the relaxation process after a jump change of U is discussed as follows.

If the virtual mass is ignored, the increments $\Delta\alpha_p$, $\Delta\alpha_f$, Δu_p and Δu_f can be obtained from Eqs. (1), (2), (3) and (5), considering the different inertia between the two phases due to the sudden increment ΔU at $t=t_0$.

$$(\Delta\alpha_p)_{TFM}=(\Delta\alpha_f)_{TFM}=0 \tag{20}$$

$$(\Delta u_p)_{TFM}=(\rho_f\Delta U)/(\alpha_p\rho_f+\alpha_f\rho_p) \tag{21}$$

$$(\Delta u_f)_{TFM}=(\rho_p\Delta U)/(\alpha_p\rho_f+\alpha_f\rho_p) \tag{22}$$

There is a relaxation process for the relative velocity between two phases to adjust it to another equilibrium state.

For the simple bed expansion and bed collapse process, fluidizing velocity U does not change after $t=t_{0+}$, and the distribution of various parameters can be thought to be uniform in the bed before the ending of the inertial relaxation process. Under such conditions, the solid phase velocity and relative velocity between the two phases in the relaxation process are

$$u_p(t)=[U(t_{0+})-u_T\alpha_f^n]\left[1-\exp(-(t-t_{0+})/\tau_{sys})\right]+ u_p(t_{0+})\exp(-(t-t_{0+})/\tau_{sys}) \tag{23}$$

$$u_f(t)-u_p(t)=(u_f-u_p)\big|_{t_{0-}}\left[1-\exp(-(t-t_{0+})/\tau_{sys})\right]+ (u_f-u_p)\big|_{t_{0+}}\exp(-(t-t_{0+})/\tau_{sys}) \tag{24}$$

where the relaxation time of mixture system τ_{sys} is

$$\tau_{sys}=\frac{u_T\alpha_f^n}{(1-\rho_f/\rho_p)g}\left[\frac{\alpha_f\rho_p+\alpha_p\rho_f}{\alpha_f\rho_p}\right]=\tau_p\alpha_f^n\left[1+\frac{\alpha_p}{\alpha_f}\frac{\rho_f}{\rho_p}\right] \tag{25}$$

and $\tau_p=u_T((1-\rho_f/\rho_p)g)^{-1}$ is the relaxation time for a single particle. For the solid-liquid system studied in this paper, $\tau_p\approx 0.032$ s.

In the expansion process when fluidizing velocity U suddenly increases from $U=U_1=0.055$ m/s to $U=U_2=0.128$ m/s, $\tau_{sys}\approx 0.36\tau_p\approx 0.012$ s, and in the collapse process when U decreases from $U=U_2=0.128$ m/s to $U=U_1=0.055$ m/s, $\tau_{sys}\approx 0.81\tau_p\approx 0.026$ s. The two relaxation processes after the sudden changes of U are shown in Fig. 4. In order to be convenient for comparison, the changes of velocity from LEM are also shown in the figures.

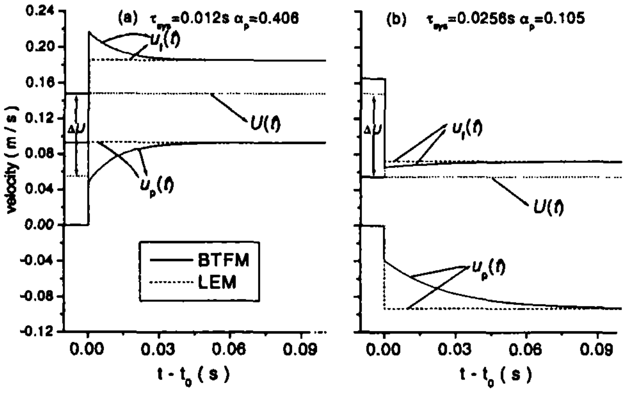

Fig. 4 The relaxation processes of the solid and fluid phase velocity when fluidizing velocity suddenly changes

From Fig. 4, Eqs. (23) and (24), when $(t-t_{0+})$ passes several times of τ_{sys} (about $m \approx 3 \sim 4$ times), $u_p(t)_{t>t_0+m\tau_s} \approx U(t_{0+}) - u_T\alpha_f^n = \Delta U + u_p(t_{0-}) = (u_p)_{LEM}\big|_{t>t_{0+}}$, $[u_f(t)-u_p(t)]_{t>t_0+m\tau_s} \approx (u_f-u_p)\big|_{t_{0-}} = (u_f-u_p)_{LEM}\big|_{t>t_{0+}}$, the velocities almost reach the values computed from LEM.

