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BEHAVIOR OF FLUIDIZED BEDS OF SMALL PARTICLES AT ELEVATED TEMPERATURES

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Key Words: Fluidization, Fluidity, Elevated Temperature, Bubble Frequency, Bubble Size, Pressure Fluctuations, Electrostatic Force

Pressure fluctuations and bubble frequency in fluidized beds were measured at several stages of temperature ranging from 280 K to 640 K. Four types of powders belonging to group A of Geldart's classification were used. The quality of fluidization at various temperatures was evaluated by a uniformity index based on pressure fluctuations and by bubble size obtained from bubble frequency. The reduction both in the deviation of amplitude of pressure fluctuations and in bubble size showed that the quality of fluidization improved with increasing temperature. However, at room temperature, beds of dry particles were affected by electrostatic phenomena and thus the fluidity was decreased. The influence of the electrification decreased at elevated temperature, or at room temperature when the particles held water in the pores.

Introduction

Studies of fluidized beds have generally been carried out by using air under ambient conditions. Industrial processes are, however, operated at elevated temperatures. Geldart *et al.*[6] have suggested that the fluidization behavior of powders in the cold model using air should be treated with caution in scaling-up with other gases and operating conditions.

Most of the studies at elevated temperatures have been concerned with the effect of bed temperature on minimum fluidizing velocity. Several studies have been carried out on behavior of bubbling or turbulent fluidization. Otake *et al.*[14] have measured bubble frequency at various temperatures. They found that bubble frequency increased with bed temperature. Similar results were obtained by Mii *et al.*[9] Tone *et al.*[18] have proposed a correlation between bubble diameter and bed temperature by measuring bubble frequency. Yoshida *et al.*[21] have measured bubble size with changing temperature in two-dimensional beds. Geldart *et al.*[5] have estimated bubble size from eruption diameter. According to their results the bubble size decreased with increasing temperature. The decrease in bubble size seems to indicate improvement in the quality of fluidization with increasing temperature.

The fluidity can also be judged from pressure fluctuations. Svoboda *et al.*[17] have studied the dependence of frequency spectrum, dominant frequency, and mean amplitude of pressure fluctuations on temperature. The mean amplitude decreased and the frequency increased with increasing temperature.

The average particle size employed in the studies referred to above was limited to that larger than 70 μm. Fluidized beds of small particles ($d_p = 50$–$70\,\mu$m) at elevated temperature have not sufficiently been studied, although the bed behavior with small particles differs from that with large particles even at ambient temperature. Thus the purpose of the present study is to find the effect of temperature both on bubble size and on pressure fluctuations in a fluidized bed of small particles.

1. Experimental Apparatus and Procedure

1.1 Particles used

Four types of powders of different properties were used. Their physical properties are summarized in **Table 1**. Only the silica particles are not classified as A′ group of Ikeda's criterion[7] for good fluidization,

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Table 1. Properties of particles

Particles	d_p [m]	ρ_b [kg/m^3]	U_{mf} at 280 K [m/s]
Alumina	60×10^{-6}	3.7×10^{2}	1.4×10^{-3}
FCC	60×10^{-6}	4.6×10^{2}	1.5×10^{-3}
Catalyst	56×10^{-6}	8.0×10^{2}	2.0×10^{-3}
Silica	138×10^{-6}	6.3×10^{2}	7.7×10^{-3}

while all of the particles belong to group A in Geldart's classification.[4)]

Alumina, FCC and catalyst particles were chosen since they have optimal fluidizing properties concerning bulk density, average particle size and fraction of fine particles ($d_p < 44\,\mu$m). The catalyst particles are about twice as heavy as the other two, but these three kinds of particles have almost the same size distribution.

1.2 Apparatus

Measurements of U_{mf} were carried out in a 0.051 m i.d. acrylic column under ambient conditions. The settled bed height above the distributor was 0.3 m and nitrogen was used as the fluidizing gas. The distributor was made of sintered brass.

