Incipient Fluidization at Different Temperatures and Powder Characterization

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Introduction

The phenomenon of gas fluidization at high temperatures has been investigated by many researchers because of its importance in many industrial operations. In particular, the superficial fluidizing velocity at incipient fluidization has been examined to establish the dependence of the minimum fluidizing velocity, U_{mf}, on temperature. Most of the works along this line are referred to in the studies by Desai et al. (1977), Saxena and Vogel (1977), Pattipati and Wen (1981), and Botterill et al. (1982). A number of correlations have been developed and have been assessed on the basis of available U_{mf} data by Babu et al. (1978), and Grewal and Saxena (1980), among others. Most of the investigations have substantiated the applicability of the well-known Ergun (1952) correlation, which can be expressed in the following form for an incipiently fluidized bed:

$$\left(\frac{1.75}{\phi_s\,\epsilon_{mf}^3}\right) Re_{mf}^2 + \left[\frac{150\,(1-\epsilon_{mf})}{\phi_s^2\,\epsilon_{mf}^3}\right] Re_{mf} - Ar = 0. \qquad (1)$$

In all these works, the coefficients of Re_{mf} and Re_{mf}^2 were assigned constant numerical values, implying that ϵ_{mf} does not depend on Re_{mf}.

Botterill et al. (1982) experimentally found that ϵ_{mf} initially decreased, and thereafter increased with increasing Ar. Lucas et al. (1986) found that ϵ_{mf} was approximately constant for $Re_{mf} < 0.75$, decreased for $0.75 < Re_{mf} < 2$, and remained constant for $Re_{mf} > 2$. Lucas et al. (1986), and Mathur and Saxena (1986) have interpreted these variations of ϵ_{mf} with Re_{mf}, or alternatively with Ar through Eq. 1, on the basis of the fluid flow field surrounding the particles. This feature therefore has an important impact on the development of a powder classification scheme. It has been experimentally investigated with the results reported here.

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Experimental

The fluidized-bed pilot plant facility employed in the present series of experiments is described in detail by Saxena and Mathur (1985); some modifications were adopted in the context of the present work primarily to visually examine the propane combustion patterns and the solids fluidization behavior. The fluidized air was supplied by a 18.65 kW two-stage compressor capable of supplying a maximum of 0.45 m^3/s of air at 375 kPa. The compressed air was dried and passed through two filters for the removal of oil and other vapors. Metered amounts of air were passed through an electric preheater to be heated to a maximum temperature of 525 K, and mixed with proper amounts of propane gas in the calming section of the bed prior to combustion in the fluidization column by an electric igniter located just above the bubble-cap distributor plate. The combustion flame was visually observed to be uniformly spread over the entire distributor plate. The top section of the fluidization column was removed to enable visual observations. The solids were then added gradually to build up a uniformly well-heated fluidized bed. Typical bed heights in these experiments ranged between 25 and 42 cm. Temperatures were recorded by three thermocouples located 2, 7, and 36 cm above the distributor plate. The temperatures of the first two thermocouples never differed by more than 2 K. Five pressure probes (located 2.5 cm below, and 1.5, 7.6, 28, and 45 cm above the distributor plate) were used to establish the distributor pressure drop, voidage in two regions of the bed, and bed height. The two values of the bed voidage corresponding to two regions of the bed agreed with each other within 1.5%; the upper bed region voidage was either equal to or greater than that in the lower bed region. This implies that there was negligible segregation in a substantial portion of the bed.

Beds of silica sand particles of 751 and 1,225 μm avg. dia. were used with particles varying in size from 500 to 1,000 μm in the former case, and from 600 to 2,430 μm in the latter. Bed pressure drop values, ΔP_b, were evaluated as a function of the superficial fluidizing velocity, U, and were plotted at each temperature level for a given bed. Figure 1 shows such plots for the

