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THE EFFECT OF VIBRATION ON BED VOIDAGE BEHAVIORS IN FLUIDIZED BEDS WITH LARGE PARTICLES

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Abstract - The effects of vibration parameters, operating conditions and material properties on bed voidage were investigated using an optical fiber probe approach in a vibrating fluidized bed with a diameter of 148 mm. Variables studied included frequency (0-282 s^{-1}), amplitude (0 mm-1 mm), bed height (0.1 m-0.4 m) as well as four kinds of particles (belonging to Geldart's B and D groups). The axial and radial voidage distribution with vibration is compared with that without vibration, which shows vibration can aid in the fluidization behaviors of particles. For a larger vibration amplitude, the vibration seriously affects bed voidage. The vibration energy can damp out for particle layers with increasing the bed height. According to analysis of experimental data, an empirical correlation for predicting bed voidage, giving good agreement with the experimental data and a deviation within ±15%, was proposed.
Keywords: Vibrating fluidized beds; Voidage; Vibration intensity.

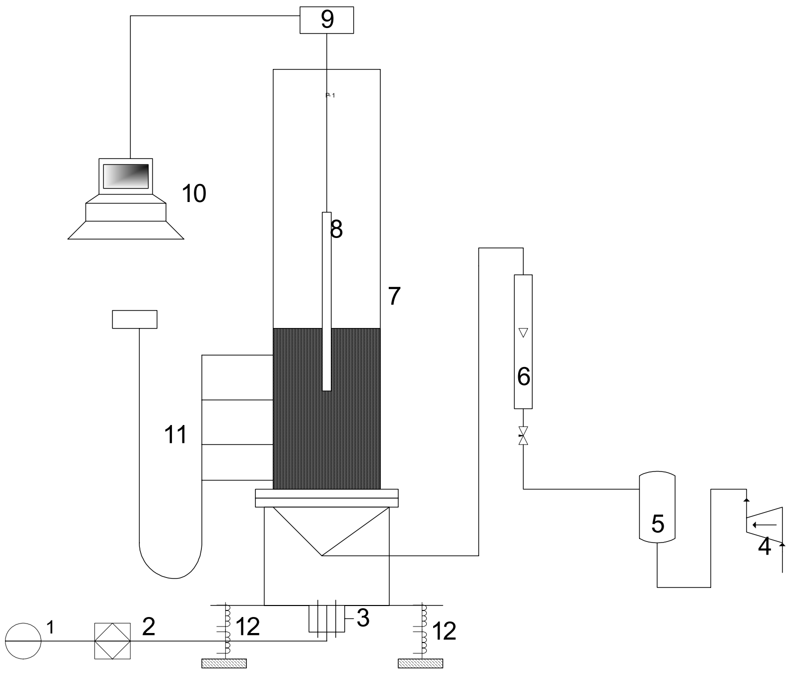
INTRODUCTION

The vibrating fluidized bed has been widely employed in a variety of physical and chemical processes (Bratu and Jinescu, 1972; Gupta and Mujumdar, 1980). The advantages of the vibrating fluidized bed over the conventional fluidized bed include increased efficiency of gas-solid contact, reduced minimum fluidization velocity and fluidization pressure drops and increased homogeneity and stability of the fluidized bed layers. These advantages can be used in drying, cooling, heating, separating and mixing processes, chemical reactions, etc.

