On Partial Fluidization in Rotating Fluidized Beds

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The understanding of the operation of rotating fluidized beds has been of interest to many researchers (Lindauer et al., 1966; Levy and Chen, 1977; Levy et al., 1978; Pfeffer and Hill, 1978; Takahashi et al., 1984; Fan et al., 1985; Gal et al., 1986; Chen, 1986) since these devices have some industrial applications, such as in coal combustion, drying, and dust filtration. The rotating fluidized bed is essentially a cylinder with porous walls that rotates around its axis of symmetry, as shown in Figure 1. Fluidization material in the form of granules is introduced into the cylinder and is forced to the wall due to the large centrifugal forces produced by the rotation. The wall serves as the gas distributor, and the gas flows radially inward through it and through the bed of granules. When the drag forces on the granules balance the centrifugal forces, the bed becomes fluidized. Minimum fluidization can, in principle, be achieved at any gas flow rate by changing the rotating speed of the bed. The rotating fluidized bed permits a much higher gas flow rate per unit area of the distributor than is possible in a conventional fluidized bed that operates only against the force of gravity.

In a rotating fluidized bed, unlike in a conventional fluidized bed, the granules are fluidized layer by layer from the (inner) free surface outward at increasing radius as the gas velocity is increased. This is a very significant and interesting phenomenon and is extremely important in the design of these fluidized beds. The phenomenon was first suggested in a theoretical analysis by Chen (1986) and recently verified experimentally in our laboratory. However, in Chen's paper, the equations presented are too cumbersome and the influence of bed thickness is not clearly stated.

In this note we present simplified equations, based on Chen's paper, for the pressure drop and the minimum fluidizing velocities in a rotating fluidized bed. Experimental data are also shown and compared with the theoretical model, and the effect of bed thickness is shown. Furthermore, an explanation for the observation of a maximum in the pressure drop vs. velocity curve reported by Takahashi et al. (1984) and Fan et al. (1985) instead of the plateau derived by Chen is proposed.

Theoretical Model

The theoretical analysis of the pressure drop and the fluidization velocity is based on the semiempirical equations of Chen (1986). In the fixed-bed region the pressure drop is given by

$$\frac{dP}{dr} = \phi_1\left(\frac{U_o r_o}{r}\right) + \phi_2\left(\frac{U_o r_o}{r}\right)^2 + \rho_f r\omega^2 + \frac{\rho_f U_o^2 r_o^2}{\epsilon^2 r^3} \quad (1)$$

where

$$\phi_1 = \frac{150(1-\epsilon)^2\mu}{\epsilon^3(\phi_s d_g)^2}, \quad \phi_2 = \frac{1.75(1-\epsilon)\rho_f}{\epsilon^3\phi_s d_g} \quad (1a)$$

and is based on the Ergun equation. In the fluidized-bed region it is given by

$$\frac{dP}{dr} = \rho_g(1-\epsilon)r\omega^2 + \rho_f\epsilon r\omega^2 + \frac{\rho_f U_o^2 r_o^2}{\epsilon r^3} + \frac{\rho_f U_o^2 r_o^2}{\epsilon^2 r^2}\frac{d\epsilon}{dr}. \quad (2)$$

In Eqs. 1 and 2, however, the major contribution in the fixed-bed region is the drag force per unit volume of fluid (the first two terms on the righthand side), while in the fluidized-bed region the major contribution is the total mass of particles (the first term on the righthand side). The remaining terms, including the effect of inertia and variable porosity, contribute less than 1% of the total pressure drop and can therefore be neglected. Hence, Eqs. 1 and 2 reduce to

$$\frac{dP}{dr} = \phi_1\left(\frac{U_o r_o}{r}\right) + \phi_2\left(\frac{U_o r_o}{r}\right)^2 \quad (3)$$

in the fixed-bed region and to

$$\frac{dP}{dr} = (\rho_g - \rho_f)(1-\epsilon)r\omega^2 \quad (4)$$

in the fluidized-bed region.

