PRESSURE FLUCTUATIONS IN A MULTI-SOLID FLUIDIZED BED

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The pressure fluctuations in a Multi-Solid Fluidized Bed (MSFB) are investigated under various experimental conditions with a lab-scale MSFB and a pilot-scale MSFB. The main purpose of the studies is to show the effect of coarse particles on pressure fluctuations in MSFBs and to identify the MSFB operating mode using power spectrum analysis. The dominant frequencies of pressure fluctuations are also determined under various experimental conditions. The pressure fluctuations show the difference in coarse particle bed behavior depending on whether fine particles are circulated or not.

The power spectra of CFBs change qualitatively in the presence of a dense bed of coarse particles. If a sharp peak is observed in the power spectrum, it means that a dense bed of coarse particles exists in the bottom part of the riser; otherwise, coarse particles are dispersed in the riser and/or circulate in the reactor.

Introduction

The Multi-Solid Fluidized Bed (MSFB) is a circulating fluidized bed consisting of a circulating dilute-phase bed and a more stable dense bed of large particles (Fig. 1). As compared to a circulating fluidized-bed boiler, in addition to the circulating bed material (ash, limestone, fine coal particles) with a particle size of approximately 300 μm , the reducing zone of the combustor contains a dense bed of coarse particles (ceramic balls) with a size of 10–15 mm. Fine particles circulate while the dense bed of coarse particles stabilizes the combustion process and increases the residence time of fine particles. In addition, the dense bed promotes the breakdown of coarse particles, enabling us to handle run-of-mine coal up to 50 mm in size. A very important feature of the MSFB is the ability to recycle uncooled solid at a controlled rate independently so that the total solid inventory can be completely decoupled from the unit load. This allows greater control of the conditions governing pollutant formation and destruction reactions. Therefore, the MSFB can operate with very low NO_x , N_2O and SO_x emissions while utilizing a variety of fuels, including industrial and urban wastes.

Both CFBs and MSFBs are characterized by the presence of pressure fluctuations in the reactor due to the influence of a variety of phenomena, including bubbling in a dense bed and vigorous motion of particles. The pressure fluctuations in the bottom part of MSFB boilers are of particular importance since this type of boiler operates with negative pressure in the combustion chamber.

Many investigators have observed the cause of the pressure fluctuations in a bubbling fluidized bed. How-

ever, the relations between pressure fluctuations and operating conditions of a MSFB have not yet been described quantitatively. Verloop and Heertjes¹⁰⁾ stated that the pressure fluctuations were related to bubble formation. Kang³⁾ concluded that changes in gas flow and in the porosity of the dense phase owing to the action of bubbles were the source of the pressure fluctuations. Tamarin⁹⁾ suggested that these fluctuations were associated with bubble eruption at the bed surface. Fan¹⁾ concluded that in the lower part of the fluidized bed the pressure fluctuations were caused by the formation of large bubbles but those in the upper part by the motion of clusters. Kehoe⁴⁾ reported that the pressure fluctuations were related to the length and velocity of slugs and the space between them. Winter¹²⁾ described the character of pressure fluctuations as similar to that of density fluctuations. Recently, Shrikant⁸⁾ found that the power spectrum of pressure fluctuations can be used to identify flow patterns in pneumatic conveying systems.

The objective of the present work is to investigate the effect of the dense bed of coarse particles on the pressure fluctuations in a MSFB and to identify a MSFB operating mode by using power spectrum analysis.

1. Experimental Apparatus and Procedure

Both lab-scale MSFBs and pilot-plant MSFBs were used in the present work. Figure 2 shows a schematic of the lab-scale and pilot-plant scale units. The lab-scale unit was a column of 0.05 m i.d. and 1.5 m height, made of acrylic resins to permit visual observation. The pilot-plant unit was 0.4 $\times$ 0.8 m and 13 m high. Glass beads (74–125 μm , 2500 $\text{kg}\cdot\text{m}^{-3}$) were used as fine particles and porous alumina (2–4 mm, 1250 $\text{kg}\cdot\text{m}^{-3}$)

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Circulating Particles: ash, limestone, fine coal
 diameter $300\ \mu\text{m}$
 density $2600\ \text{kg}\cdot\text{m}^{-3}$
 Solid Flow Rate: $5 - 15\ \text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
 Dense Bed: ceramic particles
 diameter $10 - 15\ \text{mm}$
 density $3400\ \text{kg}\cdot\text{m}^{-3}$

Fig. 1 Multi-Solid Fluidized Bed concept

Fig. 3 Relation between standard deviations of pressure fluctuations and gas velocity

Fig. 2 Schematic diagram of the experimental unit

were used as coarse particles for the lab-scale unit and sand ($130\ \mu\text{m}$, $2599\ \text{kg}\cdot\text{m}^{-3}$) were used as fine particles and ceramic balls ($10\ \text{mm}$, $3600\ \text{kg}\cdot\text{m}^{-3}$) as coarse particles for the pilot-plant unit. Air at room temperature was used as fluidizing gas. The solid rate of fine particles at a constant gas velocity was controlled by a mechanical valve located in the downcomer line. The flow patterns in both units could be observed through transparent walls.