Bubble signal and pressure fluctuations were measured in a stainless-steel column at ambient and elevated temperatures. The column consisted of a straight main part and an expansion zone at the top. The main part was 0.081 m i.d. and 1.5 m high. The expansion zone was 0.2 m i.d. and contained two cyclone separators to prevent particles from being carried away. The column was equipped with a sparger with 17 holes of 0.7 mm diameter facing downward in the bottom.

1.3 Measurements

The bubble signal was detected by using the optical probe shown in **Fig. 1**. The light signals received were so small (below 100 mV) that they were amplified to a voltage range between 0.2 and 1.5 V. The probe was settled on the central axis of the bed about 0.45 m above the sparger.

Dry particles adhered on the surface of the quartz rod when beds were fluidized at room temperature, so that light could not be transmitted even when the probe was in a bubble. This adhesion could be prevented by impregnating the pores of particles with 2–3 wt% water. This water was adsorbed on the inner surface of particles with considerable heat of adsorption. Therefore, the amount of water in the pores will not change during experiments at room temperature. Since adhesion did not occur at elevated temperatures, dry particles were used under these conditions.

The pressure signal was detected by using a differential pressure transducer (P-3000S, COPAL) fitted to pressure taps at the bottom of the column and the expansion zone. The response of the transducer is up to about 1 kHz and its sensitivity is about 1.5 μV/Pa. The output of the transducer was amplified, recorded by a data recorder, and then converted to digital signals. The sampling frequency of the A–D converter was 400 s^{-1}. The dominant frequency was obtained from the auto-correlation function of pressure fluctuation signals.

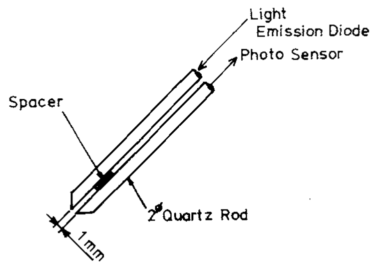

Fig. 1. Optical probe.

The electrostatic charge arising in a fluidized bed was measured at room temperature by using a brass spherical probe of 9 mm diameter. The probe was attached to a steel rod and fixed on the central axis of the column 0.45 m above the sparger. The electric potential between the probe and the earth was charged in a capacitor. The potential of the capacitor at the instant of discharge was measured by a digital memoriscope (VC-801B, Hitachi-denshi).

The bed temperature was 280 K, 400 K, 530 K and 640 K, and the pressure was atmospheric. The superficial gas velocity under the experimental conditions was 0.05–0.26 m/s. The height of settled bed was set at 0.6 m.

2. Results

2.1 Pressure fluctuations

Average deviation of amplitude of pressure fluctuations is shown in **Figs. 2** to **5** for each powder. The deviation is defined by the following relation:

$$\delta_p = \frac{\left\{\frac{1}{n}\sum\left(\Delta P_i - \frac{1}{n}\sum \Delta P_i\right)^2\right\}^{1/2}}{\frac{1}{n}\sum \Delta P_i} \qquad (1)$$

where ΔP_i is pressure drop at each sampling moment.

In all cases the deviation decreased with increasing temperature, while this tendency was not significant for silica particles. The deviation increased with gas velocity at 280 K, although it was almost independent of gas velocity at elevated temperatures for particles other than silica. The catalyst particles of large densities showed lower fluidity than alumina and FCC at 280 K, though the three types have the same size distribution. At elevated temperatures, however, the fluidity of the catalyst particles was improved.

In addition, it was found that the effect of increas-

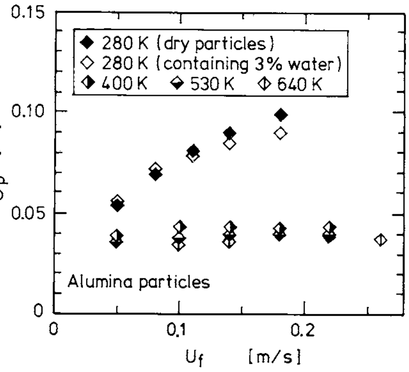

Fig. 2. Deviation of amplitude of pressure fluctuations for alumina particles.

