Prediction of Minimum Velocity and Minimum Bed Pressure Drop for Gas-Solid Fluidization in Conical Conduits

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Experimental investigations have been carried out for spherical and non-spherical particles using beds comprised of single-sized particles and mixtures in the size and particle density ranges of 439 to 1524 μm and 1303 to 4948 kg/m^3, respectively. Five conical fluidizers with varying apex angles of 8.86, 14.77, 19.60, 32.0 and 43.2 degrees were used. Experimental values of minimum velocity and bed pressure drop with air as the fluidizing medium have been compared with their respective values obtained from different models available in the literature. Deviations for each chosen model have been presented.

Des recherches expérimentales ont été réalisées pour des particules sphériques et non sphériques avec des lits emplis de particules avec des tailles et des densités uniques comprises dans une gamme variant de 439 à 1524 μm et de 1303 à 4948 kg/m^3, respectivement. Cinq fluidicateurs coniques ayant des angles au sommet variés de 8,86, 14,77, 19,60, 32,0 et 42,2 degrés ont été utilisés. Les valeurs expérimentales de la vitesse minimum et de la perte de charge du lit avec l'air comme moyen de fluidisation, ont été comparées aux valeurs correspondantes obtenues à partir de différents modèles publiés dans la littérature. Les écarts sont présentés pour chaque modèle choisi.

Keywords: gas fluidization, conical fluidized bed, minimum fluidization velocity, pressure drop ΔP.

Fluidization has found extensive applications in unit operations like drying, adsorption and in chemical processes viz. solid-catalyzed reactions, combustion, carbonization and gasification (Shi et al., 1984). In gas-solid fluidization, solids mixing often is desirable for high rates of heat and mass transfer which are attributed to enhanced turbulence in the bed. However, this brings in considerable back-mixing of the solids which is undesirable. A conventional columnar fluidized bed is prone to back-mixing (Shi et al., 1984; Toyohara and Kawamura, 1989).

The quality of fluidization, i.e., the fluctuation ratio in a conventional bed, is seriously affected by bubbling, slugging and channeling, resulting in poor gas-solid contact, and lower diffusion and heat transfer rates. In many fluid-solid contacting processes, the particle sizes are not uniform and fluidization is badly affected (Kunii and Levenspiel, 1969). The introduction of baffles in conventional beds has been reported to result in significant improvement in the fluidization quality, but there is not smooth fluidization for different particle sizes (Agarwal and Roy, 1987). Use of a conical bed for fluidization reduces back-mixing in the longitudinal direction and also ensures smooth fluidization of mixed particle sizes.

Dynamics of a conical bed

In view of its potential application in the fields of gas-solid systems, it is a pre-requisite that the dynamics of the bed be explicitly understood. Two bed characteristics of relevance in this context are the minimum velocity (U_{mf}) and pressure drop ($-\Delta P_{mf}$) for a fluidized bed.

MINIMUM FLUIDIZATION VELOCITY

Several models (approaches) are available for the prediction of U_{mf} for conventional fluidized beds. A few of these which have been tested for the present study are:

(1) Drag coefficient approach according to Kmiec (1982) and Jean and Fan (1987).
(2) Empirical equations of Lucas et al. (1969).

In addition to the above, some equations developed for conical conduits by earlier investigators have also been tested. These include,

(3) The force balance approach of Agarwal and Roy (1988) and Shi et al. (1984). Here the entrance diameter of the cone to the bed is used to calculate U_{mf}.

The equations for all the above models are presented in Table 1.

PRESSURE DROP AT MINIMUM FLUIDIZATION

For calculation of pressure drop at minimum fluidization of spherical particles in a conical fluidized bed, three models have been tested, out of which two are of Agarwal and Roy (1988) and Biswal et al. (1984) for conical conduits and the third one is of Leva (1959) for a conventional bed. The Agarwal and Roy (1988) model for conical beds is based on a force balance, while the model of Biswal et al. (1984) is an empirical development. The model of Leva (1959) is the well-known force balance model for cylindrical beds. In addition to the above, the drag force approach of Kmiec (1982) and Jean and Fan (1987) has also been tested for non-spherical particles. The mathematical expressions for these models are presented in Table 2.