In recent years, there has been growing interest in utilizing mechanical vibration to improve the performance of a fluidized bed for group C powder or wet powders in the processing of particles. Mori et al. (1990) studied fluidization characteristics of group C particles in a vibrofluidized bed and found that bed expansion with vibration could be obtained at low superficial gas velocities. Jataiz et al. (1992) estimated the interparticle forces for fine particles based on expansion and pressure drop experiments. Marring et al. (1994) studied the effect of vibration on fluidization behavior of cohesive potato starch that did not fluidize in a conventional fluidized bed. Noda et al. (1998) gave the flow patterns of fine particles in a vibrating fluidized bed under atmospheric or reduced pressure. Mawatari et al. (2002b, 2003) examined the effects of vibration and particle diameter on flow patterns and fluidization characteristics, including minimum fluidization velocity, voidage and the bed expansion ratio for

*To whom correspondence should be addressed group A and C powders. Meanwhile, the minimum fluidization velocities for the vibrating fluidized beds of group A and C particles were predicted. Silva-Moris et al. (2003) studied the fluidization behavior of dry adipic acid with 75-600 μm particle diameters using mechanical vibration for different sample loads. Tatemoto et al. (2005) adopted the discrete element method to simulate cohesive particle motion characteristics in vibrating fluidized beds. Wang et al. (2000, 2002) analyzed the resonance characteristics and bed wave propagation process and reported the energy transfer mechanism in a vibrating fluidized bed.

However, there are few studies of the effect of vibration on bed voidage for large particles in the literature. Chenvilank et al. (1979) obtained the correlation of bed voidage in a vibrating fluidized bed using a capacitance probe, which only included fluidization velocity and vibration parameters. Erdesz and Ormos (1983) simply described the relationship between the bed expansion and vibration parameters. Hunt et al. (1994) studied the relationship between expansion ratio and vibration parameters in a shallow vibrated bed. Mawatari et al. (2002a) studied the void fraction at the minimum fluidization velocity and the expansion ratio for group A. The effect of vibration on bed voidage of dense medium in separation processes of mixtures decides the separation efficiency and the moving direction of particles (Jin et al., 2004, 2005; Liu et al., 1998). Therefore, bed voidage is one of the important factors in designing and scaling-up the vibrating fluidized bed. In this study, the effect of vibration on bed expansion characteristics is presented using a PC-4 optical fiber probe. The profile of voidage is observed for large particles under certain experimental conditions. The vibration parameters and operating conditions have some significant effects on the bed expansion characteristics.



1. power;
2. inverter;
3. vibrator;
4. blower;
5. banker;
6. flowmeter;
7. fluidized bed;
8. optical fiber probe;
9. A/D converter;
10. computer;
11. pressure gauge;
12. spring.

Figure 1: Experimental apparatus

EXPERIMENTAL SECTION

Experimental Apparatus

The experiments were carried out in a steel column with 0.148 m diameter and a 1.20 m height as shown in Figure 1. Air was supplied through the distributor, consisting of a perforated steel plate and a sheet of textile. The perforated steel plate was 1.2 mm thick with 2 mm diameter holes and a free area of 9.16 percent. The textile was of type 120-7 and 1.42 mm thick. A hydraulic vibrator under the bed generates a sinusoidal waveform. The vibration frequency was determined by an inverter (Japan Sanken Corp, SSF-552) and the amplitude was measured by an optical microscope (±0.02 mm). The experimental conditions are summarized in Table 1.

The vibration radian frequency (ω) could be calculated with the equation $\omega=2\pi f$. Vibration intensity (K) can be defined as the ratio of acceleration of vibration to that of gravity, as follows:

$$K = A\omega^2 / g = A(2\pi f)^2 / g \quad (1)$$

where a is amplitude, g is gravitational acceleration, ω is angular frequency and f is frequency of vibration.

The local voidage signals were collected by a data acquisition system consisting of an optical fiber probe (PC-4, Institute of Process Engineering, CAS), an analog/digital converter and a personal computer. The optical fiber probe was suspended from the top into the fluidized layer, which decreased the effect of vibration on the experimental data. The data used to derive the axial local voidage was sampled at different fixed fluidization velocities and vibration intensities.

The sampling time was about 30-40s at a sampling frequency of 150 Hz. Several materials with different vibration parameters and different operating conditions were used in the experiments. The physical properties are listed in Table 2.

