The Characteristics of Wave Propagation in a Vibrating Fluidized Bed

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Based on experiments, this paper describes that the vibration energy imported to a packed bed is through the collision between the vibration plate and the bed, and the vibration energy imported to a fluidized bed is through continuous wave propagation. A new type sensor was used to measure the wave signals in VFB. The wave characteristics are affected by bed properties. By analyzing the wave frequency spectrum, the bubble's behavior in the bed can be followed.

1 Introduction

When vibration is introduced into a fluidized bed, the minimum fluidization velocity (u_{mf}) is reduced, and the efficiency of gas-solid contact is increased [1, 2]. Thus, the vibrating fluidized bed (VFB) has been widely used in drying, cooling, mixing, heat treatment, separation processes, etc.

When an ultrafine powder needs to be fluidized, it is seriously affected by the van der Waals forces, because of the particles' large specific surface area [3, 4]. For obviously cohesive characteristics, it can not be well fluidized under conventional conditions. When gas flows, channels are formed [5, 6]. It can be fluidized only at high gas velocity as the particles agglomerated [7, 8]. Because of a VFB's advantages, it can be used as a chemical reactor to treat the ultrafine powder at lower gas velocities in order to increase the gas and solid conversion and control the reaction process efficiently.

Kroll studied the vibrating bed (VB) with no gas flow and proposed a model in which the gas was regarded as incompressible and the bed as a rigid body [9]. Gutman considered gas to be compressible and proposed another VB model [10]. Akiyama et al. [11–13] retreated Gutman's model with a numerical calculation and explained the model in two parts: when the bed acceleration is lower than that of the vibration plate, the bed and the plate move together while they collide, when the bed acceleration is greater than that of the plate, the bed leaves the plate once they collide due to its throwing action. It was derived that the collision point on the displacement curve of sinusoidal shape shifts backwards as the bed acceleration increases.

In the published literature, VFB studies were based on the mechanism of the collision between the vibration plate and the bed. It can be used to explain the experimental phenomenon in a shallow fluidized bed [14]. But when the bed height is enlarged, for the case that the reactor demands a high filling capacity, the fluidized bed can not be regarded as a rigid body. In that case, the interaction of particles can not be neglected, and the action of gas on particles obviously affects the interaction between the vibration plate and the bed. Therefore, the collision mechanism needs to be reconsidered.

2 Vibrating Bed and Vibrating Fluidized Bed

The experimental apparatus is shown in Fig. 1. The electromagnetic vibration plate provides a sinusoidal vibration in the vertical direction. The vibration strength is adjusted by changing the driving electric current, and the vibration frequency is kept constant. The experimental powder is Geldart A group magnetite beads with a density of 3.5 g/
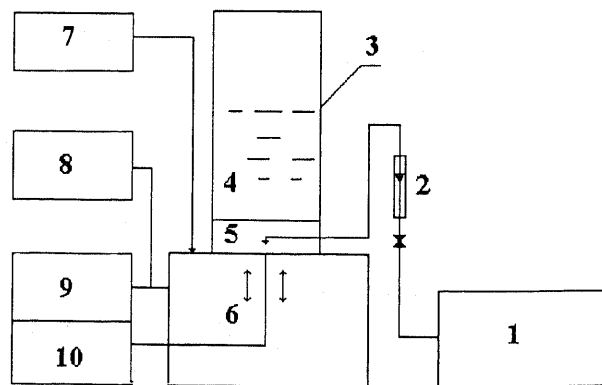

Figure 1. Schematic diagram of the VB and VFB experimental apparatus. 1. Compressed air source, 2. flowmeter, 3. vibration body, 4. powder bed, 5. air chamber, 6. electric-magnetic vibration plate, 7. displacement measurement, 8. frequency measurement, 9. vibration source, 10. oscilloscope.