The above analyses show that ignoring the difference of inertial forces between the two phases introduces certain errors in a very short period only about tens of milliseconds after U changes suddenly. After that, LEM is applicable.

Structure of the Particle Concentration Discontinuity in Simple Collapse Process

Eqs. (1), (2), (5), (16) show that the flow field is continuous except for finite number of discontinuities in pulsed flow field. According to LEM, these discontinuities are planes without any thickness, relative velocity between the two phases has a jump change through the discontinuous planes. The difference of the inertial forces between the two phases must have an important influence when the relative velocity has a jump. Therefore, it is improper to ignore the difference of inertia near the discontinuities. In experiment, one can observe that the discontinuity has certain thickness, though it is very thin. The transition from the upper dilute section to the lower dense section in the collapse process is analyzed using GTFM.

According to the experimental observation, the discontinuity speed V_s does not change during the collapse process (it can also be derived from LEM, Eq. 19). First, we make a coordinates transform, using a moving coordinate ξ with the discontinuity speed V_s to substitute the laboratory coordinate x, i.e., $\xi = x - V_s t$, so Eqs. (1) and (3) can be transformed into

$$\frac{\mathrm{d}[\alpha_p(u_p - V_S)]}{\mathrm{d}\xi} = 0 \qquad (26)$$

$$\rho_p(u_p - V_s)\frac{\mathrm{d}u_p}{\mathrm{d}\xi} - \rho_f(u_f - V_s)\frac{\mathrm{d}u_f}{\mathrm{d}\xi} = \frac{F_p}{\alpha_p\alpha_f} - (\rho_p - \rho_f)g + \frac{1}{\alpha_p}\frac{\mathrm{d}(-p_p + \tau_{p,xx})}{\mathrm{d}\xi} \qquad (27)$$

Eqs. (7), (8), (9) and (11) are used to model the drag force F_p, virtual mass force F_{vm}, solid phase pressure p_p and viscous coefficient μ_p respectively, where s, C_{vm} and C_μ are model parameters.

Letting $\rho_r = \rho_f/\rho_p$, $L_a = \alpha_{p,1}\alpha_{p,2}(\alpha_{f,2}^n - \alpha_{f,1}^n)/(\alpha_{p,1} - \alpha_{p,2})$, $L_b = \alpha_{f,1}\alpha_{f,2}(\alpha_{p,1}\alpha_{f,1}^{n-1} - \alpha_{p,2}\alpha_{f,2}^{n-1})/(\alpha_{p,1} - \alpha_{p,2})$, $L_c = \alpha_{p,c}/(\alpha_{p,c} - \alpha_p)^2$, $L_d = \frac{3}{4}C_\mu(1-\rho_r)gd_p/u_T^2$, $Y = \xi(1-\rho_r)g/u_T^2$, $B = sL_a/\alpha_p - (1 + C_{vm}\rho_r/\alpha_f)L_a^2/\alpha_p^3 - \rho_r(1 + C_{vm}/\alpha_f)L_b^2/\alpha_f^3$, $Q = 1 - \left[\alpha_{p,1}\alpha_{f,1}^n/(\alpha_{p,1} - \alpha_{p,2}) - \alpha_{p,2}\alpha_{f,2}^n/(\alpha_{p,1} - \alpha_{p,2}) + L_a/\alpha_p\right]\alpha_f^{-n}$, one can get $u_p = V_s - L_a u_T/\alpha_p$ and $u_f = V_s + L_b u_T/\alpha_f$ from Eqs. (26) and (2). Introducing them into Eq. (27) yields

$$B\left(\frac{\mathrm{d}Y}{\mathrm{d}\alpha_p}\right)^{-1} = -Q - L_d L_a\left[\frac{1}{(\alpha_{p,c} - \alpha_p)\alpha_p^3}\left(\frac{\mathrm{d}Y}{\mathrm{d}\alpha_p}\right)^{-3}\frac{\mathrm{d}^2Y}{\mathrm{d}\alpha_p^{\,2}} + \frac{2\alpha_{p,c} - 3\alpha_p}{(\alpha_{p,c} - \alpha_p)^2\alpha_p^4}\left(\frac{\mathrm{d}Y}{\mathrm{d}\alpha_p}\right)^{-2}\right]$$