Table 1: Experimental Conditions

Parameter	Range of parameter
Frequency f (Hz)	0, 10, 15, 20, 25, 30, 35, 40, 45
Amplitude A (mm)	0, 0.41, 0.75, 1.01
Static bed height H_0 (mm)	100, 150, 200, 300, 400
Vibration intensity $K=a\omega^2/g$	0-8.24
u/u_{mf}	1.0-3.0

Table 2: Physical Properties of the Particles

Particle	Particle size d_p (mm)	Particle density ρ_s (kg/m^3)	Φ_s	Minimum fluidization velocity in absence of vibration u_{mf} (m/s)	Voidage at minimum fluidization velocity ε_{mf}
Millet	1.64	1330	0.90	0.43	0.407
Resin	0.94	1474	1.00	0.19	0.416
Glass beads	0.72	2660	1.00	0.72	0.414
Sand	0.30	2560	0.71	0.12	0.510

Measurement Method

The bed voidage of the vibrating fluidized bed is measured by a PC-4 optic fiber probe. The probe has two bundles of fibers. One transmits light from the light source and projects it onto a swarm of particles; the other transmits light reflected by the particles to a photomultiplier where the light signals are converted into electrical signals. The voltage output is proportional to the intensity of the reflected light. The electrical signals are then transformed into concentrations, which are displayed or stored in the computer. This allows the fluctuating deviations of bed voidage to be compared. Each bundle of fibers is composed of some thousands of optic fibers, which are 16 μm in diameter. Prior to the experiments, the probe was calibrated using the methods described by Qin and Liu (1982).

The PC-4 optic fiber probe made measurement at six levels: 50 mm, 100 mm, 150 mm above the top of the distributor –37 mm and +37 mm from the axis at 100 mm and 200 mm static bed heights, respectively. For the 300 mm and 400 mm static bed heights, eight points were measured. For radial voidage, the probe measured at three levels: 0 mm, 37 mm and 70 mm from the axis. For every experimental condition, 4500 points or 6000 points were sampled at a sampling rate of 150 Hz. The signals were either stored on a hard disk or processed online. The sensor signals were later used to analyze the voidage behaviors of the bed. In order to reduce the fluctuating effect on bed voidage during vibration and fluidization, each point was measured three times and the mean concentration of particles was obtained by averaging.

The Correction of Overall Bed Voidage

In classical fluidization, some researchers found that bed expansion depended on the function of fluidization velocity, $\frac{H_f}{H_{mf}} = f(u)$. But in vibrating fluidization, the fluidization velocity may impede the bubbles and improve particle motion. Meanwhile, the bed height and properties of the particles can also directly affect the transfer of vibration energy and the bed layer stability. Besides the fluidization velocity, there are the effects of vibration parameters and bed height on bed expansion. The bed expansion should give the following relationship: $\frac{H_f}{H_{mf}} = f(u, H_0, A, \omega)$. From the additional height at fluidization and the height at the minimum fluidization, the bed expansion ratio can be obtained as follows:

$$m = \frac{H_f - H_{mf}}{H_{mf}} = \frac{1-\varepsilon_{mf}}{1-\bar{\varepsilon}} - 1 = \frac{\bar{\varepsilon} - \varepsilon_{mf}}{1-\bar{\varepsilon}} \tag{2}$$

To use these parameters, which include the vibration intensity (K), the fluidization velocity ratio (u/u_{mf}), and the ratio of vibration amplitude to static bed height (A/H_0), an expansion ratio is defined

$$\frac{\bar{\varepsilon} - \varepsilon_{mf}}{1-\bar{\varepsilon}} = 1 - a_0 \left(\frac{A}{H_0}\right)^{a_1} \exp\left[a_2\left(\frac{u}{u_{mf}} - 1\right)\left(\frac{A\omega^2}{g}\right)^{(a_3 u_{mf}/u)}\right] \tag{3}$$