Experimental

The experimental set up and the steps followed have been detailed in Biswal et al. (1984). Table 3 depicts the ranges of variables investigated in the present study. The shape factor was determined using the equation, $(1 - \epsilon)/\phi_s = 0.231 \log d_p + 1.417$ where d_p is the particle diameter in feet (Narsimhan, 1965).

Results and discussion

Experimental values of the minimum velocity and bed pressure drop at the minimum fluidization velocity for gas-solid fluidization of spherical and non-spherical particles are compared with their respective values obtained from different

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TABLE 1
Equations for Minimum Fluidization Velocity

Authors	Model No.	Equations
Agarwal and Roy (1988)	1	$U_{mf} = -B_1 + [(B_1^2 + 4A_1C_1)^{0.5}]/2A_1$
		$A_1 = \pi BD_o^3H/4(D_o + 2H \tan \alpha/2)$
		$B_1 = \pi AD_o^2H/4$; $C_1 = K[(H + h_o)^3 - h_o^3]/3$
		$K = g(1 - \epsilon)(\rho_p - \rho_f)\pi D_o^2/4h_o^2$
Lucas et al. (1986)	2	$Re_{mf} = (32.1^2 + 0.0571\ Ar)^{0.5} - 32.1$(non-spherical particles)
		$Re_{mf} = (29.5^2 + 0.0357\ Ar)^{0.5} - 29.5$(round particles)
Kmieć (1982)	3	$\epsilon^{-n}\ C_D\ \pi\ d_P^2\ U_{mf}^2\ \rho_f/8 = \pi d_P^3\ g(\rho_P - \rho_f)/6$
		$n = 4.62$ to 4.78
		$C_D = (24/Re_P)(1 + 0.15\ Re_P^{0.687})$
Jean and Fan (1987)	4	$\epsilon^{-2}\ C_D\ \pi\ d_P^2\ U_{mf}^2\ \rho_f/8 = \pi\ d_P^3\ g(\rho_P - \rho_f)/6$
		$C_D = (24/Re_P)(1 + 0.15\ Re_P^{0.687})$

TABLE 2
Equations for Pressure Drop at Minimum Fluidization Velocity

Authors	Model No.	Equations
Agarwal and Roy (1988)	1	$-\Delta P_{mf} = 9.807\ A\ H\ h_o\ U_{mf}/(H + h_o) + B\ h_o/3\ [(H + h_o)^3 - h_o^3]\ U_{mf}/(H + h_o)^3$
Kmieć (1982)	3	$-\Delta P_{mf} = 29.421\ \epsilon{-4.78}\ C_D\ U_{mf}^2\ \rho_f\ M/(4\ d_P\ \phi_S\ \rho_P\ A_m\ g)$
Jean and Fan (1987)	4	$-\Delta P_{mf} = 29.421\ \epsilon^{-2}\ C_D\ U_{mf}^2\ \rho_f\ M/(4\ d_P\ \phi_S\ \rho_P\ A_m\ g)$
Leva (1959)	6	$-\Delta P_{mf} = L_{mf}(1 - \epsilon)(\rho_P - \rho_f)9.807$
Biswal et al.	7	$-\Delta P_{mf} = \cos(\alpha/2)\{37.17(\tan\alpha)^{-0.47}\ \mu(1 - \epsilon)^2\ R_o(R - R_o)U_o/(g_C\ d_P^2\ \epsilon\ R) + 0.75\ \rho_f(1 - \epsilon)R_o[1 - (R_o/R)^3]\ U_o^2/(3\ g_{C}\ {}_{d_p}\ \epsilon^3)\}9.807$