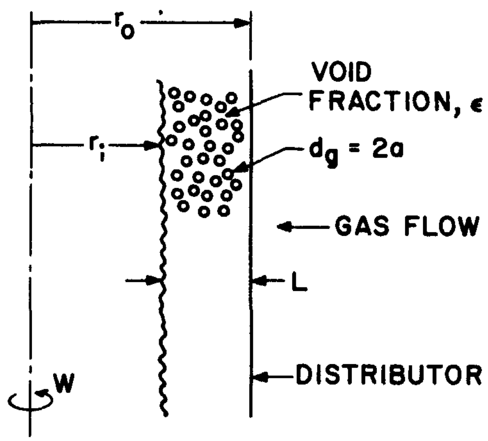

Figure 1. Rotating fluidized bed.

If the sphericity, ϕ_s in Eq. 1a, is not known, the correlations suggested by Wen and Yu (1966) can be used:

$$\frac{1}{\phi_s \epsilon^3} \approx 14 \quad \text{and} \quad \frac{(1-\epsilon)}{\phi_s^2 \epsilon^3} \approx 11$$

and thus:

$$\phi_1 = \frac{1{,}650(1-\epsilon)\mu}{d_g^2}, \quad \phi_2 = \frac{24.5(1-\epsilon)\rho_f}{d_g}. \tag{1b}$$

The minimum fluidization velocity in the rotating fluidized bed can be found by equating the pressure drop across the rotating fluidized bed with that across a packed bed. However, the air velocity is a function of radius, r, and it decreases outward with increasing r, resulting in a reduction in fluid drag. In contrast, the centrifugal force increases with increasing r. Consequently, fluidization occurs layer by layer outward, starting with the inner surface, as the superficial air velocity increases. The average minimum fluidization velocity, U_{mf}, is found by equating the total pressure drop across the fixed bed to that of the fluidized bed (integrating Eqs. 3 and 4 from r_i to r_o, respectively) to obtain:

$$\frac{U_{mf}\rho_f d_g}{\mu} = \left[\left(33.7\frac{C_2}{C_1}\right)^2 + 0.0408\frac{\rho_f(\rho_g-\rho_f)d_g^3\omega^2}{\mu^2}\frac{C_3}{C_1}\right]^{1/2} - 33.7\frac{C_2}{C_1} \tag{5}$$

where

$$C_1 = r_o^2(1/r_i - 1/r_o)$$
$$C_2 = r_o \ln(r_o/r_i)$$
$$C_3 = (r_o^2 - r_i^2)/2.$$

In addition to the average minimum fluidization velocity U_{mf}, which is also used by other investigators (Takahashi et al., 1984 and Fan et al., 1985), the surface and critical minimum fluidization velocities, U_{mf_s} and U_{mf_c}, are also introduced to further explain the transition from the packed to the fluidized state in the rotating fluidized bed. As stated earlier, fluidization in the rotating fluidized bed occurs layer by layer and thus the surface minimum fluidization velocity U_{mf_s}, defined as the velocity at which the bed's inner surface first experiences fluidization, is calculated by equating the local pressure drop across the fluidized bed and the packed bed, using Eqs. 3 and 4 evaluated at $r = r_i$. This yields:

$$\frac{U_{mf_s}\rho_f d_g}{\mu}\frac{r_o}{r_i} = \left[(33.7)^2 + 0.0408\frac{\rho_f(\rho_g-\rho_f)d_g^3\omega^2 r_i}{\mu^2}\right]^{1/2} - 33.7. \tag{6}$$

Similarly, the critical minimum fluidization velocity U_{mf_c}, defined as the velocity at which the whole bed is fluidized, can be computed using Eqs. 3 and 4 evaluated at $r = r_o$. The result is:

$$\frac{U_{mf_c}\rho_f d_g}{\mu} = \left[(33.7)^2 + 0.0408\frac{\rho_f(\rho_g-\rho_f)d_g^3\omega^2 r_o}{\mu^2}\right]^{1/2} - 33.7. \tag{7}$$

From the above definitions, the pressure drop across the bed is determined depending on the superficial velocity, U_o, as follows.