When $u=u_{mf}$ without vibration, $\bar{\varepsilon} = \varepsilon_{mf}$. The energy transfer is damped out with an increase in fluidization velocity, and the bed expansion ratio directly increases. This reflects that the relationship of parameters in the corralation is very rational. Chevileank et al. (1979) gave a correlation for bed voidage including the vibration intensity to fluidization velocity ratio as follows:

$$\frac{\bar{\varepsilon} - \varepsilon_{mf}}{1-\bar{\varepsilon}} = 1 - \exp\left[-0.54\left(\frac{u}{u_{mf}} - 1\right)\left(\frac{A\omega^2}{g}\right)^{(0.75 u_{mf}/u)}\right] \tag{4}$$

So we give a correlation for bed voidage in vibrating fluidized beds based on the experimental results and discuss the comparison between predictions of overall bed voidage by eqs. (3) and (4).

RESULTS AND DISCUSSION

Axial Distribution of Bed Voidage in a Vibrating Fluidized Bed

The relationship between bed voidage and height for different vibration intensities and superficial velocities is shown in Figure 2. The experimental results show that the axial distribution of bed voidage with vibration is much more homogeneous than that without vibration, and vibration improves the particle fluidization at the bottom of the bed. When u/u_{mf}=1.10, the bottom voidage in H=10 mm is slightly larger than that in H=50mm and the type of voidage distribution is a 'C' form. But the bed voidage with vibration is smaller than that without vibration. In u/u_{mf}=1.80, the bed voidage under vibration conditions along the axial height from H=50 mm to H=150 mm is very closely compared with the results for a conventional fluidized bed, and particle fluidization at the bottom of the bed is very bad, namely ε of only about 0.43.

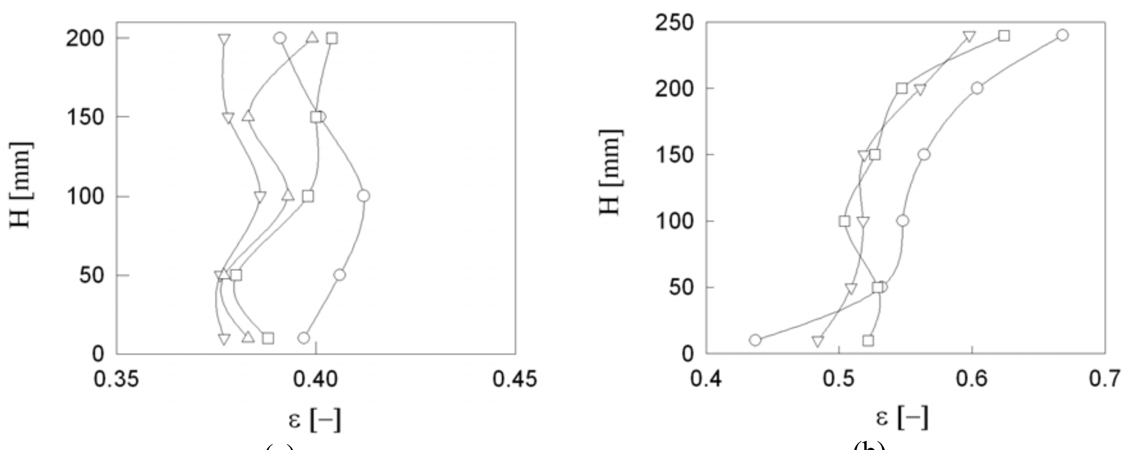


Figure 2: Axial distribution of bed voidage in a vibrating fluidized bed
(a) u/u_{mf}=1.10; (b) u/u_{mf}=1.80; ○ K=0; ∇ K=1.21; □ K=2.72; Δ K=3.70