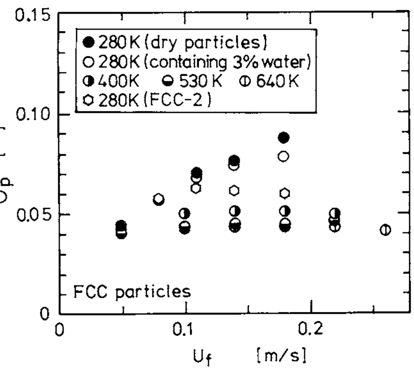

Fig. 3. Deviation of amplitude of pressure fluctuations for FCC particles.

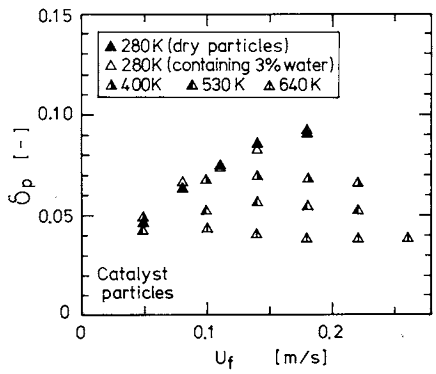

Fig. 4. Deviation of amplitude of pressure fluctuations for catalyst particles.

ing temperature on the deviation δ_p was not so large for alumina and FCC particles at elevated temperatures. Yerushalmi *et al.*[20] have shown that pressure fluctuations increased with gas velocity when U_f was under 0.6 m/s. They used FCC as fluidizing particles. From these results it is expected that the bed behavior at elevated temperature differs from that at ambient temperature.

The difference in amplitude between particles containing 2–3% water in the pores and dry ones was very little. It is considered that containing a small amount of water does not affect bed behavior significantly, while adhesion of particles is prevented by this

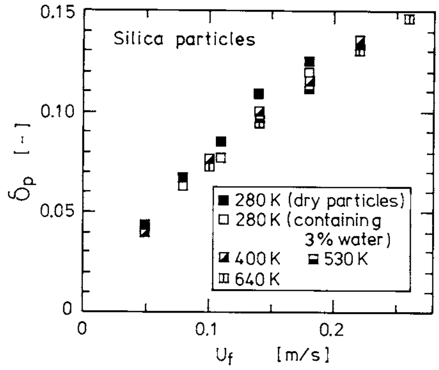

Fig. 5. Deviation of amplitude of pressure fluctuations for silica particles.

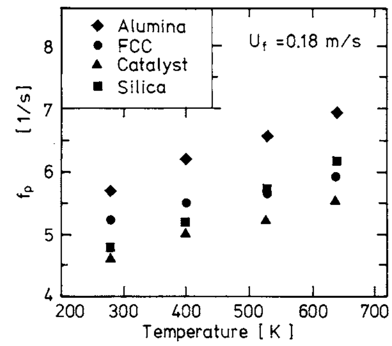

Fig. 6. Dependence of dominant frequency on temperature.

treatment.

As for the results for the alumina and FCC particles, there is a marked difference between δ_p at 280 K and at elevated temperatures, though the difference at elevated temperatures is small. This trend cannot be explained by the change of gas properties alone. Forces conditioned by static electricity may dominate bed behavior at 280 K. The influence of the electrostatic charge is discussed in a later section.

Figure 6 shows that the dominant frequency of pressure fluctuations was slightly affected by temperature. High frequency of fluctuations is considered to be associated with good quality of fluidization. This tendency agreed with the result given by Svoboda *et al.*,[17] while the frequency in the present study was about three times higher than that given by them. This was probably caused by good fluidity of the small particles used in the present study.

Morse *et al.*[10] have proposed a uniformity index defined by the percent deviation in bed density divided by the frequency of density fluctuations in order to give a numerical value to the fluidization quality. Shuster *et al.*[16] have suggested a similar index for pressure fluctuations. The uniformity index here is given by

$$\text{Index} = \frac{2\sqrt{2}\,\delta_p}{\pi f_p} \times 100 \qquad (2)$$

The results calculated by Eq. (2) are given in **Table 2**.