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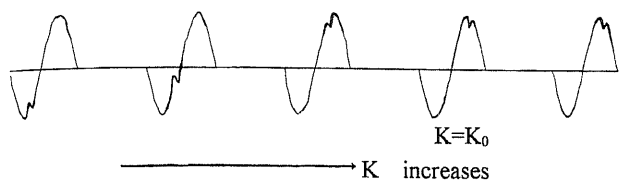
Figure 2. The change of collision point between the vibration plate and the bed as the vibration strength increases.
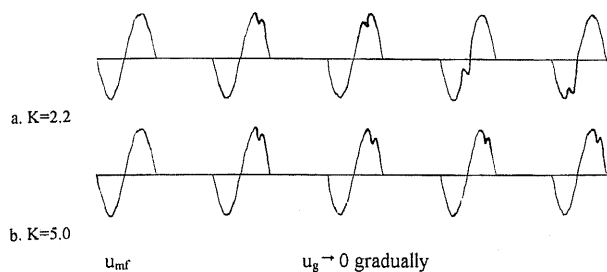

a. K=2.2

b. K=5.0

u_{mf} $u_g \rightarrow 0$ gradually

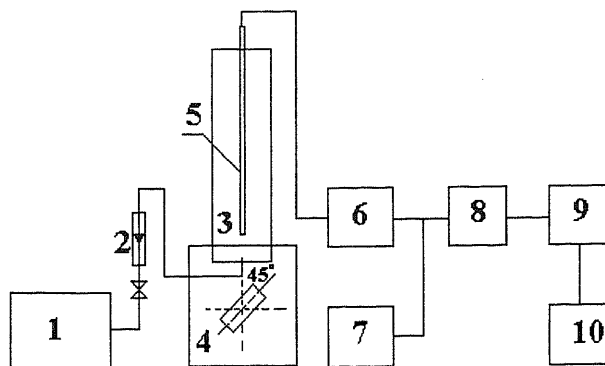Fibure 3. The effects of gas velocity on the collision point.

Figure 4. The experimental apparatus for wave measurement. 1. Compressed air, 2. flowmeter, 3. fluidized bed, 4. vibration plate, 5. pressure sensor, 6. amplifier, 7. oscilloscope, 8. cassette recorder, 9. A/D convertor, 10. computer.

cm^3, a bulk density of 1.75 g/cm^3, and a size of 76–41 μm.

The cyclical force is transferred to the bed by collisions in the VB. The collision characteristics are different as the vibration parameters change. The impulsive force of the collision forms a disturbed point on the displacement curve of the vibration plate. It is shown in Fig. 2 that the disturbed point changes as the vibration strength changes with the experimental frequency in the range of 30 to 60 Hz. The experimental results are consistent with the Akiyama model.

In order to study the interaction between the vibration plate and the bed, the bed is allowed to stably fluidize for a given time; afterwards the gas velocity is reduced to u_{mf}, then the air source is cut off. The compressed air in the chamber passes through the bed smoothly. A sensor is used to monitor the displacement curve of the vibration plate. Fig. 3 shows that the curve shape changes when the gas velocity is adjacent to u_{mf}, and the position of disturbed point changes as the gas velocity decreases, which is the reverse process of gas velocity continuously increasing.[1] By comparing Figs. 2 and 3 a, it can be found that whether increasing the vibration strength or gas velocity, the changing tendency of disturbed point is the same. It means that the vibration seems to have a similar function of the gas flow to a certain extent. When the operation gas velocity (u_g) is lower than u_{mf}, the disturbed point exists no matter how strong the vibration strength is, and the interaction type must be a collision.

The disturbed point on the displacement curve diappears when the gas velocity reaches u_{mf} at any vibrating frequency. It shows that the type of interaction between the plate and the bed has changed. In this case, the fluidized

bed is similar to an elastic medium; thus, the action of vibration on the bed can be considered as a continuous wave propagation process in a pseudo-continuous and pseudo-elastic medium.

3 The Measurement of Wave Characteristics in a VFB

In the fluidized bed, the interaction of the vibration plate on the bed can be regarded as a continuous wave propagation by which the energy is imported to the fluidized bed. It can also be demonstrated by the following experiments.

The other experimental apparatus is shown in Fig. 4. Two vibration motors are cross mounted at 90° angles to produce a complex vibration. Mori [15, 16] reported that complex vibration is better than single directional vibration. The bed's motion can be separated into x, y, and z directions, and each of these can be independently detected. The agglomerated particles of goethite with an average size of 20.3 μm and a bulk density of 0.4–0.6 g/m^3 are used as the experimental powder, which belong to the C group powder by Geldart classification. Fig. 5 shows the size distribution. The still bed height is 300 mm.