Radial Distribution of Bed Voidage in a Vibrating Fluidized Bed

Figure 3 shows the plot of radial voidage of millets in the vibrating fluidized bed against radial distance for different axial heights, superficial velocities and vibration intensities. Figure 3(a) shows that the effect of vibration on voidage at the bottom of the fluidized bed is slightly greater and the values of voidage in the radial direction are very close with an increase in vibration intensity in the case of H=10mm. The radial voidage with vibration condition is relatively lower than that without vibration in the cases of H=100 mm and 200 mm, and the distribution of radial voidage decreases slightly from axis to wall of the bed. In Figure 3 (b), fluidization without vibration at the bottom of the fluidized bed is very bad at u/u_{mf}=1.80. When vibration is introduced， the vibration improves particle fluidization. Bed voidage at H=100mm is slightly higher than that at H=10mm. In the case of H=10mm, the bed voidage at K=2.72 and K=3.70 is larger than that without vibration. An interpretation of the cause is that vibration can improve the fluidization of particles at the bottom of the bed.

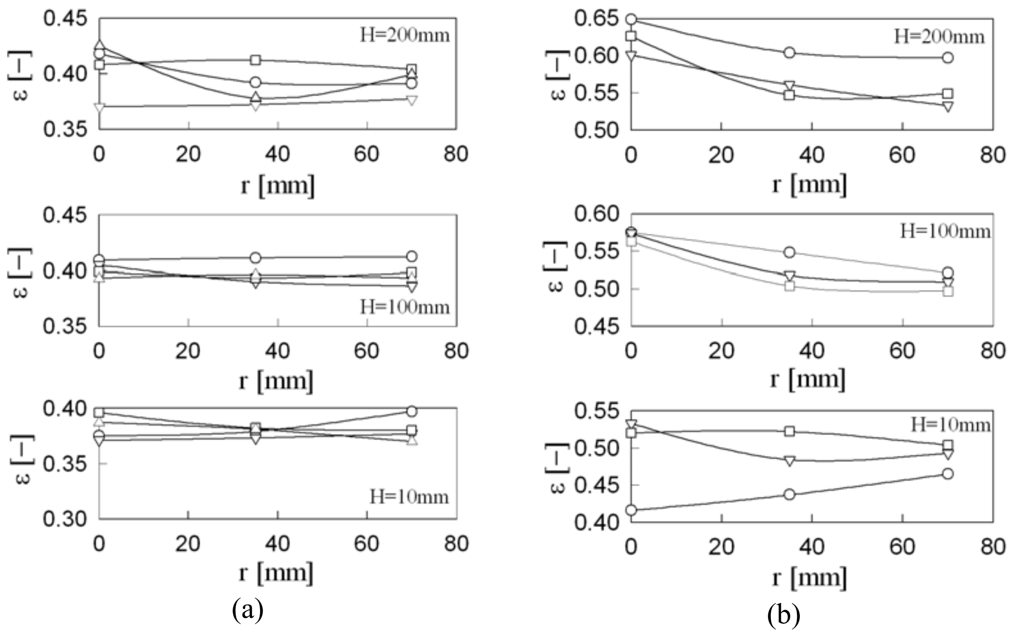


Figure 3: Radial distribution of bed voidage with vibration
(a) u/u_{mf}=1.10; (b) u/u_{mf}=1.80; ○ K=0; ∇ K=1.21; □ K=2.72; Δ K=3.70

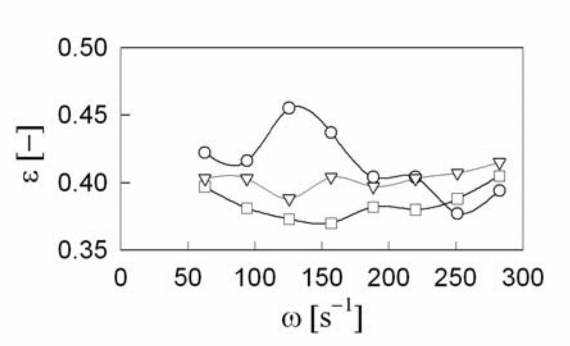
Effect of Operating Parameters

Figure 4 shows the relationship between overall voidage and vibration parameters for millet material. The effect of vibration amplitude on bed voidage at A=0.41mm is slightly small. When vibration frequency is greater than 200 s^{-1}, the bed expansion ratio decreases with an increase in vibration frequency. A larger vibration amplitude has a much greater effect on bed voidage at u/u_{mf}=1.10 and u/u_{mf}=1.50. For example, the bed expansion ratio at A=1.10 mm and A=0.75 mm is larger than that at A=0.41 mm.