TABLE 3
Ranges of Variables Studied

S1.No.	Material	ρ_P (g/cm^3)	ϵ (—)	ϕ_S (—)	d_p (mm)	α (deg.)	H (cm)
1	Chromite	4.050	0.380	0.78	0.5765	19.60	6.0
2	Chromite	4.050	0.375	0.79	0.5345	19.60	6.0
3	Chromite	4.050	0.360	0.80	0.4980	19.60	6.0
4	Chromite	4.050	0.360	0.80	0.4980	19.60	7.7
5	Chromite	4.050	0.360	0.80	0.4980	19.60	9.5
6	Chromite	4.050	0.360	0.80	0.4980	19.60	10.5
7	Chromite	4.050	0.350	0.81	0.4666	19.60	6.0
8	Chromite	4.050	0.340	0.82	0.4387	19.60	6.0
9	Chromite+ pyrolusite	4.50	0.380	0.84	0.6000	19.60	6.0
10	Zinc ore + pyrolusite	3.890	0.420	0.75	0.6000	19.60	8.4
11	Dolamite+ Zinc ore	2.786	0.370	0.84	0.6000	19.60	8.4
12	Dolamite+sand	2.680	0.370	0.80	0.6000	19.60	8.5
13	Dolamite+ manganese ore	3.845	0.380	0.78	0.6000	19.60	7.0
14	Sand+chromite	3.335	0.360	0.80	0.6000	19.60	6.0
15	Chromite	4.055	0.390	0.80	0.4980	14.77	6.0
16	Chromite	4.055	0.395	0.80	0.4980	8.86	6.0
17	Chromite	4.055	0.320	0.80	0.4980	32.00	6.0

cont......

Table 3 Continued

18	Chromite	4.055	0.300	0.80	0.4980	43.20	6.0
19	Sagu	1.303	0.380	1.00	1.3300	14.77	6.5
20	Sagu	1.303	0.380	1.00	1.3785	14.77	6.5
21	Sagu	1.303	0.380	1.00	1.4300	14.77	6.5
22	Sagu	1.303	0.380	1.00	1.4755	14.77	6.5
23	Sagu	1.303	0.380	1.00	1.5240	14.77	6.5
24	Sagu	1.303	0.380	1.00	1.2815	14.77	6.5
25	Sagu	1.303	0.38	1.0	1.3785	14.77	7.9
26	Sagu	1.303	0.38	1.0	1.3785	14.77	9.1
27	Sagu	1.303	0.38	1.0	1.3785	14.77	10.1
28	Sagu	1.303	0.38	1.0	1.3785	19.6	9.1
29	Sagu	1.303	0.38	1.0	1.3785	9.00	9.1
30	Sagu	1.303	0.38	1.0	1.3785	8.86	9.1
31	Glass beads+urea	2.240	0.38	1.0	1.2815	19.6	9.1
32	Sagu+urea	1.462	0.38	1.0	1.2815	19.6	9.1
33	Sagu+glass beads	1.822	0.38	1.0	1.2815	19.6	9.1
34	Glass bead+ mustard seed	2.017	0.38	1.0	1.2815	19.6	9.1
35	Sagu+mustard seed	1.239	0.38	1.0	1.2815	19.6	9.1
36	Urea+mustard seed	1.477	0.38	1.0	1.2815	19.6	9.1