An electric vortex transducer is used to measure the displacement signals of the vibration plate. An electret condenser microphone, which possesses high sensitivity and a good linear property, is used to measure the pressure wave signals in the bed. A thin film is pasted carefully at the sensor terminal to protect the electret film. The finished sensor's sensitivity is 0.891 mv/Pa. The output signal is amplified 35.8 times, and the amplified signal is sampled by a computer. Because the fibration frequency is about 30 to 80 Hz, the sample frequency, f_s, is taken as 1500 Hz, which keeps the signal's original character. Fig. 6 shows the wave signals and its frequency spectrums at different heights measured in the fluidized bed along the axial direction. The analysis shows that the dominant frequency of the pressure wave is consistent with the vibration frequency of the vibration plate.

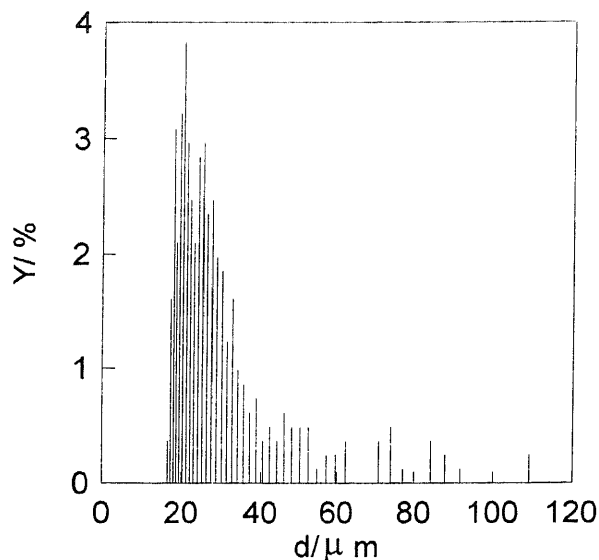1) List of symbols at the end of the paper.

Figure 5. The size distribution of the experimental powder.

Figure 6. The pressure wave and its frequency spectrum ($u=0.6$ cm/s, $f=30$ Hz, $A=0.35$ mm).

Based on the wave propagation principle, the phase-delay of the sine wave should exist along the wave propagation direction if there is indeed a wave propagation process in the bed. The pressure wave and the vibration displacement signals are sampled by computer.

Suppose $\Delta\phi$ is the phase-delay between the dominant frequency signals of the pressure wave in the bed and the displacement signals of vibrating plate; $\Delta\phi_5$ is the phase-delay at the position of 5 cm above the distributor. $\Delta\phi_{30}$ is the phase-delay at the position of 30 cm above the distributor. Then:

$$(\Delta\phi_5 - \Delta\phi_{30}) = \frac{2\pi}{\lambda}\Delta z \tag{1}$$

$$\bar{\lambda} = 2\pi \, 0.25/(\Delta\phi_5 - \Delta\phi_{30}) \tag{2}$$

$$\bar{U} = \bar{\lambda}f = 0.25\,\omega/(\Delta\phi_5 - \Delta\phi_{30}) \tag{3}$$

Tab. 1 shows the average wave propagation parameters. It can be seen that the wave does propagate in the fluidized bed, and the gas velocity and vibration frequency affect the average wave length and wave velocity. The wave length is shorter than in air or a solid, and the wave velocity is lower than in air or a solid, but the bulk density of the fluidized bed is between the two media. The pseudo-fluid density of the bed is different due to the bed voi-
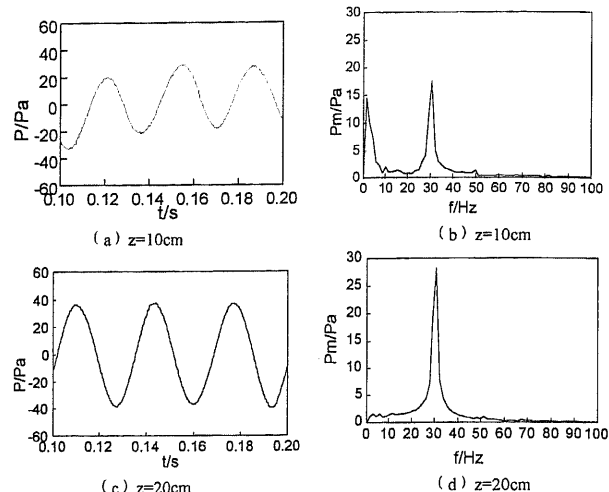
dage change at different gas velocities. The bed parameters naturally affect the wave propagation because the suspended powder bed is a propagation medium.