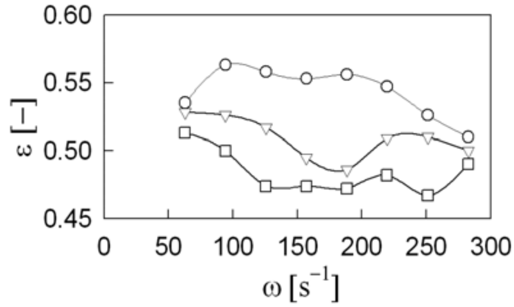
In Figure 5 the relationship between vibration intensity and bed expansion ratio for millet, resin and sand is shown. The effect of vibration on bed voidage for sand at H_0=100 mm is larger than that at H_0=300 mm and H_0=200mm. The bed expansions for millet and resin also show the same trend.

The reason could be that vibration is damped out with an increase in bed height. For a higher bed height, there is a larger resistance to the vibration energy transfer, and this should decrease the vibration energy.

In Figure 6 the relationship between bed average voidage and fluidization velocity is shown for different vibration intensities. In Figure 6, bed average voidage shows the same trend with an increase in fluidization velocity. It is concluded that the function of vibration on the particles is due to momentum transfer. Energy is transferred to the particles, and at the same time there is an upward flow of gas bubbles through the layers resulting in a weakening of the effect of vibration. Thus, the beneficial impact of vibration on bed voidage is significantly weakened with an increase in velocity.

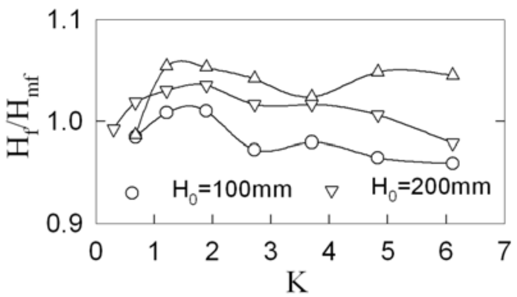


(a)

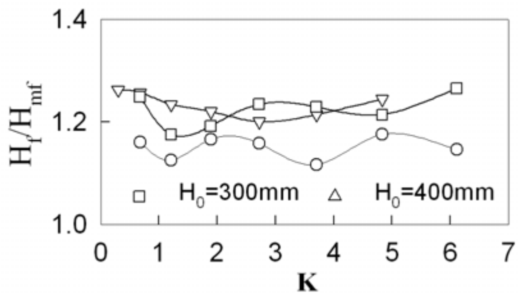


(b)

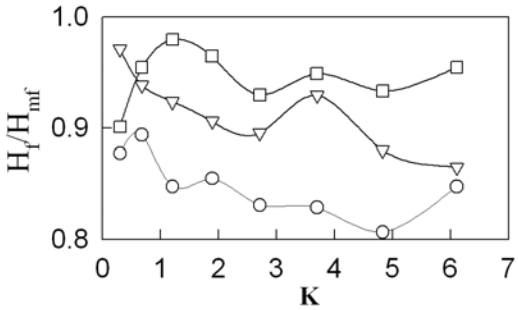
Figure 4: Effect of vibration parameters on bed voidage of millet (a)u/u_{mf}=1.10; (b)u/u_{mf}=1.50.



(a)



(b)



(c)

Figure 5: Relationship between bed expansion ratio and vibration intensity (a) millet; (b) sand; (c) resin.