Table 2. Uniformity index at $U_f = 0.18$ m/s

T [K]	Alumina	FCC	Catalyst	Silica
280	1.73	1.51	1.77	2.39
400	0.60	0.85	1.23	1.92
530	0.54	0.71	0.93	1.79
640	0.51	0.69	0.66	1.71
High fluidity		Index < 1		
Good fluidity		1.5 < Index < 5		
Poor fluidity		5 < Index		

The particles other than silica showed high fluidity at elevated temperatures. The index shows a decrease of the quality of fluidization at 280 K.

2.2 Bubble signal

Holdup of gas bubbles has been expressed[11] as

$$\varepsilon_b = \varepsilon_{b0}\{1-(r/R)^n\} \tag{3}$$

where ε_{b0} is the holdup of gas bubbles at the central axis of the bed. The parameter n is said to be about 2.[11]

The bubble-frequency distribution was found by experimental measurement to follow the similar relationship:

$$f_b = f_{b0}\{1-(r/R)^2\} \tag{4}$$

where f_{b0} is the frequency at the central axis of the bed. Nozaki[12] has shown similar results. Mean bubble size can be obtained from the balance of gases coming into and going through the bed as bubbles by using Eq. (4) on the assumption that there is no radial distribution of the average bubble size. Therefore, the calculated bubble size is the volume-average diameter when bubbles are assumed to be spherical. The value of U_{mf} at elevated temperatures was calculated from that at room temperature by considering that U_{mf} changes inversely with gas viscosity. Here the bubble flow was calculated as $U_f - U_{mf}$.

Bubble sizes at various temperatures are shown in **Figs. 7** to **10**. It is revealed that bubble size decreased with increasing temperature for each powder. Bubble-size reduction with temperature was distinct between 280 K and 400 K for alumina and FCC particles. The effect of superficial gas velocity on bubble size was small at elevated temperature for particles other than silica. This trend is found in the literature[13] for the case of room temperature.

Average holdup of gas bubbles can be obtained by integrating Eq. (3). **Figure 11** shows the relationship between average holdup $\bar{\varepsilon}_b$ and gas velocity at three levels of temperature for FCC and silica. The value of $\bar{\varepsilon}_b$ increased with temperature.

Since the mass-transfer capacity coefficient between bubble and emulsion phases, $k_{ob}a_b$, is dependent on both d_b and $\bar{\varepsilon}_b$, the value of $k_{ob}a_b$ will be influenced by bed temperature. Therefore, the dependence of d_b and

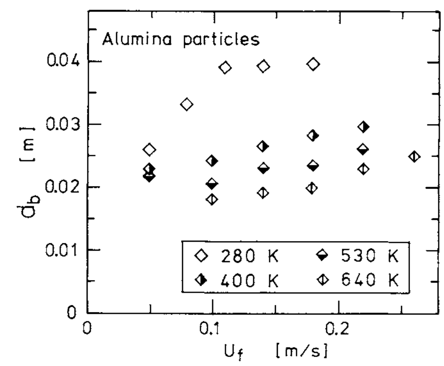

Fig. 7. Effect of increasing temperature on bubble size for alumina particles.

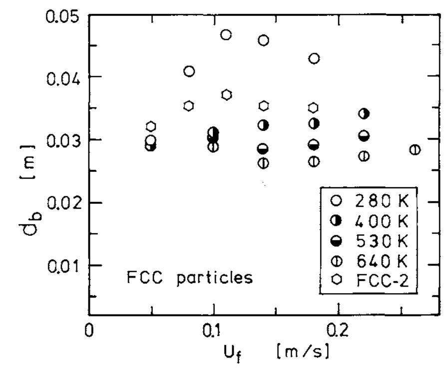

Fig. 8. Effect of increasing temperature on bubble size for FCC particles.

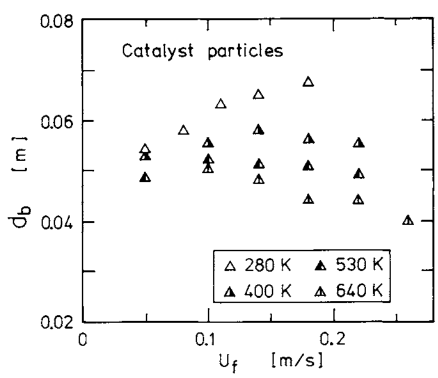

Fig. 9. Effect of increasing temperature on bubble size for catalyst particles.