For a small value of C_μ, the above equation can be approximated as

$$\frac{\mathrm{d}Y}{\mathrm{d}\alpha_p} \approx -\frac{B}{Q} \times \left\{1 - L_d L_a\left[\frac{1}{(\alpha_{p,c} - \alpha_p)\alpha_p^3}\frac{B'Q - BQ'}{B^3} + \frac{2\alpha_{p,c} - 3\alpha_p}{(\alpha_{p,c} - \alpha_p)^2\alpha_p^4}\frac{Q}{B^2}\right]\right\} \qquad (28)$$

where B' and Q' are the derivatives of B and Q to α_p respectively.

The asymptotic conditions are: $Y \to +\infty$ when $\alpha_p \to \alpha_{p,2}$, and $Y \to -\infty$ when $\alpha_p \to \alpha_{p,1}$. Integrating Eq. (28), the line for $\alpha_p(Y)$ is shown in Fig. 5. For comparison, the result about $\alpha_p(Y)$ computed from LEM is also shown in it (represented by a solid line, there is a discontinuity at $Y = 0$).

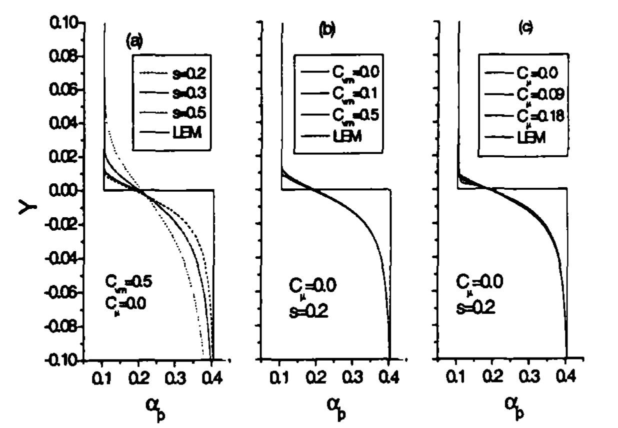

Fig. 5 Influence of s, C_{vm} and C_μ on the structure of the transitional layer

From the results above, one can see that the particle concentration gradually transits from the upper dilute section to the lower dense section when the inertial force, solid phase pressure, viscous stress, and virtual mass forces are considered in GTFM. The thickness of the transition layer depends on the values of coefficients s, C_{vm} and C_μ. Letting the three coefficients be zero and only maintaining the inertia terms of the two phases, TFM becomes ill-posed for initial-value problems [10]. Therefore, the three forces are very important. Further researches show that the most important term is the solid phase pressure and the variation of the coefficient s greatly influences the thickness of the transition layer (Fig. 5a). When the coefficient s is small (its exact value depends on C_{vm} and C_{μ}, generally speaking, when it is less than $0.1 \sim 0.2$), the correct solution does not exist. C_{vm} and C_{μ} may be zero (Fig. 5b and c), but s can not be.

However, the above results are only of qualitative significance, because the models used in this paper for virtual mass force F_{vm}, solid phase pressure p_p and viscous coefficient μ_p can not be accurately determined and the values are chosen at will to some extent.

It is not true that the thickness of transition layer is zero and there is a jump for every parameter through the discontinuity according to LEM. In fact, the transition layer has certain thickness and every parameter transits smoothly (but quickly). However, this layer is very thin (commonly it is only several millimeters, equivalent to several times of particle diameter), LEM is approximately proper except for the sections near the discontinuity planes.

In order to get reasonable results from GTFM, the principle for choosing the coefficients s、C_{vm} and C_{μ} is to insure the eigenvalues be real numbers firstly, then to let them be small enough because the too thick transitional layer does not fit the result observed in the experiment.

The errors in the simulation results from LEM only exist in a time interval of tens of milliseconds (several times of particle relaxation time) and a spatial interval of several millimeters (several times of particle diameter) when simulating the pulsed flow in the fluidized bed. The above limitations of LEM are insignificant for practical simulation.

