FREQUENCY ANALYSIS OF PRESSURE FLUCTUATION IN FLUIDIZED BED PLENUM

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Pressure fluctuations in the plenum chamber of a solid-gas fluidized bed were measured and analyzed in order to develop a method for the diagnosis of fluidization conditions.

Power spectral density functions obtained by FFT analysis of the pressure fluctuation data had three principal frequencies. These frequencies were compared with the bubble eruption frequency observed at the bed surface and the bubble generation frequency, which was obtained by an optic fiber probe installed above the distributor opening, and two of the three frequencies were found to agree well respectively with the obtained frequencies of bubble generation and of eruption. The third principal frequency was judged to be a natural frequency of the fluidized bed, since the frequency depended on the particle content in the fluidized bed and on the plenum volume. The frequency corresponding to bubble generation was observed to be influenced significantly by the natural frequency of the fluidized bed when the natural frequency had a low value.

Introduction

Pressure fluctuations in fluidized beds have been studied by many investigators^{1-3,5-7,9,11)} so as to find their fundamental relationship to the behaviour of bubbles in the bed, because it is very important for safe operation of fluidized beds that the bed fluctuation be made small. Hiby³⁾ and Lirag and Littman⁷⁾ measured such pressure fluctuations and concluded that changes in bed height, resulting from bubble eruption at the bed surface, cause the pressure

fluctuations.

On the other hand, Kang *et al.*⁵⁾ concluded that changes in gas flow and in the porosity of the dense phase owing to the action of bubbles are the source of the pressure fluctuations.

Moritomi *et al.*⁸⁾ measured pressure fluctuations in the plenum chamber as well as in the bed and derived an equation for predicting the angular frequency of the natural oscillation of the fluidized bed. Recently, analyses of pressure fluctuations in the plenum chamber and the freeboard have been attempted for diagnosis of the fluidization state, that is, in order to detect the fluidization condition in the bed,^{4,10)} because the pressure fluctuation data contain

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information about bubble eruption at the bed surface. The pressure fluctuations in the plenum or in the freeboard can be measured quite easily and effectively without erosion and abrasion, even in severe conditions, in comparison with other means such as electric conductivity probes, optic fiber probes and capacitance probes which have been used to measure bubble size and velocity in the bed. Moreover, the pressure measurement does not influence the fluidization condition in the bed.

In the present work, the pressure fluctuation in the plenum chamber of a fluidized bed containing glass beads was measured under the freely bubbling condition. The results of fast Fourier transform (FFT) analysis of the pressure fluctuation data gave us the frequencies of both the eruption and the generation of bubbles. Then the possibility of diagnosing the fluidization state by FFT analysis of the pressure fluctuation in the plenum chamber was examined.

1. Experimental

Figure 1 is a schematic diagram of the experimental apparatus employed in the present work. The fluidized bed column was made of an acrylic resin tube to permit visual observation. Its inner diameter was 0.146 m and the column height was 1 m. The freeboard was exposed to the atmosphere. A perforated plate made of acrylic resin was used as a distributor.

Fluidized particles used in this study were glass beads of three mean diameters, 0.057, 0.161 and 0.456 mm, and their density was 2520 kg/m³. Air at the room temperature was used as fluidizing gas.

Pressure fluctuations in the plenum chamber were measured by a pressure transducer (Toyoda Koki, PD104). Signals detected by the transducer were sent to a microcomputer system through an amplifier and an A/D converter and recorded on floppy disks. The pressure fluctuation data were treated to calculate the power spectral density function by the fast Fourier transform (FFT) analyzer.

The pressure was sampled for 40 sec for each run, and the number of data points in this period were 4096. The data sampling for 40 sec was repeated 10 times under the same experimental conditions to obtain the mean value. The time-averaged pressure was also measured by a water manometer connected to the plenum chamber.

The behavior of the bed surface was recorded by a camera connected to a video tape recorder. The frequency of bubble eruption at the bed surface was counted by slowly rerunning the video tapes.

The frequency of bubble generation was also measured by an optic fiber probe of transmission type. Its flow diagram is illustrated in Fig. 2. A tungsten-halogen lamp was used as a light source. The light projected from the tip of the optic fiber is received

Fig. 1. Schematic diagram of experimental apparatus

Fig. 2. Outline of optic fiber probe

Table 1. Experimental conditions

D_b [m]	0.146
W [kg]	1.0, 2.0, 3.0
V [m ³]	2.0×10^{-3} – 5.0×10^{-2}
m [—]	0.0036–0.267
D_p [mm]	0.057, 0.161, 0.456

by the light detector when there is a bubble between the tips of the two fibers, while the light is reflected and is not detected when the space between the fibers is filled with bed particles instead of bubbles. The space between fiber tips was 10 mm, and the optic fiber probe was located 40 mm above the distributor to measure the frequency of bubble generation.