In fact, because the powder of the fluidized bed is in a suspended state, the action force from the vibration plate to the bed is transferred by the gas flow. The gas flow links the suspended particles by a pseudo-elastic action of drag force. When the vibrating plate transfers the cyclical force to the gas flow, a cyclical pressure acting on the suspended particles is produced. It forces the suspended particle to vibrate roughly at the same pace. The cyclical pressure, changing with time, is in the form of a sine function at any position.

4 Wave Propagation in VFB

Moving the electret sensor along the axial direction, the local wave parameters in the fluidized bed can be detected. They are measured and recorded at different positions at a specific vibration frequency and gas velocity. The wave amplitude of the dominant frequency at the frequency spectrum is taken as the nominal wave amplitude. Because the wave signals are disturbed by bubbles, some instantaneous signal values may be very large.

Fig. 7 shows that the wave amplitudes change along the bed height at different u_g values, with $f=30$ Hz and

Table 1. The average wave parameters in the fluidized bed.

u (cm/s)	f (Hz)	$\Delta\phi_5$ (arc)	$\Delta\phi_{30}$ (arc)	$\Delta\phi$ (arc)	$\bar{U}$ (m/s)	$\bar{\lambda}$ (m)
0.6	30	1.62	1.04	0.58	81	2.7
0.6	40	1.58	1.18	0.41	154	3.9
1.0	30	2.19	1.39	0.76	62	2.1
1.0	40	1.66	1.02	0.62	101	2.5
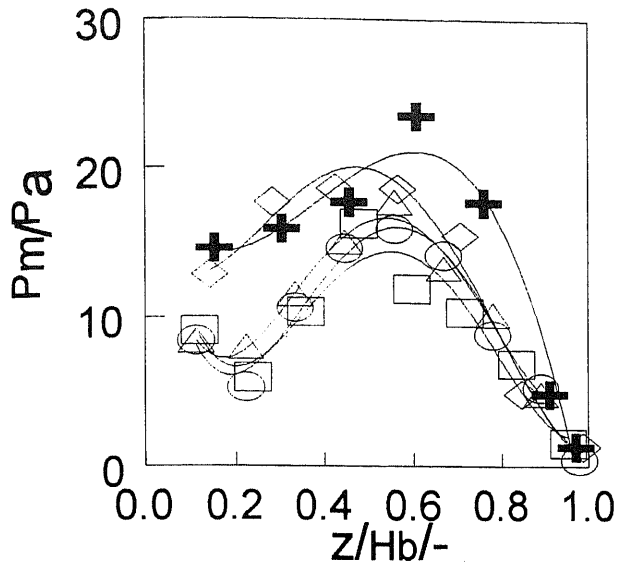
Figure 7. The change of pressure wave amplitude along the height; u cm/s: +0.6; ◇1.0; □1.5; ○2.0; △3.0.
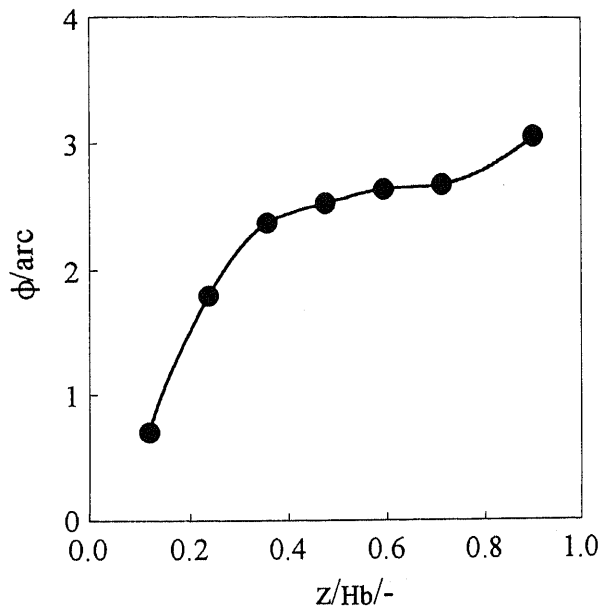

Figure 8. The phase-delay of the pressure wave along the height.