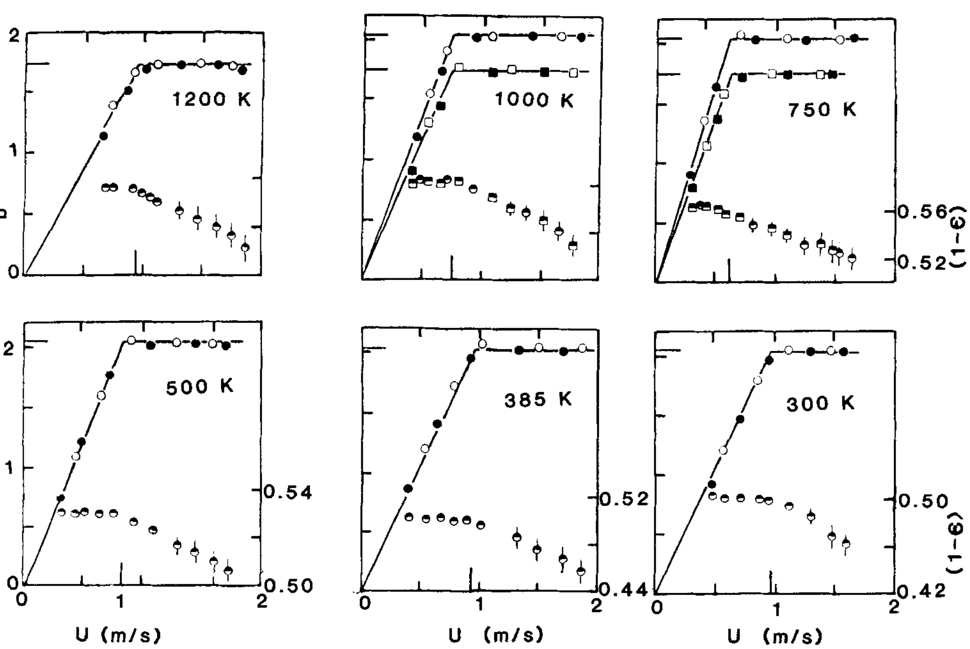

Figure 1. Bed pressure drop and particle concentration as a function of fluidizing velocity.

1,225 μm sand particles at temperatures noted
●■ decreasing velocities
○□ increasing velocities
○□ corresponding values of particle concentration

1,225 μm silica sand particle beds. Both sets of ΔP_b values, corresponding to increasing and decreasing values of U are shown, and in determining U_{mf}, the set of decreasing U values was given preference. The constant bed pressure drop values are in excellent agreement with the weight of the solids, W, per unit bed area, A. This confirms good fluidization, as was also visually observed. The beds were well mixed and vigorously bubbling. The bed voidage, ϵ, of a region of height h was determined from the corresponding pressure drop, ΔP_h, by the following relation:

$$\Delta P_h = h(\rho_s - \rho_g)g(1 - \epsilon). \qquad (2)$$

The computed values of ϵ are also shown plotted in Figure 1 as particle concentration, $1 - \epsilon$. The bed voidage values are relatively more uncertain due to pressure fluctuations at higher U values. The uncertainties are shown by vertical bars in Figure 1. Also, it was found that the bed height did not influence U_{mf}. The U_{mf} and ϵ_{mf} values are given Table 1 as a function of temperature together with similar results for beds of 751 μm silica sand particles. Also shown in this table are the calculated values of Re_{mf} and Ar from their defining relations and experimental data. ϕ_s values were then computed at each temperature from Eq. 1 and with the data listed in Table 1. The reasonably constant nature of ϕ_s values with temperature for the two sands indicates the general applicability of Eq. 1. This result is even more significant when viewed in the context of the wide size distribution of particles in the two beds. The present results, as well as earlier experimental data of ϕ_s for beds of a wide size range over a wide range of temperatures (Botterill et al., 1982), as well as for wide ranges of temperatures and pressures (Saxena and Vogel, 1977), suggest that Eq. 1 successfully represents the bed properties ϵ_{mf} and ϕ_s over a wide range of operating conditions and system parameters.

Discussion

In Figure 2 ϵ_{mf} values are plotted as a function of Re_{mf} for the two sands. It may be noted that for both sands, ϵ_{mf} first decreases with an increase in Re_{mf}, goes through a minimum, and then increases with further increase in Re_{mf}. The positions of the minima in the two cases are at different values of Re_{mf}, and for these two particles they lie in the approximate range of 10–14. Similar plots of ϵ_{mf} vs. Ar in Figure 3 exhibit minima that lie in the approximate range of 20,000–25,000. Botterill et al. also found similar minima in their plots of ϵ_{mf} vs. T_b for sands of $\bar{d}_p$ = 560, 780, and 890 μm. They characterized the position of the minimum by approximate values of 12.5 for Re_{mf} and 26,000 for

Table 1. Experimental Results

T_b K	Ar	U_{mf} m/s	Re_{mf}	ϵ_{mf}	ϕ_s
		$\bar{d}_p$ = 751 μm			
1,150	1,633	0.70	3.5	0.58	0.70
925	2,672	0.56	4.0	0.57	0.75
725	4,618	0.47	5.1	0.53	0.72
500	10,886	0.35	6.8	0.47	0.73
385	20,283	0.40	7.2	0.40	0.74
300	38,013	0.30	15.0	0.43	0.72
		$\bar{d}_p$ = 1225 μm			
1,200	6,400	0.96	7.3	0.53	0.78
1,000	9,728	0.75	7.8	0.48	0.80
750	18,534	0.62	10.2	0.44	0.80
500	47,258	0.82	26.4	0.47	0.79
385	88,060	0.94	47.6	0.49	0.81
300	165,050	0.96	74.7	0.50	0.81