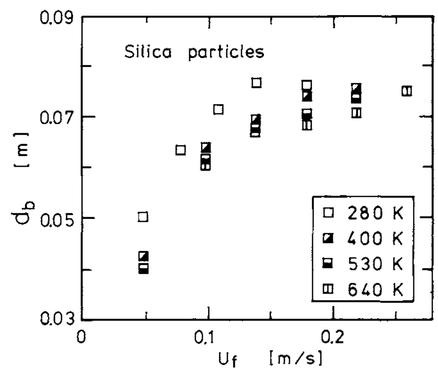

Fig. 10. Effect of increasing temperature on bubble size for silica particles.

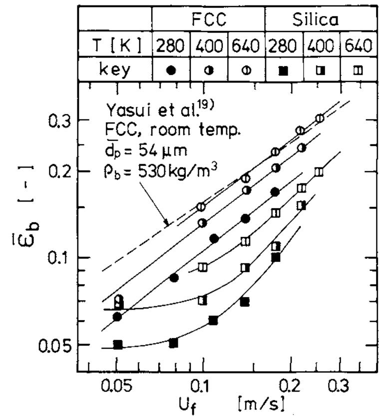

Fig. 11. Variation of bubble holdup with gas velocity.

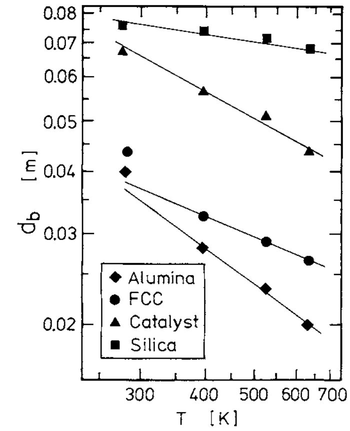

Fig. 12. Dependence of bubble size on temperature at $U_f = 0.18$ m/s.

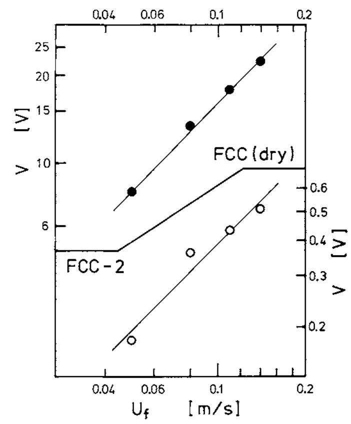

Fig. 13. Values of electrode potential at room temperature.

$\bar{\varepsilon}_b$ on temperature must be taken into consideration in calculating the extent of reactions in fluidized beds.

3. Discussion

The behavior of fluidized beds is found to be considerably affected by properties of the particles, even though the particles fall in Geldart's group A. Silica particles, which are not classified as A′ group[7] because of their large size, showed the lowest fluidity. Yasui *et al.*[19] have pointed out that the density of particles strongly affects bed behavior. In this study, the fluidity was lower for the catalyst particles, which were heaviest, than for alumina and FCC. The quality of fluidization increased with temperature for all four kinds of powders, but the effect was small for silica.

According to the result of Tone *et al.*,[18] the influence of increasing temperature on bubble size can be written as

$$d_b = \frac{a}{T^{1.21}} + b \tag{5}$$

Figure 12 shows the relationship between bubble size and temperature. From this figure it is clear that the dependence of bubble size on temperature differed by kind of particle. For the present case the exponents of temperature were 0.16–0.74.

The values of d_b at 280 K for alumina and FCC particles deviate from the linear correlation. This was caused, as already noted, by the electrostatic charge in the bed. The influence of electrification was, however, smaller on bubble size than on pressure fluctuations.