$A=0.35$ mm. Fig. 8 shows the wave phase-delay changing along axial direction at $f=34$ Hz.

According to the wave propagation equations:

$$P(t, z) = P_m(z) \sin(\omega t + 2\pi z/\lambda(z)) \tag{4}$$

$$\Delta\phi = 2\pi \Delta z/\bar{\lambda} \tag{5}$$

$$\frac{\Delta\phi}{\Delta z} = \frac{2\pi}{\lambda} \tag{6}$$

$$\Delta_z \to 0 \quad \frac{\partial\phi}{\partial z} = \frac{2\pi}{\lambda(z)} \tag{7}$$

$$\lambda(z) = 2\pi \left/ \frac{\partial\phi}{\partial z}\right. \tag{8}$$

$$U(z) = f\lambda(z) = \omega \left/ \frac{\partial\phi}{\partial z}\right. \tag{9}$$

The wave propagation properties are not uniform along the axis because the fluidized bed is not uniform as a wave propagation medium. The wave parameters change along the axial direction not only in amplitude, but also in wave length and wave propagation velocity, which reflect the characteristics of the fluidized bed, such as voidage distribution. The relation between the wave propagation properties and the bed properties needs to be studied further.

5 The Bubble Behavior in a VFB

A low-frequency disturbance in the pressure wave spectrum occurs when bubbles pass through the bed. For this reason the bubble disturbance can be detected by the wave sensor. The bubble frequency and characteristics in the bed can be studied from the low-frequency fraction in the frequency spectrum. Experiments were carried out to analyze the bubble behavior. It was found that little low-frequency fraction in the frequency spectrum can be obtained when no bubble appears. The low-frequency fraction obviously exists when the gas velocity is more than the value at which bubbles appear. As u_g increases, the fraction of low-frequency disturbances also increases.

The pressure wave signals and their frequency spectra for different gas velocities at $z=10$ cm are shown in Fig. 9. When $u_g>0.6$ cm/s, the wave is obviously disturbed by violent fluctuations, which have a frequency of several Hz. With an increase of the gas velocity, the amplitude of the low-frequency fraction increases as gas velocity increases, but the bubbling disturbance frequency roughly remains the same. It shows that the bubbles become larger at the position.

The pressure wave signals and their frequency spectrum with different gas velocities at $z=20$ cm are shown in Fig. 10. We can see that the low-frequency disturbance just appears until $u_g>2.0$ cm/s. Comparing Figs. 9 and 10, it is obvious that the fluidization is better in the upper part of the bed where the small bubbles exist.