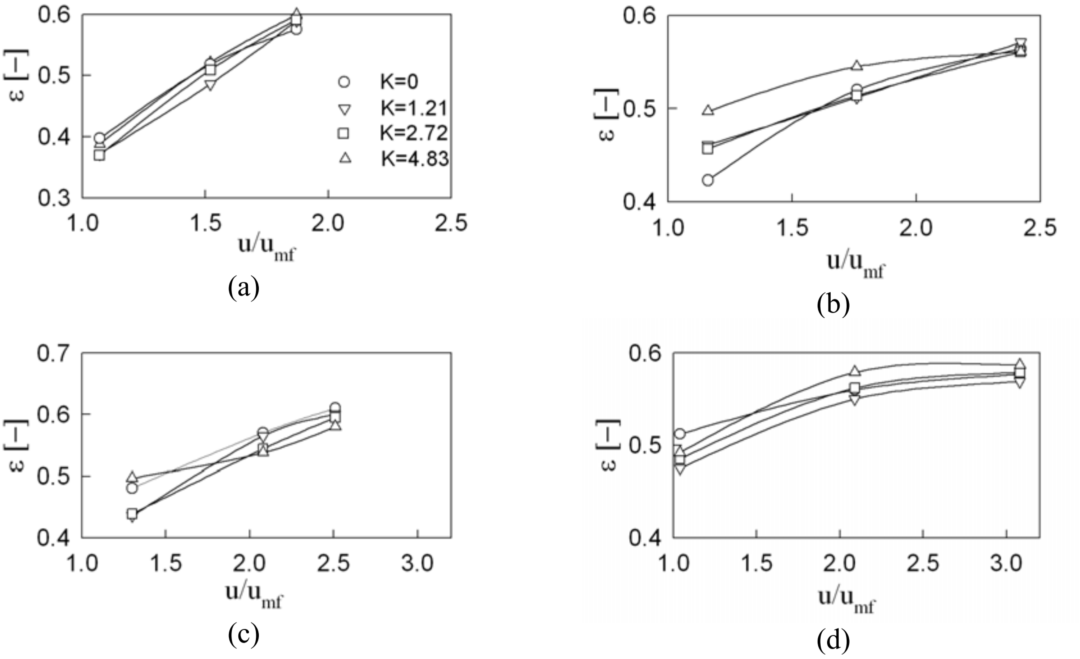


Figure 6: Relationship between bed average voidage and fluidization velocity
(a) millet; (b) sand; (c) resin; (d) glass beads

Comparision of Predicted Values and Experimental Values

The correlation of 529 experimental data points for four kinds of materials under different operating conditions gives the parameters in eq. (3) shown in Table 3. In Table 3, we can see that the vibration energy decreases the bed voidage when K ≤ 1, namely a_3 is a negative value. When K>1, vibration can improve the expansion of the bed, namely a_3 is a positive value. Meanwhile the comparison between the calculated values and experimental values is shown in Figure 7 and the average error is 8.3%. However, there is some difference the comparison between the value calculated with eq. (4) and the experimental data in this study, as shown in Figure 8. The cause can be that eq. (4) did not consider the effect of bed height on bed voidage.

Table 3: Result of multiple regression for the experimental data

Operating condition	a_0	a_1	a_2	a_3
K<1	1.10	0.030	-0.12	-0.68
K>1	1.01	0.010	0.12	0.57
Eq. (4) (Chevilank et al., 1979)	1.0	---	-0.54	0.75