$U_o \le U_{mf_s}$

Since the superficial air velocity U_o is less than the surface minimum fluidization velocity U_{mf_s}, the bed is packed everywhere and the pressure drop is calculated using Eq. 3:

$$\Delta P_p = \phi_1 U_o r_o \ln(r_o/r_i) + \phi_2 U_o^2 r_o^2 (1/r_i - 1/r_o). \tag{8}$$

$U_{mf_s} < U_o < U_{mf_c}$

For this condition, the bed is partially fluidized and the resulting pressure drop across the bed is a combination of the pressure drop across the fluidized bed and the packed bed: $\Delta P = \Delta P_f + \Delta P_p$, or,

$$\Delta P = (1-\epsilon)(\rho_g - \rho_f)\omega^2(r_{pf}^2 - r_i^2) + \phi_1 U_o r_o \ln(r_o/r_{pf}) + \phi_2 U_o^2 r_o^2 (1/r_{pf} - 1/r_o) \tag{9}$$

where r_{pf} is the interface of the fluidized and packed beds and can be computed by equating Eqs. 3 and 4 at a given superficial air velocity.

$U_o \ge U_{mf_c}$

When the air velocity finally equals or exceeds that of the critical minimum fluidization velocity U_{mf_c}, the bed is completely fluidized and the pressure drop is calculated using Eq. 4:

$$\Delta P_f = (1-\epsilon)(\rho_g - \rho_f)\omega^2(r_o^2 - r_i^2)/2. \tag{10}$$

Results and Discussion

Figure 2 shows experimental data for the pressure drop in a rotating fluidized bed of outside radius r_o = 10 cm containing 0.3 cm dia. polyethylene granules (ρ_g = 0.932 g/cm^3) as a function of air velocity for various *initial* bed thicknesses. Also shown

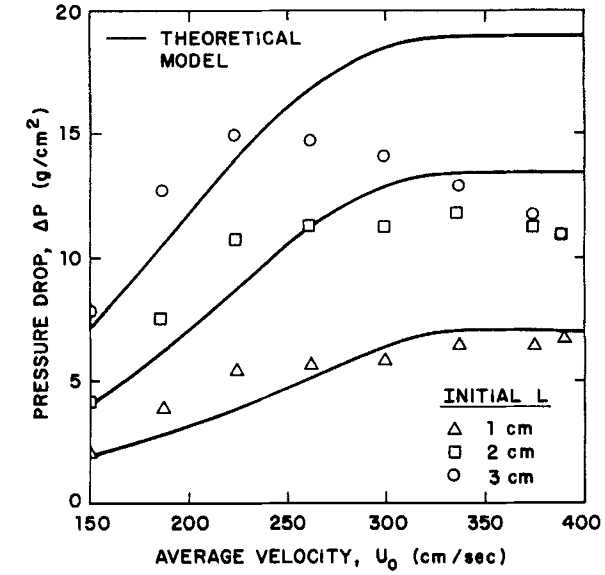

Figure 2. Pressure drop in rotating fluidized bed as a function of air velocity for various initial bed thicknesses.

Polyethylene granules, 0.3 cm dia., density 0.932 g/cm^3; Rotating speed W = 345 rpm; Bed porosity ϵ = 0.4

