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Dynamics of Liquid-Solid Semifluidization: Prediction of Semifluidization Velocity & Packed Bed Formation

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The necessity of a generalized correlation for the prediction of the packed bed height in semifluidization is stressed. Methods available for calculating the same are reviewed. Based on experimental data, a dimensionless correlation has been developed for the variation of packed bed height with the semifluidization velocity. The values calculated by this method are compared with those observed experimentally and calculated by the method using material balance.

SEMIFLUIDIZATION is a unique and novel technique of contacting solids with fluids. It can be visualized as a combination of packed and fluidized beds. The special features of such a bed have been reported in literature[1]. Investigations dealing with various aspects of liquid-solid semifluidization reported earlier have been reviewed by the authors[2,3]. A glance into literature reveals that although correlations are available for the prediction of the onset and the maximum semifluidization velocities, scanty information is available on packed bed formation. While it is necessary to know the velocity at which semifluidization begins and also the velocity at which all the particles are transferred to the packed bed below the screen, it is also necessary to know the variation of the height of the packed bed with change in the velocity of the fluid, the two limits of the velocity being the onset of semifluidization and the maximum semifluidization velocity. Hence, an attempt has been made to develop a correlation for the prediction of packed bed formation in terms of a few dimensionless groups which influence the system.

Experimental Procedure

The experimental set-up used in the present study has been described in detail in an earlier paper[4].

Results and Discussion

Altogether 104 sets of runs were taken. One spherical material, viz. glass beads of size 0.0164 ft, and four non-spherical materials, like coal, stone chips, dolomite and iron ore of two different sizes (6/8 and 14/16 BSS) were studied. The lowest and the highest specific gravities of the materials studied were 1.58 and 5.05 respectively.

The properties of the solid particles used in the experiments have been given earlier[4]. The variation of bed pressure drop and packed bed formation with liquid mass velocity for one system is shown in Table 1 and Fig. 1. Bed expansion data for the same system are given in Table 2.

Prediction of packed bed formation — Fan and Wen[5] proposed an equation for the prediction of packed bed height from the maximum semifluidization velocity and the minimum fluidization velocity for both gas-solid and liquid-solid systems. The equation is

$$f\left(\frac{h-h_s}{h-h_{pa}},\ \frac{G_{sf}-G_{mf}}{G_{msf}-G_{mf}}\right)=0 \quad \ldots(1)$$

In addition, the above authors suggested a different correlation from material balance considerations and also taking into account the assumptions of Richardson and Zaki[6]. The correlation is

$$h_{pa}=(h_f-h)\frac{(1-\epsilon_f)}{\epsilon_f-\epsilon_{pa}} \quad \ldots(2)$$

The observed and calculated values of packed bed formation tallied well up to a value of $\epsilon_f = 0.8$.

Roy and Sarma[4] introduced the minimum semifluidization velocity term in place of the minimum fluidization velocity in the equation of Fan and Wen (Eq. 1), and developed the following expression:

$$\frac{h-h_s}{h-h_{pa}}=\left(\frac{G_{sf}-G_{osf}}{G_{msf}-G_{osf}}\right)^{0.2} \quad \ldots(3)$$

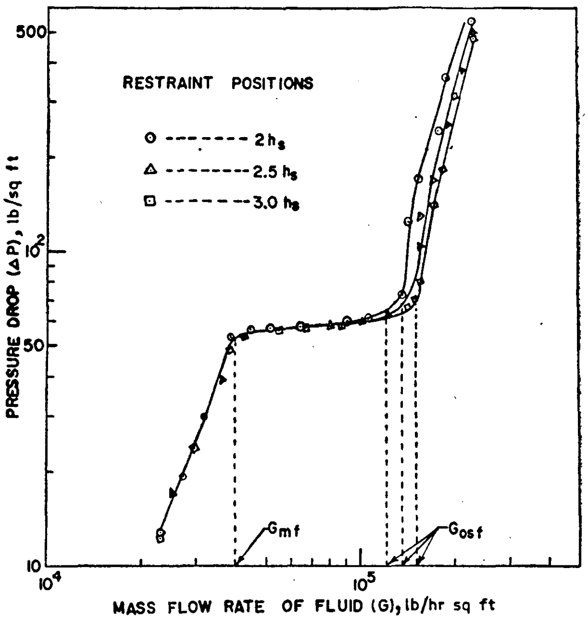

Fig. 1 — Variation of pressure drop with flow rate of liquid [System: Glass bead-water, static bed height, 5 in]

TABLE 1 — VARIATION OF PRESSURE DROP AND PACKED BED FORMATION (BELOW THE TOP RESTRAINT) WITH FLUID MASS VELOCITY

(System: Glass bead-water; particle diam.=0·0164 ft; h_s=5 in.)