The experimental conditions are summarized in Table 1.

2. Results and Discussion

2.1 Power spectral density function

Figure 3 shows an example of the power spectral density function obtained directly by FFT analysis of the pressure fluctuation data. The power spectral density function in Fig. 3 has three typical peaks. Three such peaks were observed for the other experimental conditions as well.

Fig. 3. Typical example of power spectral density function

In Fig. 4, the frequencies corresponding to these three peaks are plotted against the excess gas velocity, $U_0 - U_{mf}$. Hereafter we refer to the three frequencies in Figs. 3 and 4 as F_b , F_e and F_g respectively, in order of magnitude. In Fig. 4, F_e and F_b are almost constant, independently of U_0 . In fact, F_b was commonly observed to be almost constant under all other experimental conditions shown in Table 1, but F_e became lower at low values of $U_0 - U_{mf}$ when the particle content of the fluidized bed was low. In the low $U_0 - U_{mf}$ region, F_g gradually became larger as the gas velocity increased, while it remained constant at high $U_0 - U_{mf}$.

Next we will discuss F_b , F_e and F_g in detail. The values of F_b , F_e and F_g used in the following discussion are the average frequencies in the region where the frequencies maintained constant values. In Fig. 4, they are shown by horizontal lines.

2.2 Frequency F_b and natural oscillation of fluidized bed

Figures 5 and 6 respectively show the effects of the particle weight in the fluidized bed, W , and the volume of the plenum chamber, V , on the frequency F_b . F_b becomes lower as W or V increases. Moritomi *et al.*⁸⁾ derived the following equation for the natural angular frequency of a fluidized bed by their model in which the momentum of splashed particles was considered.

$$\omega_n = (PA_t / \rho L_{mf} V)^{1/2} = 2\pi F_n \quad (1)$$

F_n values predicted from Eq. (1) are shown by solid lines in Figs. 5 and 6. F_b and F_n agree very well in these figures. From this agreement we conclude that F_b is exactly the same as the natural angular frequency of the fluidized bed reported by Moritomi *et al.* We also examined the effects on F_b of the particle diameter and of the opening ratio of the distributor and thereby confirmed the agreement between F_b and F_n .

2.3 Frequency F_e and bubble eruption at bed surface

According to Kaneko *et al.*⁴⁾ and Tagashira *et al.*,¹⁰⁾ we can obtain information on the bubble eruption from

Fig. 4. Three principal frequencies of power spectral density function

Fig. 5. Effect of W on F_b

Fig. 6. Effect of V on F_b

pressure fluctuation data for the freeboard and the plenum chamber. Then we compared the frequency of the bubble eruption at the bed surface measured

by the video camera with the frequency F_e . In Fig. 7 F_e is shown against W together with the bubble eruption frequency. Based on the good agreement between the frequency of the bubble eruption and F_e , we judge that one of the principal frequencies of the pressure fluctuation in the plenum chamber corresponds to the bubble eruptions at the bed surface or to the accompanying changes in bed height. As W increases, the frequency of bubble eruption becomes lower because of the coalescence of the bubbles as they rise.

Figure 8 shows the relationship between F_e and V . F_e is almost independent of V and also agrees well with the bubble eruption frequency in this figure. Because F_b gradually decreases with the increase of V as mentioned in 2.2, and F_e maintains a constant level, the value of F_e becomes greater than the natural frequency of the bed at the value of $7 \times 10^{-3} \text{ m}^3$ under the present conditions.

2.4 Frequency F_g and bubble generation

Bubbles are generated on the distributor when the gas in the plenum chamber passes the distributor at a stretch. As a necessary consequence, the plenum pressure is greatly reduced. Therefore, we guess that there may be some relation between the pressure fluctuations in the plenum and the bubble generation frequencies.

To measure the real frequency of bubble generation we installed the optic fiber probe right above an opening located in the center of the distributor. Figure 9 compares the frequency F_g and the bubble generation frequency obtained by the optic fiber probe. They agreed very well. We obtained the same results when the optic fiber probe was transferred to a position above any other hole in the distributor. In Fig. 9, the bubble generation frequencies at $r=50 \text{ mm}$ are also shown for reference.