The above analysis shows that the fluidization behavior near the distributor, where bubbles form and aggregate, is controlled by the air distributor. The rising bubbles become finer and the gas-solid contact becomes more uniform because of the vibration effect. We can concluded that the VFB is obviously different from the conventional fluidized bed in which bubbles become larger along the bed height.
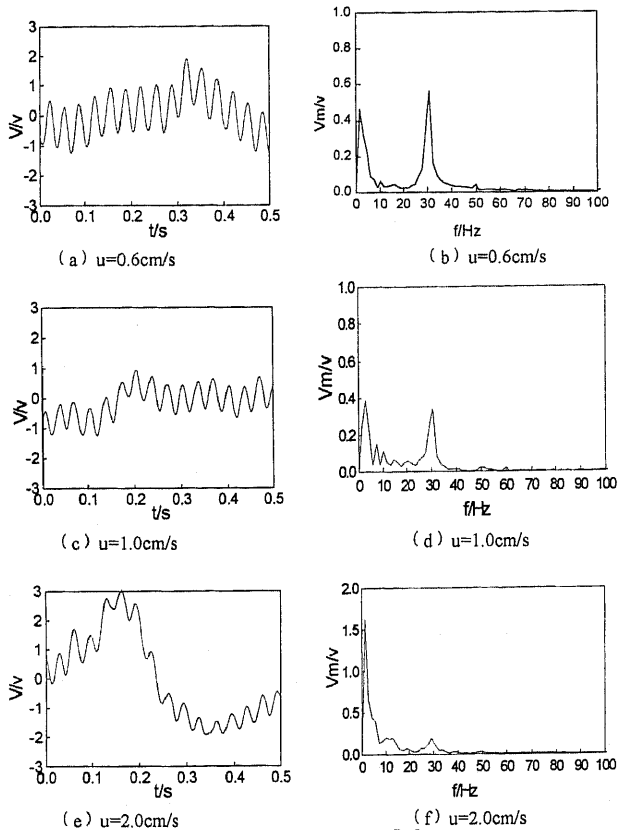
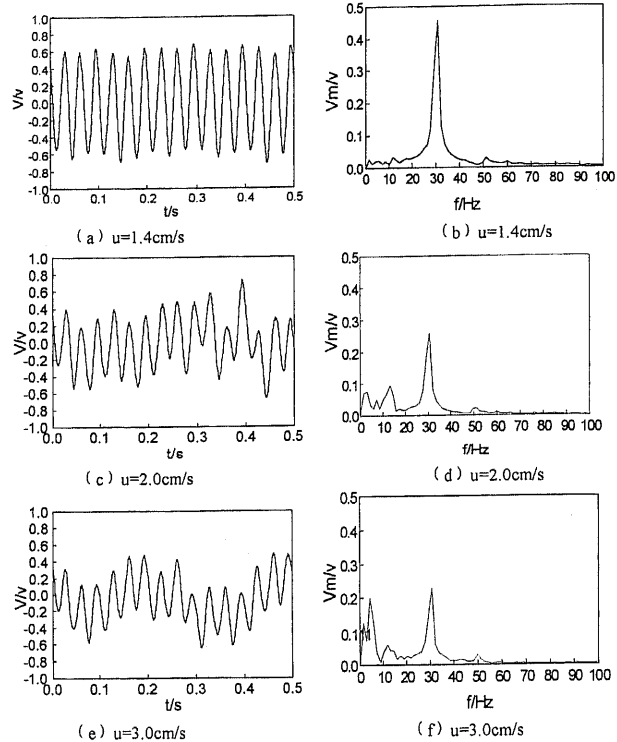Figure 9. The bubble disturbance on the pressure wave and its frequency spectrum at $z=10$ cm. ($f=30$ Hz, $A=0.35$ mm).

Fig. 10. The bubble disturbance on the pressure wave and its frequency spectrum at $z=20$ cm ($f=30$ Hz, $A=0.35$ mm).

6 Conclusions

In the VB the interaction between the vibration plate and the packed bed is by the collision of two bodies. Whereas, in the VFB the action of the vibration plate on the fluidized bed can be considered as a continuous wave propagation in a pseudo-continuous and pseudo-elastic medium. The wave propagation in the fluidized bed is not uniform along the axial direction. The pressure wave amplitude, wave length, propagation velocity, and other parameters change with local properties. The wave propagation velocity is lower than in air or solid. Wave detection can be used to investigate bubble behavior. Research results showed that the vibration can shear bubbles and form a better gas-solid contact because the particle motion was enhanced by the vibration wave.

Symbols used

A	[mm]	vibration amplitude
f	[Hz]	vibration frequency
f_s	[Hz]	sampling frequency
H_b	[cm]	expansion height
K	[–]	vibration strength
P_m	[N/m^2]	pressure wave amplitude
t	[s]	time
u	[cm/s]	gas velocity
U	[m/s]	wave propagation velocity
V	[v]	electric wave signals
X	[m]	vibration displacement
Y	[%]	weight percent
z	[cm]	height from the distributor

Greek symbols

ρ	[g/cm^3]	fluid density
ω	[Hz]	angular frequency
ϕ	[arc]	phase
λ	[m]	wave length
ε	[–]	bed voidage

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