Sl No.	ΔH cm	ΔP lb/ft²	W lb/hr	G lb/hr ft²	h_{pa} in.	h_{pa}/h_s
			R=2·0, T_w=27°C			
1	3·9 CCl_4	12·80	315	23150	—	—
2	5·8 ,,	19·05	375	27550	—	—
3	9·1 ,,	29·85	420	30850	—	—
4	16·3 ,,	53·50	525	38600	—	—
5	17·0 ,,	55·80	615	45100	—	—
6	17·3 ,,	56·75	705	51750	—	—
7	17·5 ,,	57·40	885	65000	—	—
8	17·7 ,,	58·10	990	72600	—	—
9	18·1 ,,	59·40	1110	81500	—	—
10	18·3 ,,	60·00	1230	90400	—	—
11	18·8 ,,	61·60	1440	105800	—	—
12	19·5 ,,	64·00	1530	112200	—	—
13	2·6 Hg	72·50	1875	137700	1·0	0·2
14	4·4 ,,	123·00	1950	143100	2·0	0·4
15	6·1 ,,	170·50	2130	156500	2·5	0·5
16	8·7 ,,	243·00	2430	178500	3·0	0·6
17	12·9 ,,	360·00	2700	198200	4·0	0·8
18	19·8 ,,	552·00	3120	229200	4·5	0·9
			R=2·5, T_w=26°C			
1	5·7 CCl_4	17·05	345	25320	—	—
2	12·0 ,,	39·40	495	36350	—	—
3	16·8 ,,	55·10	585	42950	—	—
4	17·0 ,,	55·80	705	51750	—	—
5	17·3 ,,	56·80	900	66100	—	—
6	17·7 ,,	58·10	1110	81500	—	—
7	18·0 ,,	59·00	1200	88200	—	—
8	18·5 ,,	60·60	1380	101500	—	—
9	18·7 ,,	61·40	1485	109000	—	—
10	19·1 ,,	62·60	1680	123300	—	—
11	19·6 ,,	64·40	1800	132200	—	—
12	3·7 Hg	103·20	2112	155100	1·0	0·20
13	6·1 ,,	170·50	2352	172800	2·0	0·40
14	9·1 ,,	254·00	2604	191200	3·0	0·60
15	13·9 ,,	388·00	2910	214000	3·6	0·72
16	18·1 ,,	505·00	3135	230200	4·1	0·82
			R=3·0, T_w=25°C			
1	3·8 CCl_4	12·5	315	23150	—	—
2	7·1 ,,	23·5	405	29700	—	—
3	15·0 ,,	49·2	525	38600	—	—
4	16·5 ,,	54·1	585	42950	—	—
5	17·2 ,,	56·4	750	55000	—	—
6	18·0 ,,	59·0	1065	78200	—	—
7	19·0 ,,	62·4	1365	100200	—	—
8	20·6 ,,	67·6	1830	134300	—	—
9	21·0 ,,	68·9	1920	141000	—	—
10	22·0 ,,	72·1	2040	150000	—	—
11	2·9 Hg	81·0	2130	156500	0·5	0·10
12	5·0 ,,	139·5	2352	172800	1·5	0·30
13	6·5 ,,	181·4	2520	185000	2·0	0·40
14	11·3 ,,	315·0	2820	207000	3·2	0·64
15	17·5 ,,	489·0	3135	230200	4·1	0·82