Next, two sets of optic fiber probes were attached above any two distributor openings at the same time, and the correlation of the bubble generations at these two holes was measured. The measurement was repeated for many combinations of two openings at various distances from the center of the distributor. A very strong correlation between two signals could be observed regardless of the location of the probe. An example of the correlation between the two signals is shown in Fig. 10. As a result, we consider that many bubbles are generated at the holes of the distributor with synchronism. F_g in Fig. 4 is smaller than F_e despite the existence of the bubble coalescences, because many bubbles are generated simultaneously at many distributor openings.

2.5 Interaction of F_g and F_b

Figure 11 represents the effect of V on F_g and F_b . F_b , which corresponds to the natural angular frequency of the fluidized bed reported by Moritomi

Fig. 7. Effect of W on F_e

Fig. 8. Effect of V on F_e

Fig. 9. Comparison of F_g with bubble generation frequency

et al.,⁸⁾ gradually decreased with the increase of V . In contrast to F_b , F_g maintained a constant value for low values of V . However, in the higher- V region, where F_b gradually became close to F_g , the latter was still a little smaller than F_b ; finally, they could not be

Fig. 10. Correlation between two optic signals measured at different holes of distributor $V=5.0 \times 10^{-3} \text{ m}^3$, $W=3.0 \text{ kg}$, $m=0.0036$, $D_p=0.161 \text{ mm}$

Fig. 11. Interaction of F_g and F_b

distinguished at a value of V of about $1.0 \times 10^{-2} \text{ m}^3$. The frequencies of the combined peak are plotted by the key of F_g in Fig. 11, because they are confirmed to agree with the bubble generation frequencies measured by the optic fiber probe. The combination of F_g and F_b suggests that the bubble generation is controlled by the natural oscillation of the bed when the two frequencies are close to each other. In this case the fluidized bed is in a resonant state and the bubbles are generated by the bed oscillation. Such a phenomenon was also reported by Moritomi *et al.* for the pressure responses caused by the periodic oscillation of inlet gas flow.⁸⁾ When F_b is much larger than F_g , however, the bubble generation is not able to follow the bed oscillation.

Although Moritomi *et al.* used almost the same experimental apparatus and conditions ($D_b=0.148 \text{ m}$, $V=5.0 \times 10^{-3}$ – $4.0 \times 10^{-2} \text{ m}^3$, particles: sand, $D_p=0.160 \text{ mm}$), they reported only one kind of frequency, which is presumed to correspond to the combined frequency of F_b and F_g . If they had conducted the experiment with V less than $5.0 \times 10^{-3} \text{ m}^3$ and had treated the data by FFT analysis, they might have

found F_g as well as F_n .

Conclusions

(1) The pressure fluctuation in the plenum chamber of a fluidized bed were measured under spontaneous oscillation and were analyzed by the FFT method.

(2) The power spectral density functions obtained by FFT analysis have three principal frequencies. These three agree well with the bubble eruption frequency, the bubble generation frequency and the natural frequency of the fluidized bed reported by Moritomi *et al.*, respectively.

(3) When the plenum volume is large, the frequency corresponding to the bubble generation is controlled by the natural frequency of the bed. Then the fluidized bed is in a resonant state and the bubbles are generated by the bed oscillation.

Since we succeeded in obtaining the frequencies of bubble generation and eruption solely from the measurement of the pressure fluctuation in the plenum chamber, instrumentation for pressure fluctuation measurement should be highly useful as part of a fluidized-bed diagnosis method. However, a more detailed study is required to determine whether similar results to those of this study can be obtained for various fluidization systems and conditions.

Nomenclature

A_t	= cross-sectional area of fluidized bed	[m ²]
D_b	= fluidized bed diameter	[m]
D_p	= particle diameter	[mm]
F	= frequency	[s ⁻¹]
F_b	= principal frequency corresponding to natural frequency of fluidized bed	[s ⁻¹]
F_e	= principal frequency corresponding to bubble eruption frequency	[s ⁻¹]
F_g	= principal frequency corresponding to bubble generation frequency	[s ⁻¹]
F_n	= natural frequency of fluidized bed in Eq. (1) = $\omega_n/2\pi$	[s ⁻¹]
L_{mf}	= bed height at incipient fluidization	[m]
m	= ratio of opening area to distributor	[—]
P	= average pressure in plenum chamber	[N/m ²]
r	= radius	[mm]
T	= time	[s]
U_{mf}	= incipient fluidization gas velocity	[m/s]
U_o	= superficial gas velocity	[m/s]
V	= volume of plenum chamber	[m ³]
W	= particle content of fluidized bed	[kg]
ρ	= density of incipient fluidized bed	[kg/m ³]
ω_n	= natural angular frequency of fluidized bed	[rad/s]

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