D_o = 4.2; Atmospheric temp. = 28°C to 40°C

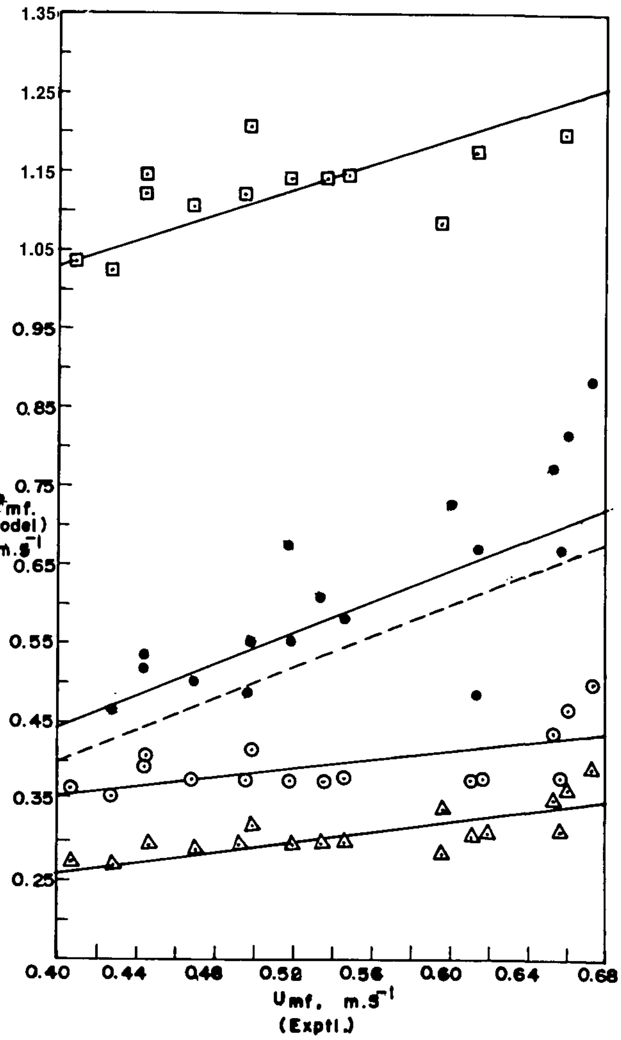

Figure 1 — U_{mf} (model) Vs. U_{mf} (exptl.) for spherical particles

LEGEND
- ● — MODEL 1
- ○ — MODEL 2
- △ — MODEL 3
- □ — MODEL 4
- - - — 45° LINE

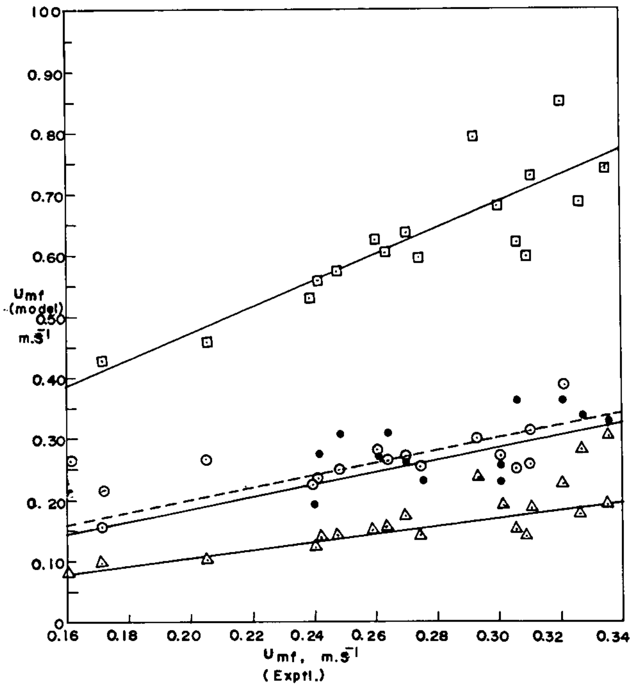

Figure 2 — U_{mf} (model) Vs. U_{mf} (exptl.) for non-spherical particles

LEGEND
- ● — MODEL 1
- ○ — MODEL 2
- △ — MODEL 3
- □ — MODEL 4
- - - — 45° LINE

models (Tables 1 and 2 in Figures 1 to 3. Mean and standard deviations for the calculated values for several chosen models (i.e., the models giving calculated values with less than thirty percent error, either in pressure drop or velocity from experimental ones) are presented in Table 4. Values for the pressure drop at the minimum fluidization velocity and deviations for spherical particles could not be calculated due to non-availability of data applicable to the models of Kmieć (1982) and Jean and Fan (1987).