The only equation for the prediction of semifluidization velocity has been given by Babu Rao and Doraiswamy[7] as

$$\frac{G_{sf}}{G_t} = 17 \cdot 3 \frac{(Ar)^{-0 \cdot 15}}{D^{0 \cdot 372}} \cdot (Sf)^{-0 \cdot 186} \quad ...(4)$$

correlation- *The* parameters of importance tor this case are: G_{Sf}/G_{msf}, h_s/D_c, D_c/dp, P_s/P_f, h_{pa}/h_s and *JR.* The relation between the group G_{sf}/G_{msf} and the other parameters can be written in the following manner:

$$\frac{G_{sf}}{G_{msf}} = \Psi \left[\frac{D_c}{d_p}, \frac{h_s}{D_c}, \frac{\rho_s}{\rho_f}, \frac{h_{pa}}{h_s}, R \right] \quad ...(5)$$

or

$$\frac{G_{sf}}{G_{msf}} = A \left(\frac{D_c}{d_p}\right)^{a_1} \left(\frac{h_s}{D_c}\right)^{a_2} \left(\frac{\rho_s}{\rho_f}\right)^{a_3} \left(\frac{h_{pa}}{h_s}\right)^{a_4} (R)^{a_5} \quad ...(6)$$

$$\frac{G_{sf}}{G_{msf}} = A \left[\left(\frac{D_c}{d_p}\right)^{-0 \cdot 14} \left(\frac{h_s}{D_c}\right)^{0 \cdot 09} \left(\frac{\rho_s}{\rho_f}\right)^{-0 \cdot 10} \left(\frac{h_{pa}}{h_s}\right)^{0 \cdot 60} (R)^{0 \cdot 52} \right] \quad ...(7)$$

Where *A* is the coefficient. Taking *B* as the exponent of the overall product (Prod.), which acts as a correlation factor, for the exponents of the system variables, Eq. (7) can be written as

$$\frac{G_{sf}}{G_{msf}} = A \ (\text{Prod.})^B \quad ...(8)$$

The ratio of G_{sf}/G_{msf} is plotted on a log-log coordinates against the product $(D_c/d_p)^{-0 \cdot 14}(\rho_s/\rho_f)^{-0 \cdot 10}(R)^{0 \cdot 52}(h_s/D_c)^{0 \cdot 09}(h_{pa}/h_s)^{0 \cdot 60}$ in Fig. 2, and two different straight lines, one for the spherical and the other for the non-spherical particles, are obtained. Accordingly, the empirical correlations are:

For non-spherical particles:

$$\frac{G_{sf}}{G_{msf}} = 0 \cdot 945 \left(\frac{D_c}{d_p}\right)^{-0 \cdot 15} \left(\frac{h_s}{D_c}\right)^{0 \cdot 10} \left(\frac{\rho_s}{\rho_f}\right)^{-0 \cdot 11} \left(\frac{h_{pa}}{h_s}\right)^{0 \cdot 66} (R)^{0 \cdot 57} \quad ...(9a)$$

For spherical particles:

$$\frac{G_{sf}}{G_{msf}} = 0 \cdot 684 \left(\frac{D_c}{d_p}\right)^{-0 \cdot 11} \left(\frac{h_s}{D_c}\right)^{0 \cdot 07} \left(\frac{\rho_s}{\rho_f}\right)^{-0 \cdot 08} \left(\frac{h_{pa}}{h_s}\right)^{0 \cdot 48} (R)^{0 \cdot 42} \quad ...(9b)$$

Writing in terms of packed bed formation in semifluidization, Eqs. (9a) and (9b) become

For non-spherical particles:

$$\frac{h_{pa}}{h_s} = 1 \cdot 09 \left(\frac{G_{sf}}{G_{msf}}\right)^{1 \cdot 51} \left(\frac{D_c}{d_p}\right)^{0 \cdot 23} \left(\frac{\rho_s}{\rho_f}\right)^{0 \cdot 17} (R)^{-0 \cdot 86} \left(\frac{h_s}{D_c}\right)^{-0 \cdot 15} \quad ...(10a)$$

For spherical particles:

$$\frac{h_{pa}}{h_s} = 2 \cdot 21 \left(\frac{G_{sf}}{G_{msf}}\right)^{2 \cdot 08} \left(\frac{D_c}{d_p}\right)^{0 \cdot 23} \left(\frac{\rho_s}{\rho_f}\right)^{0 \cdot 17} (R)^{-0 \cdot 88} \left(\frac{h_s}{D_c}\right)^{-0 \cdot 15} \quad ...(10b)$$

Eq. (9) gives the values of semifluidization velocity (in terms of G_{sf}/G_{msf}) for a desired packed bed formation, whereas by Eq. (10), the values of top packed bed formation can be estimated for a known semifluidization velocity. The ranges for various variables over which the equations are applicable are as follows:

(i) $D_c/d_p = 8 \cdot 02\text{-}36 \cdot 40$

(ii) $\rho_s/\rho_f = 1 \cdot 58\text{-}5 \cdot 05$

(iii) $R = 2 \cdot 0\text{-}3 \cdot 0$

(iv) $h_s/D_c = 3 \cdot 17\text{-}5 \cdot 07$

(v) $h_{pa}/h_s = 0 \cdot 01\text{-}1 \cdot 00$

The values of packed bed formations have been calculated with the help of Eq. (10) for a few typical runs (Table 3). Packed bed formations have also been calculated by the material balance equation (Eq. 2) for the above runs and are given in Table 4. The experimental values and ' the values calculated both from the correlation and the material balance, as also the percentage deviations of these

TABLE 2 — VARIATION OF EXPANDED BED HEIGHT AND BED POROSITY WITH FLUID MASS VELOCITY

(System: Glass bead-water; particle diam. = 0·0164 ft; h_s = 4·75 in.; T_w=26°C; and ϵ_{pa}=0·526)

Sl No.	Mass velocity of fluid lb/hr ft²	h_f in.	ϵ_f	h_f/h_s
1	47400	5·000	0·550	1·050
2	55000	5·375	0·580	1·135
3	60500	5·625	0·600	1·188
4	65000	5·875	0·617	1·240
5	68250	6·125	0·631	1·290
6	77050	6·375	0·647	1·347
7	83700	6·875	0·672	1·451
8	90400	7·250	0·690	1·530
9	98000	7·750	0·709	1·636
10	105800	8·250	0·727	1·740
11	112200	8·750	0·743	1·840
12	120000	9·250	0·756	1·948
13	127800	9·875	0·770	2·075
14	134300	10·750	0·790	2·265
15	141000	11·500	0·805	2·420
16	155200	13·500	0·832	2·530
17	163000	14·250	0·844	2·840
18	169800	15·500	0·855	3·000
19	176000	16·750	0·865	3·260
20	183000	18·000	0·875	3·530
21	189500	19·500	0·885	3·790
22	196000	21·000	0·893	4·000
23	202500	22·750	0·900	4·430
24	202500	24·750	0·905	4·800
25	216000	26·750	0·916	5·220

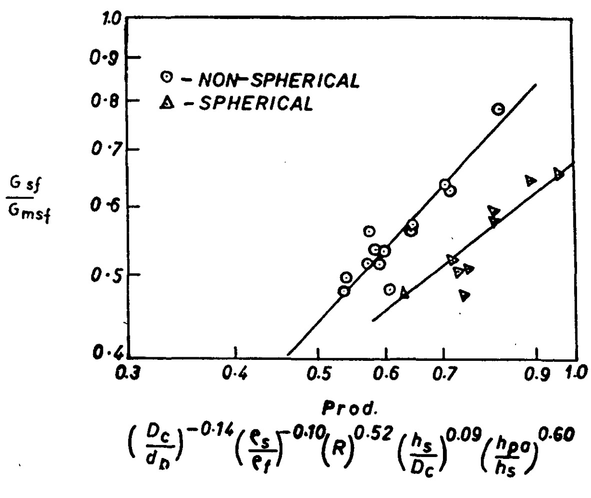

Fig. 2 — Relation between G_{sf}/G_{msf} and system variasble

TABLE 3A — VALUES OF PACKED BED FORMATION CALCULATED BY THE CORRELATION (10b)

(System: Glass bead-water; $G_{msf}=3\cdot0\times10^5$ lb/hr ft²; $D_c/d_p=8\cdot02$; $\rho_s/\rho_f=2\cdot43$; $R=2\cdot0$; $h_s/D_c=3\cdot17$)

Sl No.	G_{sf} lb/hr ft²	$\frac{G_{sf}}{G_{msf}}$	$\left(\frac{G_{sf}}{G_{msf}}\right)^{2\cdot08}$	$\left(\frac{D_c}{d_p}\right)^{0\cdot23}$	$\left(\frac{\rho_s}{\rho_f}\right)^{0\cdot17}$	$(R)^{-0\cdot88}$	$\left(\frac{h_s}{D_c}\right)^{-0\cdot15}$	h_{pa} in.
1	143100	0·477	0·214	—	—	—	—	2·02
2	156500	0·521	0·258	—	—	—	—	2·46
3	178500	0·598	0·340	1·615	1·163	0·544	0·840	3·22
4	198200	0·661	0·422	—	—	—	—	4·01
5	229200	0·765	0·572	—	—	—	—	5·42