The differential pressure between the two taps ($182\ \text{mm}$ apart for a lab-scale and $1320\ \text{mm}$ for a pilot-plant MSFB) located in the bottom part of units was measured by a diffusion-type pressure transducer of high response

Fig. 4 Relation between standard deviations and gas velocity with the presence of fine particles

and accuracy. An analog voltage signal proportional to the pressure was amplified by a DC amplifier and filtered by a low-pass filter below $40\ \text{Hz}$. Analog signals were digitized using a 16-bit AD converter. Data sampling was performed at a frequency of $256\ \text{Hz}$. All signals were analyzed and stored using a 4-channel FFT analyzer (CF-6400 Ono Sokki Co., Ltd.). The power spectrum was determined by a high-speed version of Discrete Fourier Transform.

Fig. 5 Effect of solid rate and gas velocity on pressure fluctuations ($H/D = 4/5$)

2. Experimental Results and Discussion

2.1 Effect of a dense bed of coarse particles on pressure fluctuations

In this part of our experiments, the effect of a dense bed of coarse particles on pressure fluctuation was studied and the results were plotted as a graph of the standard deviation of pressure fluctuations versus the superficial gas velocity and the solid rate of fine particles.

Figure 3 shows the relation between the standard deviation of pressure fluctuations and the superficial gas velocities for coarse particles in the absence of the circulation of fine particles in the unit. The results are exactly as one would expect: as the gas velocity is increased, the pressure fluctuations reach a maximum followed by a decrease to a low value. This progression corresponds to the transition from bubbling to turbulent fluidization. The velocity at which the pressure fluctuations are maximum can be identified as U_c . The velocity where the pressure fluctuations begin to level off as U_k (onset of turbulent fluidization, Yerushalmi and Cankurt¹³).

Figure 4 illustrates the relation between the standard deviation of pressure fluctuations and the superficial gas velocities at different dense bed heights and solid rates of fine particles for a lab-scale unit. In the case of a deep dense bed of coarse particles ($H/D = 4/5$) a choking effect appeared when the gas velocity was reduced and the solid rate was sufficiently high, resulting in high-pressure fluctuations. For a shallow dense bed of coarse particles ($H/D = 2/5$), however, the pressure fluctuations decreased significantly and were slightly affected by the gas velocity for a low solid rate of fine particles. This suggests that fairly small bubbles were formed in the dense bed under these conditions. When coarse particles circulated, the pressure fluctuation level was almost the same for both CFBs and MSFBs. Comparing the data for the system with coarse particles (Fig. 3) with that with a mixture of coarse and fine particles indicated that circulation of fine particles changed the

Fig. 6 Effect of solid rate and gas velocity on pressure fluctuations ($H/D = 2/5$)

transition regime of coarse particles. The transition from bubbling to turbulent flow regime occurred at a lower gas velocity than a bed operating with coarse particles only.

In Figs. 5 and 6 the standard deviations of the pressure fluctuations are shown as a function of the solid rate for two initial bed heights of coarse particles, $H/D = 4/5$ and $H/D = 2/5$ respectively. In a bed of small diameter as used in our study (50 mm i.d.) and a deep dense bed of coarse particles, slugs or relatively large bubbles existed and grew as the gas velocity and solid rate were raised until losing their stability. When the solid rate of fine particles was below $7 \text{ kg.m}^{-2}.\text{s}^{-1}$ and the gas velocity was high enough to fluidize coarse particles, pressure fluctuations were low. On the other hand, if the solid rate of fine particles was increased, coarse particles were pulled from the surface of the bed and became more widely dispersed in the riser. At high gas velocity they were carried by clusters into the upper part and circulated in the unit. This means that the transition velocities for coarse particles are very sensitive to changes in the solid rate of fine particles⁶.

The effect of coarse particles on the pressure fluctuations may be observed by comparing the curves given for a CFB and a MSFB in Fig. 7. Results indicate that when the dense bed existed in the bottom part (solids rate below $5 \text{ kg.m}^{-2}.\text{s}^{-1}$) the circulation of fine particles slightly reduced the pressure fluctuations. Under the above conditions, the amplitude of pressure fluctuations was related to the size of bubbles escaping from the bed. Since, for a given bed height, the amplitude increases with particle size (Lirag and Littam⁵), the pressure fluctuations for a binary mixture of 100 μm - and 3-mm par-

Fig. 7 Comparison of pressure fluctuations in the CFB and MSFB

Fig. 8 Dominant frequencies of pressure fluctuations in the CFB and MSFB

ticles should be lower than those for a bed of coarse particles consisting only of 3-mm balls. This is caused by the mean particle diameter of a binary mixture that is smaller than that of coarse particles only. The expected decrease in amplitude is clearly seen in Fig. 7, indicating that the stability in a fluidized bed of coarse particles can be improved by adding fine particles. This can be attributed to the fact that the size of the bubbles was more uniform. With further increase in the solid rate, however, the pressure fluctuations increase. Recent studies of the fluid mechanics phenomena inside large-scale CFB combustors by Werther¹¹⁾ have shown that the CFB combustor is characterized by a bubbling bed of fine particles at the bottom of the combustor and an upper dilute zone. The solid concentration in the upper zone is very low. Therefore, it may be possible to improve the performance of the bottom bed of the CFB combustor by adding coarse particles to a bubbling bed of fine particles.