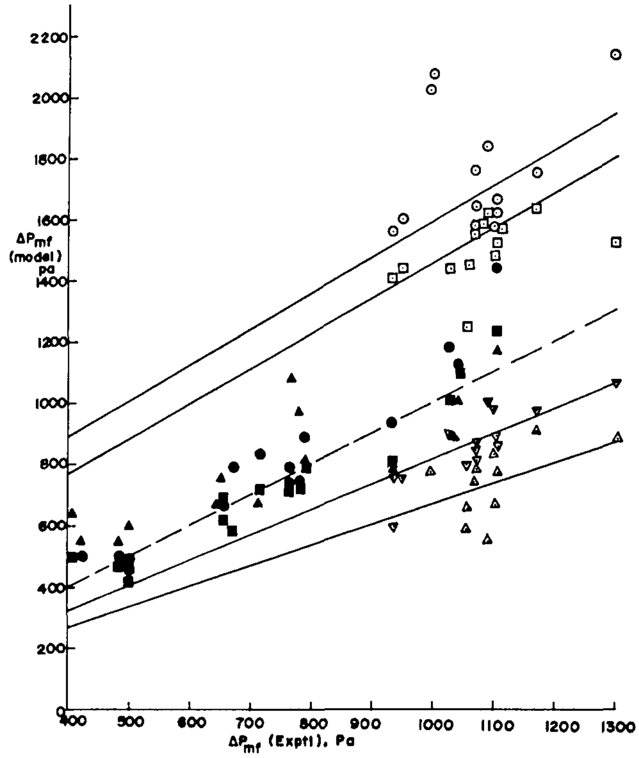

Figure 3 — ΔP_{mf} (model) Vs. ΔP_{mf} (exptl.) for spherical and non-spherical particles

LEGEND

(SPHERICAL)	(NON SPHERICAL)
■ — MODEL 6	○ — MODEL 1
▲ — MODEL 7	▽ — MODELS 3 and 4
● — MODEL 1	□ — MODEL 6
- - — 45° LINE	△ — MODEL 7

Conclusion

For the minimum fluidization velocity, the models proposed by Agarwal and Roy (1988), Lucas et al. (1986) and Kmieć (1982) show fairly good agreement with observations. For the minimum fluidization pressure drop, the models of Agarwal and Roy (1988), Kmieć (1982), Jean and Fan (1987), Leva (1959) and Biswal et al. (1984) provide reasonable results and are acceptable. In general, the deviations observed for the case of non-spherical particles were greater than those for the spherical particles, specifically for the minimum fluidization bed pressure drop. This may be attributed to the sphericity factor. The sphericity factor used' in the present study for calculation of ΔP_{mf} using different models has been obtained from an empirical equation involving the minimum bed voidage, the accurate measurement of which is fairly difficult under existing experimental conditions. However the models of Agarwal and Roy (1988), Lucas et al. (1986) and Kmiec (1982) for the minimum fluidization velocity and the models of Agarwal and Roy (1988), Leva (1959) and Biswal et al. (1984) for minimum fluidized bed pressure drop can be used with fairly good accuracy for gas-solid fluidization in conical conduits.

In summary, the present investigation has established the superiority of the model of Agarwal and Roy (1988), except for ΔP_{mf} for non-spherical particles. The model equation can be used effectively in making suitable computations for the dimensions and power consumption in the design of conical fluidizers having potential applications in various gas-solid systems.

Nomenclature

A	$= 150(1 - \epsilon)^2\mu/(g_c\, d_p^2\, \epsilon^3\, \phi_s^2)$
A_m	= mean area, m^2
Ar	= Archimedes number, $g\, d_p^3\, (\rho_p - \rho_f)\, \rho_f/\mu^2$
B	$= 1.75\, \rho_f\, (1 - \epsilon)/(g_c\, d_p\, \epsilon^3\, \phi_s)$
C_D	= drag coefficient, (-)
D_o	= diameter at the entrance of the cone, m
d_p	= diameter of particle, m
g	= standard gravitational acceleration, 9.80665 m/s^2
g_c	= Newton's constant, kg · m/kg$_f$ · s^2
H	= static bed height, m
h_o	= distance between the apex and the bottom of the tapered bed, m
L_{mf}	= length of static bed, m
M	= mass of the particles, kg
R	= radial distance from the apex of the cone to the top of bed, m
Re_{mf}	= Reynolds number at minimum fluidization $= d_p\, \rho_f\, U_{mf}/\mu$
Re_p	= particle Reynolds number $= d_p\, \rho_f\, U_o/\mu$
R_o	= radial distance from the apex of the cone to the bottom of bed, m
U_{mf}	= linear velocity at minimum fluidization based on the diameter at the entrance to the bed, m/s