TABLE 3B — VALUES OF PACKED BED FORMATION CALCULATED BY THE CORRELATION (10a)

(System: Dolomite-water; $G_{msf}=1\cdot8\times10^5$ lb/hr ft²; $D_c/d_p=16\cdot45$; $\rho_s/\rho_f=2\cdot76$; $R=2\cdot0$; $h_s/D_c=3\cdot17$)

Sl No.	G_{sf} lb/hr ft²	$\frac{G_{sf}}{G_{msf}}$	$\left(\frac{G_{sf}}{G_{msf}}\right)^{1\cdot51}$	$\left(\frac{D_c}{d_p}\right)^{0\cdot23}$	$\left(\frac{\rho_s}{\rho_f}\right)^{0\cdot17}$	$(R)^{-0\cdot86}$	$\left(\frac{h_s}{D_c}\right)^{-0\cdot15}$	h_{pa} in.
1	93600	0·520	0·372	—	—	—	—	2·12
2	101300	0·564	0·421	—	—	—	—	2·40
3	109000	0·605	0·468	1·905	1·188	0·551	0·840	2·67
4	127800	0·710	0·596	—	—	—	—	3·40
5	163000	0·905	0·860	—	—	—	—	4·90

TABLE 3C — VALUES OF PACKED BED FORMATION CALCULATED BY THE CORRELATION (10a)

(System: Dolomite-water; $G_{msf}=1\cdot15\times10^5$; $D_c/d_p=36\cdot40$; $\rho_s/\rho_f=2\cdot76$; $R=2\cdot0$; $h_s/D_c=3\cdot17$)

Sl No.	G_{sf} lb/hr ft²	$\frac{G_{sf}}{G_{msf}}$	$\left(\frac{G_{sf}}{G_{msf}}\right)^{1\cdot51}$	$\left(\frac{D_c}{d_p}\right)^{0\cdot23}$	$\left(\frac{\rho_s}{\rho_f}\right)^{0\cdot17}$	$(R)^{-0\cdot86}$	$\left(\frac{h_s}{D_c}\right)^{-0\cdot15}$	h_{pa} in.
1	47400	0·412	0·221	—	—	—	—	1·51
2	55000	0·479	0·330	—	—	—	—	2·26
3	65000	0·565	0·422	2·290	1·188	0·551	0·840	2·90
4	72600	0·631	0·499	—	—	—	—	3·42
5	90400	0·785	0·694	—	—	—	—	4·76

TABLE 4 — VALUES OF PACKED BED FORMATION CALCULATED FROM MATERIAL BALANCE

Sl No.	G_f lb/hr ft²	ϵ_f	h_f/h_s	$1-\epsilon_f$	h_f	(h_f-h)	$\epsilon_f-\epsilon_{pa}$	h_{pa} in.
	(SYSTEM: GLASS BEAD-WATER; $d_p=0\cdot0164$; $h_s=5$ IN.; $R=2\cdot0$; $\epsilon_{pa}=0\cdot526$)							
1	143100	0·802	2·45	0·198	12·25	2·25	0·276	1·62
2	156500	0·827	2·88	0·173	14·40	4·40	0·301	2·53
3	178500	0·861	3·50	0·139	17·50	7·50	0·335	3·11
4	198200	0·890	4·30	0·110	21·50	11·50	0·364	3·48
5	229200	0·929	5·25	0·071	26·25	16·25	0·403	2·86
	SYSTEM: DOLOMITE-WATER; $d_p=0\cdot0080$ FT; $h_s=5$ IN.; $R=2\cdot0$; $\epsilon_{pa}=0\cdot539$							
1	93600	0·790	2·15	0·210	10·75	0·75	0·251	0·63
2	101300	0·810	2·40	0·190	12·00	2·00	0·271	1·40
3	109000	0·828	2·65	0·172	13·25	3·25	0·289	1·94
4	127800	0·875	3·70	0·125	18·50	8·50	0·336	3·16
5	163000	0·928	5·45	0·072	27·20	17·20	0·389	3·18
	SYSTEM: DOLOMITE-WATER; $d_p=0\cdot0036$ FT; $h_s=5$ IN.; $R=2\cdot0$; $\epsilon_{pa}=0\cdot452$							
1	47400	0·740	2·10	0·260	10·50	0·50	0·288	0·45
2	55000	0·781	2·45	0·219	12·25	2·25	0·329	1·50
3	65000	0·827	3·08	0·173	15·40	5·40	0·375	2·50
4	72600	0·858	3·70	0·142	18·50	8·50	0·406	2·97
5	90400	0·916	4·92	0·084	24·60	14·60	0·464	2·64