are the results of the theoretical model (solid curves) assuming partial fluidization. It is seen that the model predicts the pressure drop for the 1 cm thick bed quite well but overestimates the pressure drop for the thicker beds. The reason for this is that for the 1 cm thick bed, the surface minimum fluidization velocity U_{mf_s} is 85% that of the critical minimum fluidization velocity U_{mf_c}, as shown in Table 1. Since these velocities do not differ by much, the drag force produced by the inlet air does not exceed the centrifugal force to carry the granules out of the bed. Thus, a completely fluidized bed is achieved, as suggested by the flattening of the curve. For the thicker beds, however, the surface minimum fluidization velocity U_{mf_s} is much lower than that of the critical fluidization velocity. From Table 1, the minimum fluidization velocity U_{mf_s} is only 71 and 58% of the critical fluidization velocity for the 2 and 3 cm thick beds, respectively. Consequently, at the critical minimum fluidization velocity U_{mf_c} the drag force of the inlet air is much higher than the centrifugal force at the surface of the bed. As a result, the drag force of the air continuously carries granules at the surface out of the bed until it is balanced by the centrifugal force of the remaining granules. As shown in Figure 2, the pressure drop curve for the 3 cm thick bed exhibits the maximum described by Takahashi et al. (1984) and Fan et al. (1985) in the fluidized-bed region instead of the plateau seen for the 1 cm thick bed, because in the thick bed the effective weight of the granules is reduced due to the loss of granules by elutriation.

Furthermore, we have conducted experiments operating at the average minimum fluidizing velocity, which is between the surface and the critical minimum fluidizing velocity, with a bed originally loaded with black polyethylene granules continuously fed with white polyethylene granules, and discharging granules from inside the bed continuously at the same rate as the feed. After a given time the bed was examined and found to contain two separate layers of granules, a white layer inside and a predominantly black layer near the distributor. This experiment verifies the existence of an interface between the fluidized-bed region (white granules) and the packed-bed region (black granules) due to partial fluidization. The phenomenon of partial fluidization is strongly dependent on the thickness of the bed and the radius of the bed. As shown in Table 1, the ratio of the surface to critical minimum fluidizing velocity drops from 0.85 to 0.58 when the bed thickness is increased from 1 to 3 cm in a 10 cm bed, and back to 0.85 for a 3 cm thick bed when the radius of the bed is increased to 30 cm. Therefore partial fluidization is very significant in the 3 cm thick bed (10 cm radius) but relatively unimportant in the 1 cm thick bed (10 cm radius) and in the 3 cm thick bed of radius 30 cm. This phenomenon is very important in designing a rotating fluidized bed in order to avoid the problem of nonuniformity of the bed, which could lead to a drastic reduction in heat and mass transfer rates.

Table 1. Minimum Fluidization Velocities, Calculated from Eqs. 6 and 7

Bed Thickness L cm	Bed Diameter, cm: 20 — U_{mf_s} cm/s	20 — U_{mf_s}/U_{mf_c}	60 — U_{mf_s} cm/s	60 — U_{mf_s}/U_{mf_c}
0	335.2	1.00	592.3	1.00
1	285.5	0.85	562.7	0.95
2	238.5	0.71	533.6	0.90
3	194.5	0.58	505.0	0.85

Data: Polyethylene granules
d_g = 0.3 cm; ρ_g = 0.932 g/cm^3
Air
μ = 1.780 × 10^{-4} g/cm · s; ρ_f = 1.204 × 10^{-3} g/cm^3
Rotating speed W = 345 rpm

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Notation

d_g = granule diameter, cm
L = bed thickness, cm
ΔP = total pressure drop across rotating fluidized bed, g/cm^2
ΔP_f = pressure drop across fluidized bed, g/cm^2
ΔP_p = pressure drop across packed bed, g/cm^2
r = radial coordinate, cm
r_i = radius of inner surface of granule bed, cm
r_o = radius of rotating fluidized bed, cm
r_{pf} = radius of interface of fluidized and packed beds, cm
U_{mf} = average minimum fluidization velocity, cm/s
U_{mf_c} = critical minimum fluidization velocity, cm/s
U_{mf_s} = surface minimum fluidization velocity, cm/s
U_o = superficial air velocity based on outside radius r_o
W = rotating speed, rpm

Greek letters

ϵ = void fraction
μ = air viscosity, g/cm · s
ρ_f = air density, g/cm^3
ρ_g = granule density, g/cm^3
ϕ_s = sphericity of granule
ω = angular velocity, rad/s

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