The dominant frequency of pressure fluctuations obtained from the power spectrum density function was

Fig. 9 Power spectrum for the lab-scale CFB

Fig. 10 Power spectra for the lab-scale MSFB

measured at various gas velocities and solid rates for a CFB and a MSFB. The results are shown in Fig. 8. In the case of fluidization of coarse particles only (without the presence of fine particles), the dominant frequency was 5 Hz for all values of gas flow. This frequency is in good agreement with a frequency corresponding to a bubble eruption frequency presented by Kage *et al.*²⁾ At a low solid rate of fine particles, the frequency showed a tendency to level off and was equal to about 1.25 Hz. However, when the solid rate was further increased, the dominant frequency also increased and the trend was similar to that involving fine particles only. These results suggest that a dense bed of coarse particles was dispersed through the riser at high solid rates; thus pressure fluctuations were mainly caused by the fluctuations of a dense bed of fine particles.

2.2 Identifications of a MSFB using power spectrum

In addition, the presence of coarse particles in the bottom part of a MSFB was also identified from the power spectrum for the lab-scale and pilot-plant units.

Figure 9 shows the power spectrum of pressure fluctuations for a lab-scale CFB. The spectrum corresponding to CFB conditions consisted of several smaller peaks whose frequencies were closely distributed. The appearance of many peaks was considered with the assertion that the behavior of the reactor was likely to be non-periodic. Figures 10 A, B, C and D show the power spectra of pressure fluctuations for various operating conditions of a lab-scale MSFB. The MSFB operated at

Fig. 11 Power spectra for the lab-scale MSFB

a low solid rate of fine particles in order to keep the dense bed of coarse particles in the bottom of the riser. A sharp peak at approximately 1.45–1.8 Hz was observed in the power for a MSFB.

Figures 11 A and B present the power spectra of a MSFB with a much higher solid rate of fine particles. Under such conditions, coarse particles were spread over the height of the riser, and there was no dense bed of coarse particles in the bottom part of the riser. Clearly, the power spectrum differed considerably from that at a low solid rate and was reminiscent of the power spectrum for fine particles alone. It appears that this feature of the spectrum, particularly the presence of a sharp low-frequency peak, can be used to predict the behavior of a MSFB⁷⁾. In other words, if a sharp peak in the power spectrum is observed, it indicates that a dense bed of coarse particles exists in the bottom of the riser; otherwise, coarse particles are dispersed in the riser or they circulate in the reactor.

Prior to the start of the MSFB experiments in the pilot plant, the pressure fluctuations were measured without the presence of coarse particles. The corresponding power spectrum is plotted in Fig. 12 A. As can be seen, the power spectrum without coarse particles was almost the same as that shown in Fig. 11. Then experiments were performed with a bubbling bed of coarse particles for two superficial gas velocities of 6 and 8 m·s⁻¹. An example of the power spectrum at a superficial gas velocity of 8 m·s⁻¹ is presented in Fig. 12 B. A sharp peak at a frequency of approximately 1.5 Hz was observed for both gas velocities. Finally, a test were

Fig. 12 Power spectra for the pilot-plant MSFB

carried out with circulation of fine particles. Figures 12 C and D show the power spectrum for the pilot-plant MSFB under various operating conditions. Again, the power spectrum displayed a distinct maximum peak at a dominant frequency of about 1.5 Hz, as shown in Figs. 12 C and D. This indicates that a dense bed of coarse particles was present in the bottom of the riser. Indeed, visual observations of the flow pattern in the pilot-plant MSFB confirmed the above conclusion. Similar power spectra with a clear peak around 1.5 Hz were obtained for various operating conditions of the pilot-plant MSFB ranging from 6 m·s⁻¹ to 8 m·s⁻¹ and from 2.3 kg·m⁻²·s⁻¹ to 32.9 kg·m⁻²·s⁻¹.

Conclusions

From the results of this study the following conclusions can be drawn.

1. The pressure fluctuation data show remarkable differences in coarse-particle bed behavior depending on whether fine particles are circulated or not. The addition of fine particles to a bed of coarse particles prevents the formation of large bubbles and thus tends to reduce pressure fluctuations within the bed. When the solid rate is increased, however, the fluctuations become greater, with coarse particles spreading over the riser. The fluctuations are generally decreased with an increase in gas velocity.
2. If a sharp peak is observed at low frequency 1.45 Hz in the power spectrum, it means that a dense bed of coarse particles exists in the bottom of the riser.

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Nomenclature

D	= diameter of riser	[m]
G_s	= solid rate of fine particles	[kg·m ⁻² ·s ⁻¹]
H	= dense bed height	[m]
U_c	= superficial gas velocity corresponding to onset of turbulent fluidization regime	[m·s ⁻¹]
U_k	= superficial gas velocity where pressure fluctuations	

reach a minimum corresponding to absence
or near-absence of bubbles and slugs [m·s⁻¹]

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