TABLE 4
Deviations of Experimental and Predicted Values for the Minimum Fluidization Velocity (U_{mf}) and Pressure Drop at U_{mf}

U_{mf}(m/s)	Percentage deviation							
Model No.[(a)]	1		2		3		4	
	b	c	b	c	b	c	b	c
Mean	14.21	13.82	26.06	13.53	45.13	42.86	125.1	131.4
Standard	17.49	16.31	28.84	20.99	44.36	56.16	125.8	149.9

$-\Delta P_{mf}$(Pa)	Percentage deviations							
	1		3	4	6		7	
Model No.[(a)]	b	c	c	c	b	c	b	c
Mean	12.31	58.22	20.87	20.87	8.55	42.90	17.48	34.42
Standard	19.39	63.67	24.48	24.48	12.02	47.35	22.74	37.70

(a) see Tables 1 and 2
(b) spherical; (c) non-spherical

U_o = linear velocity of fluid at the entrance to the bed, m/s

Greek letters

α = angle of cone, deg.
$-\Delta P_{mf}$ = pressure drop at the minimum fluidization velocity
ϵ = porosity of bed
ϕ_s = sphericity factor
μ = viscosity of the fluid, kg/(m · s)
ρ_f = density of the fluid, kg/m^3
ρ_P = density of the particle, kg/m^3

References

Tayohara, H. and Y. Kawamura, "Fluidization Characteristics of Tapered Bed", Kagaku Kogaku Ronbunshu **15**, 773–780 (1989).

Kunii, D. and O. Levenspiel, "Fluidization Engineering", Wiley, New York, (1969) p. 195.

Agarwal, S. K. and G. K. Roy, "A Quantitative Study of Fluidization Quality in Baffled and Conical Gas–Solid Fluidized Beds", Institution of Engineers (India) **68**, Ch-1, 35–38 (1987).

Agarwal, S. K. and G. K. Roy, "Packed Bed Pressure Drop and Incipient Fluidization Condition in a Conical Bed of Spherical Particles: A Mathematical Model. Indian Chem. Eng. **30** (3), 40–43 (1988).

Biswal, K. C., T. Bhowmick and G. K. Roy, "Prediction of Pressure Drop for Conical Fixed Bed of Spherical Particles in Gas–Solid Systems", Chem. Eng. J. **29**, 47–50 (1984).

Jean, R. H. and L. S. Fan, "On the Particle Terminal Velocity in a Gas–Liquid Medium with Liquid as the Continuous Phase", Can. J. Chem. Eng. **65**, 881–886 (1987).

Kmieć, A., "Equilibrium of Forces in a Fluidized Bed-Experimental Verification", Chem. Eng. J. **23**, 133–136 (1982).

Leva, M. "Fluidization", McGraw Hill, New York (1959).

Lucas, A., J. Arnaldoes, J. Casal and L. Puigjaner, "Improved Equation for the Calculation of Minimum Fluidization Velocity", Ind. Eng. Chem. Proc. Des. Dev. **2**, 426–429 (1986).

Narsimhan, G., "On a Generalized Expression for Prediction of Minimum Fluidization Velocity", AIChE J. **11**, 550 (1965).

Shi, Y. F., Y. S. Yu and L. T. Fan, "Incipient Fluidization Condition for a Tapered Fluidized Bed", Ind. Eng. Chem. Fundam. **23**, 484–489 (1984).

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