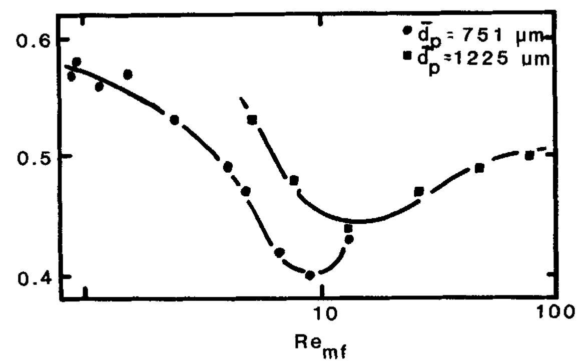

Figure 2. Variation of incipient bed voidage with Reynolds number at minimum fluidization.

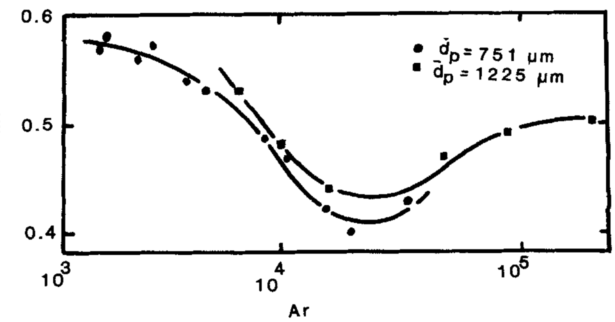

Figure 3. Variation of incipient bed voidage with Archimedes number.

Ar. Our values are in approximate but reasonable agreement with their findings.

In this context, it is important to point out that the present investigation resolves the controversy that arose out of the work of Botterill et al. (1982) and Pattipati and Wen (1981). The latter workers (Pattipati and Wen, 1982) emphasized that the mode of heating the bed was responsible for the minimum observed by Botterill et al., and that there would be no variation in ϵ_{mf} if the bed was directly heated instead of by the preheated gas, as was done by Botterill et al. Our work demonstrates that how the bed is heated is not important as long as the bed has a uniform temperature. The presence of a minimum in the plots of ϵ_{mf} vs. T_b, Re_{mf}, or Ar is clearly confirmed and demonstrated by this work, and the reason for its existence is explained in the following.

The variation in ϵ_{mf} occurs due to the changing nature of the interparticle force as the flow field around the particles alters with varying Re. The latter has been the overriding consideration in the powder classification scheme of Saxena and Ganzha (1984). The effect of the changing flow field on ϵ_{mf} has been highlighted by Mathur and Saxena (1986), and Lucas et al. (1983, 1986). This is described briefly in the following. As Re increases, the flow around the particles starts deviating from laminar, and a wake is formed on the downstream side of the particles, which being a region of low pressure attracts neighboring particles. The wake size increases with increase in Re, resulting in a continuous decrease of bed voidage with increase in Re. With futher increase in Re, the separation point moves toward the downstream side and the wake size decreases, causing an increase in the bed voidage. This is indeed the qualitative trend of ϵ_{mf} variation with R_{mf} observed in the present and in the two earlier experimental investigations. It will be interesting to perform similar experiments with particles of different sizes and shapes in order to establish more definitively the location of the minimum and its dependence on particle shape, size, size range, and on operating and system parameters.

Notation

A = cross-sectional area of bed, m^2
Ar = Archimedes number, $g\bar{d}_p^3\rho_g(\rho_s - \rho_g)/\mu_g^2$
$\bar{d}_p$ = average particle diameter, m
g = acceleration due to gravity, m/s^2
h = vertical distance in bed, m
Re_{mf} = Reynolds number at minimum fluidization, $U_{mf}\bar{d}_p\rho_g/\mu_g$
T_b = bed temperature, K
U = superficial fluidizing velocity, m/s
U_{mf} = superficial fluidizing velocity at minimum fluidization, m/s
W = weight of particles in bed, N

Greek letters

ΔP_b = pressure drop across bed, N/m^2
ΔP_h = pressure drop across a vertical distance h in bed, N/m^2
ϵ = bed voidage
ϵ_{mf} = bed voidage at minimum fluidization
ϕ_s = particle sphericity
ρ_g = density of fluidizing gas, kg/m^3
ρ_s = solids density, kg/m^3
μ_g = viscosity of fluidizing gas, kg/m · s

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