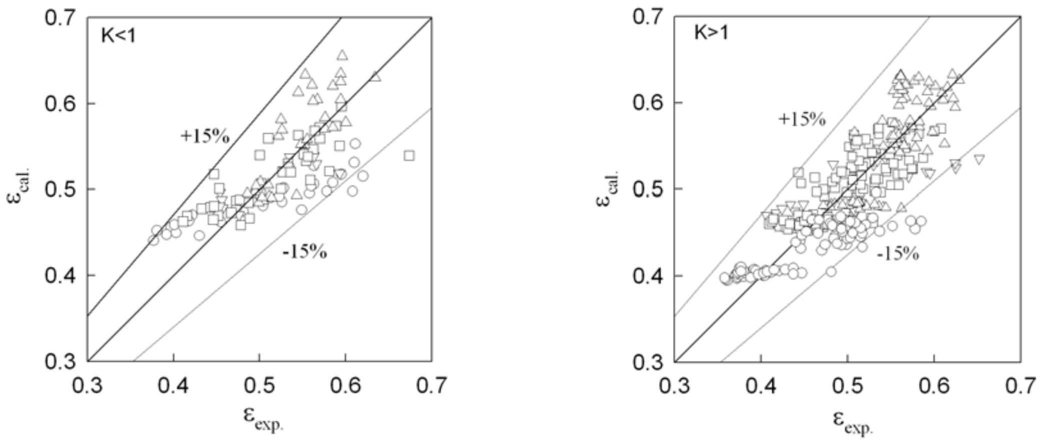


Figure 7: Comparison of prediction of $\bar{\varepsilon}$ by Eq.(3) with the experimental values
○ millet; ∇ resin; □ sand; Δ glass beads

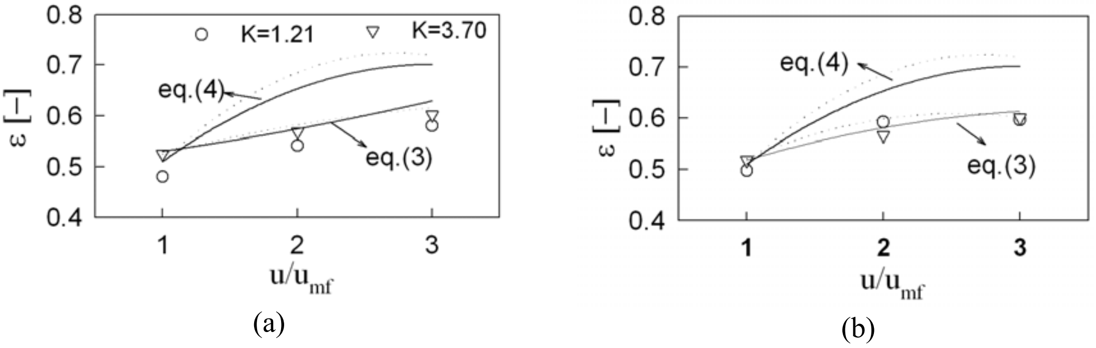


Figure 8: Comparison between prediction of overall bed voidage by eq. (3) and eq. (4) (Chevilank et al., 1979), (a) sand; (b)glass beads; Solid line: K=1.21; dashed line: K=3.70

CONCLUSIONS

The effect of vertical vibration on the voidage of a fluidized bed was investigated experimentally using PC-4 optical fiber. The experimental results show that vibration can aid in the fluidization of particles. The axial and radial voidage distribution with vibration is more homogeneous than that without vibration. For large vibration amplitudes, vibration seriously affects bed voidage. The vibration energy can damp out for particle layers with increasing bed height. According to analysis of the experimental data, an empirical correlation is obtained to estimate the values of bed voidage under vibration.

NOMENCLATURE

a	coefficient of equation (3)	(-)
A	amplitude,	mm
f	vibration frequency,	Hz
g	acceleration of gravity,	m/s^2
H	axial bed height,	mm
H_0	static bed height,	mm
H_{mf}	bed height at minimum fluidization,	mm
K	vibration intensity,	$K=a\omega^2/g$
m	bed expansion ratio	(-)
u	superficial velocity,	m/s
u_{mf}	minimum fluidization velocity,	m/s

Greek Letters

ε	local bed voidage	(-)
$\bar{\varepsilon}$	overall bed voidage	(-)
ε_{mf}	bed voidage at minimum fluidization velocity	(-)
ω	vibration angle frequency,	Hz

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