DISCUSSIONS AND CONCLUSIONS

1) It is visually observed that concentration waves and shock waves continuously travel upwards from the distributor as the pattern of a planar wave, resulting from the periodical variation of fluidizing velocity $U(t)$ (see Fig.1), which demonstrates that the pulsating two-phase flow in the bed is almost one-dimensional. The good agreement between the numerical results and experimental data further accounts for the rationality of the one-dimensional model for the flow studied in the paper.

2) Although GTFM is a general model, in which various influencing factors such as solid phase pressure p_p, viscous stress $\tau_{p,xx}$ and virtual mass force F_{vm} are included, researches on the constitutive relationships of p_p, $\tau_{p,xx}$ and F_{vm} for closing the model are not yet satisfying, the expressions used in different literatures are distinct from each other. For a particular choosing of constitutive relationships of p_p, $\tau_{p,xx}$ and F_{vm}, a group result of the flow in pulsed bed can be gotten by numerically solving GTFM, however, these results imply great undeterminedness due to the adjustable coefficients in these constitutive relationships.

3) Just as the detailed information in the wall boundary layer of the single-phase flow is lost when Navier-Stokes equation set is simplified into Euler equation set, LEM loses the capability to capture some details of the two-phase flow in pulsed fluidized bed.

The velocities of the two phases get different increments because of the different inertia of the two phases when fluidizing velocity has a jump change. The aftereffect caused by the different inertia vanishes after a short relaxation process following the jump change. In LEM, the different increments for the velocities of the two phases and the relaxation process following that are lost because the difference of the inertial forces is neglected.

The concentration shock obtained from LEM is a geometrical surface without any thickness for the same reason that the difference of the inertial forces is neglected. In fact, the very large gradients of concentration and velocities are finite in strength near the discontinuities in the flow field, the difference of the inertial forces is also very important near the discontinuities, thus making the concentration shocks have certain thickness. The flow structure in concentration shock is lost using LEM.

The relaxation process after the jump change of fluidizing velocity is very short (only tens of milliseconds, i.e., several times of system relaxation time) and the real thickness of the concentration shocks is very thin (only several millimeters, i.e., several times of particle diameter), so the above limitations of LEM are insignificant for practicality.

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REFERENCES

1. Needham D. J. and Merkin J. H., The Propagation of a Voidage Disturbance in a Uniformly Fluidized Bed, J. Fluid Mech., 131: 427-454, 1983.
2. Köksal M. and Vural H., Bubble Size Control in a Two-Dimensional Fluidized Bed Using a Moving Double Plate Distributor, Powder Technol., 95: 205-213, 1998.
3. Pence D. V. and Beasley D. E., Heat Transfer in Pulse-Stabilized Fluidization - Part 1: Overall Cylinder and Average Local Analyses, Inter. J. Heat Mass Transfer, 45: 3609-3619, 2002.
4. Slis P. L., Willemse T. H. W. and Kramers H., The Response of the Level of a Liquid Fluidized Bed to a Sudden Change in the Fluidizing Velocity, Appl. Sci. Res., Section A(8): 209-218, 1959.
5. Gelderbloom S.J., Gidaspow D. & Lyczkowski R.L., CFD simulations of bubbling/Collapsing fluidized beds for three Geldart groups. AIChE J., 49(4): 844-858, 2003.
6. Jin G. D., Nie Y. S. and Liu D.Y., Numerical Simulation of Pulsed Fluidization and Its Experimental Validation, Powder Technol., 119: 153-163, 2001.
7. Duru P., Nicolas M., Hinch J. and Guazelli É., Constitutive Laws in Liquid-Fluidized Beds, J. Fluid Mech., 452: 371-404, 2002.
8. Jiang G.-S. and Shu C.-W., Efficient Implementation of Weighted ENO Schemes. J. Comput. Phys., 126: 202-228, 1996.
9. Jin G. D., Numerical Simulation of Liquid Pulsed Fluidization and Its Experimental Validation. Doctorial Dissertation, Institute of Mechanics, Chinese Academy of Sciences, 2003.
10. Lyczkowski R. W., Gidaspow D., Solbrig C.W. and Hughes E. D., Characteristics and stability analyses of Transient one-dimensional two-phase flow equations and their finite difference approximations, Nuclear Sci. & Eng., 66: 378-396, 1978