By visual observation it can be seen that fluidity of alumina and FCC particles was lower at room temperature than at elevated temperatures. In addition, the adhesion of particles on a glass or metal rod was observed at room temperature. Rowe *et al.*[15] have pointed out that particles less than 53 μm cannot be fluidized in the generally recognized sense due to electrostatic forces. Several investigators[1–3,8] have measured electric potential by using spherical probes. The relationship between the observed potential and electrostatic phenomena in beds has not been explained sufficiently. However, electrostatic charge in beds may roughly be expressed by the measured potential values.

Figure 13 shows the electrode potential observed for FCC at room temperature. The potential is considered to depend on the materials of the column and particles. Fujino *et al.*[3] have shown that large potentials over 1000 V were generated in acrylic columns and small values under 10 V in metallic columns. We obtained a value of 30 V as the maximum potential in a steel column. The increase in the potential was almost proportional to gas velocity. This trend agrees with previous reports.[2,8] The FCC-2 particles in the figure contained about 13% water in the pores, and the bulk density was 5.2×10^2 kg/m³. The visual fluidity is much better for FCC-2 than for the particles containing 2–3% water and for dry ones. It is clearly seen from the plot that the measured potential is much larger for dry FCC than for FCC-2. Therefore, it may be considered that low fluidity is caused by adhesion of particles due to the electrostatic charge.

The data of pressure fluctuations and bubble size for FCC-2 are added in Figs. 3 and 8. The hexagonal

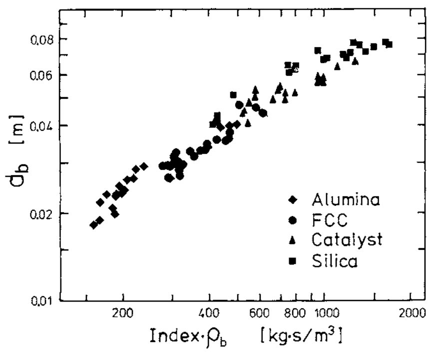

Fig. 14. Relationship between uniformity index and bubble size.

symbols in the figures show the values for FCC-2. The deviation δ_p (Fig. 3) does not depend on gas velocity at $U_f > 0.1$ m/s and approaches the results at elevated temperatures. The bubble size (Fig. 8) shows a similar tendency.

A uniformity index and bubble size have been used to evaluated the quality of fluidization in the above analysis. It is expected that there is a correlation between these two variables. They are plotted in **Fig. 14** for all data.

Conclusion

Fluidity of fluidized beds of alumina, FCC, catalyst and silica particles was studied. It can be expressed by pressure fluctuations and bubble size. The fluidity increased with temperature. The alumina and FCC particles showed considerably good quality of fluidization at elevated temperatures. The degree of their pressure fluctuations was almost independent of gas velocity. Catalyst particles of large densities showed lower fluidity than alumina and FCC at 280 K. The fluidity of catalyst increased with temperature and approached that of alumina and FCC. The effect of increasing temperature was smaller for silica than for the other particles.

It is shown that bed behavior of dry particles at ambient temperature was affected by electrostatic charge. The influence on fluidity decreased with increasing temperature. Particles containing about 13% water in the pores are much less affected by electrostatic forces at room temperature.

Nomenclature

a_b	= contact area of bubbles per unit volume of bed	[l/m]
d_b	= mean bubble size	[m]
d_p	= weight-averaged particle diameter	[m]
f_b	= bubble frequency	[l/s]
f_p	= dominant frequency of pressure fluctuations	[l/s]
k_{ob}	= overall mass transfer coefficient between bubble and emulsion phase	[m/s]
L_q	= height of settled bed	[m]
ΔP	= pressure drop	[kPa]
R	= radius of bed	[m]
r	= coordinate of radial position	[m]
T	= bed temperature	[K]
U_f	= superficial gas velocity	[m/s]
U_{mf}	= minimum fluidization velocity	[m/s]
V	= electrode potential	[V]
δ_p	= average deviation of amplitude of pressure fluctuations	[—]
ε_b	= local gas-bubble holdup	[—]
$\bar{\varepsilon}_b$	= average holdup of gas bubbles	[—]
ρ_b	= settled-bed density	[kg/m^3]

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