TABLE 5 — COMPARISON OF THE VALUES OF PACKED BED FORMATION

Sl No.	System	d_p ft	h_s in.	R	h_{pa}, in. From expt.	h_{pa}, in. From calc.	h_{pa}, in. From correlation	Deviations of the values from correlations from experimental values %
1	Glass bead-water	0·0164	5·0	2·0	2·00	1·62	2·02	1·00
					2·50	2·53	2·46	−1·60
					3·00	3·11	3·22	7·30
					4·00	3·48	4·01	0·25
					4·50	2·86	5·42	20·00
2	Dolomite-water	0·0080	5·0	2·0	2·00	0·63	2·12	6·00
					2·50	1·40	2·40	−4·00
					3·25	1·94	2·67	−17·85
					4·00	3·16	3·40	−15·00
					4·87	3·18	4·90	0·61
3	Dolomite-water	0·0036	5·0	2·0	1·125	0·45	1·51	34·00
					2·250	1·50	2·26	0·45
					3·000	2·56	2·90	−3·33
					3·625	2·97	3·42	−5·65
					4·500	2·64	4·76	5·78

values from the experimental ones are given in Table 5. It is evident from the data that the values calculated on the basis of material balance deviate widely from the experimental values. This is because of the fact that the exact measurement of expanded bed height (and hence expanded bed porosity) in a fluidized bed presents considerable difficulty, and any small error in expanded bed porosity measurement is multiplied, which results in appreciable deviation of the final value. The values calculated on the basis of the correlations compare well with the experimental ones, except for a few cases, especially either near the onset of semifluidization or towards the end of the operations, when the packed bed formation experiences a little bit of compaction.

Nomenclature

A = constant
Ar = Archimedes number, $d_p^3 g_c \rho_s (\rho_s-\rho_f)/\mu^2$, dimensionless
D_c = diam. of the column (semifluidizer), L
D = diam. of the reactor, L
d_p = particle diam., L
f = function
g_c = gravitational constant, L θ^{-2}
G = mass velocity of the fluid, M $\theta^{-1}L^{-2}$
G_{mf} = minimum fluidization velocity, M $\theta^{-1}L^{-2}$
G_{msf} = maximum semifluidization velocity, M $\theta^{-1}L^{-2}$
G_{osf} = minimum semifluidization velocity, M $\theta^{-1}L^{-2}$
G_{sf} = semifluidization velocity, M $\theta^{-1}L^{-2}$
G_t = free fall terminal velocity of particle (also called maximum semifluidization velocity), M $\theta^{-1}L^{-2}$.
h = overall height of the column (or semifluidized bed), L
h_s = height of initial static bed, L
h_{pa} = height of packed section in semifluidized bed, L
h_f = height of fully fluidized bed, L
ΔH = pressure drop across semifluidized bed, L
ΔP = pressure drop across semifluidized bed, FL^{-2}
S_f = semifluidization group, $\frac{(W_s-W_p)}{(h-h_s)^3 \rho_s}$
R = bed expansion ratio in semifluidization, (h/h_s)
T_w = temp. of water, °C
W_p = weight of solid in packed bed section in semifluidization, M
W_s = initial weight of solid in static bed, M
Δ = finite change of variable
μ = viscosity, ML$^{-1}\theta^{-1}$
ψ = function
ρ = density, ML^{-3}
ϵ = bed porosity, dimensionless

Subscripts

f = fluid or fluidized
mf = minimum fluidization conditions
msf = maximum semifluidization conditions
osf = minimum semifluidization conditions
sf = semifluidization conditions
Pa = packed bed

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