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Prediction of Pressure Drop across a Liquid-Solid Semifluidized Bed

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The necessity of having a generalized and simplified correlation for the prediction of pressure drop in a liquid-solid semifluidized bed is stressed. Methods available for calculating the same have been briefly summarized and critically reviewed. With pressure drop at the onset of semifluidization as the reference, a correlation has been developed which relates the pressure drop ratio ($\Delta P_T/\Delta P_{osf}$) with the system variables in terms of dimensionless groups.

STUDIES on the dynamics of liquid-solid and gas-soild semifluidization can be broadly, divided as (i) the prediction of the onset and the maximum semifluidization velocities, (ii) the prediction of packed bed formation, and (iii) the prediction of. pressure drop across a semifluidized bed. Although the first two aspects have been extensively studied[1-8], the third has not been explored in detail. The available correlations either indicate wide deviations between the calculated and the experimental values of pressure drop or involve labourious calculations[3-9]. They are neither handy for the designer to use nor very accurate. An attempt has, therefore, been made to develop a simplified working correlation for the prediction of. the pressure drop across a liquid-solid semifluidized bed in terms of system parameters.

Fan and Wen have measured the total pressure drop across liquid-solid semifluidized beds[3]. In semifluidization, the total pressure is ideally the algebraic sum of the pressure drop across the fluidized and the packed sections. Hence,

$$\Delta p_T = \left(\frac{\Delta p}{L}\right)_f \left(h - h_{pa}\right) + \left(\frac{\Delta p}{L}\right)_{pa} h_{pa} \quad \ldots(1)$$

Using Leva's equation for fluidized section and Ergun's equation for packed section[10], one can rewrite Eq. (1):

$$\Delta p_T = \frac{1}{g_c}\left[150\,\frac{(1-\varepsilon_{pa})^2}{\varepsilon^3_{pa}}\,\frac{\mu u}{d^2_p} + 1{\cdot}75\,\frac{(1-\varepsilon_{pa})}{\varepsilon^3_{pa}}\,.\,\frac{Gu}{d_p}\right]\times$$
$$\left[\left(h_f - h\right)\frac{1-\varepsilon_f}{\varepsilon_f-\varepsilon_{pa}}\right] + \left[h_f - \frac{(1-\varepsilon_{pa})\,(h_f-h)}{\varepsilon_f-\varepsilon_{pa}}\right]\times$$
$$\left[(1-\varepsilon_f)\,(p_s-p_f)\right] \quad \ldots(2)$$

Fan and Wen[3] measured the pressure drop in fixed and fluidized beds separately and obtained the total pressure drop using Eq. (1). This was compared with the observed bed pressure drop and also with that calculated using Eq. (2). The experimental values were nearer to those calculated using Eq. (1), whereas Eq. (2) gave lower values.

Kurian and Raja Rao[9] found the overall pressure drop in a liquid-solid semifluidized bed obtained using Eq. (2) to be valid for spherical particles of large diameters. For small and irregular shaped particles, the observed pressure drop was greater than that given by Eq. (2). This additional pressure drop was given as

$$\Delta p_a = 2{\cdot}10\times10^{-3}\, G_{sf}^{1\cdot56}\, d_p^{-0\cdot94}\, h_{pa}^{0\cdot59} \quad \ldots(3)$$

The resulting equation was

$$\Delta p_T = \frac{1}{g_c}\left[150\,\frac{(1-\varepsilon_{pa})^2}{\varepsilon_{pa}^3}\,.\,\frac{\mu u}{d_p^2} + 1{\cdot}75\,\frac{(1-\varepsilon_{pa})}{\varepsilon_{pa}^3}\,.\,\frac{Gu}{d_p}\right]\times$$
$$\left[(h_f-h)\,\frac{(1-\varepsilon_f)}{\varepsilon_f-\varepsilon_{pa}}\right] + \left[h_f - \frac{(1-\varepsilon_{pa})\,(h_f-h)}{\varepsilon_f-\varepsilon_{pa}}\right]\times$$
$$\left[(1-\varepsilon_f)\,(\rho_s-\rho_f)\right] + 2{\cdot}10\times10^{-3}\, G_{sf}^{1\cdot56}\, d_p^{-0\cdot94}\, h_{pa}^{0\cdot59} \quad \ldots(4)$$

Comparison between the experimental and calculated values showed an average deviation of 12% and a maximum deviation of 20%

In order to overcome wide discrepancies between the experimental and calculated values of liquid-solid semifluidized bed pressure drop a correction factor was suggested by Roy and Sarma[11] in terms of system parameters which is as follows :

$$c = (\Delta p_T)\text{ actual} / (\Delta p_T)\text{ calculated}$$
$$= 16.7\left(\frac{D_c}{d_p}\right)^{-0\cdot59}\left(\frac{\rho_s}{\rho_f}\right)^{0\cdot67}\left(\frac{h_s}{D_c}\right)^{-0\cdot43}\times\left(\frac{h_{pa}}{h_s}\right)^{0\cdot08} R^{0\cdot08} \quad \ldots(5)$$

The calculated values were obtained using Eq. (2).,

As it appears from above, the equations involve very laborious calculations for the prediction of semifluidized bed pressure drop.

Experimental Procedure

The experimental set-up used is shown in Fig. 1. The semifluidizer was a perspex column,, 2-54 cm internal diam. and 100 cm long, inserted between two flanges and provided with an inclined feeder at a height of 21 cm from the base for intermediate addition and

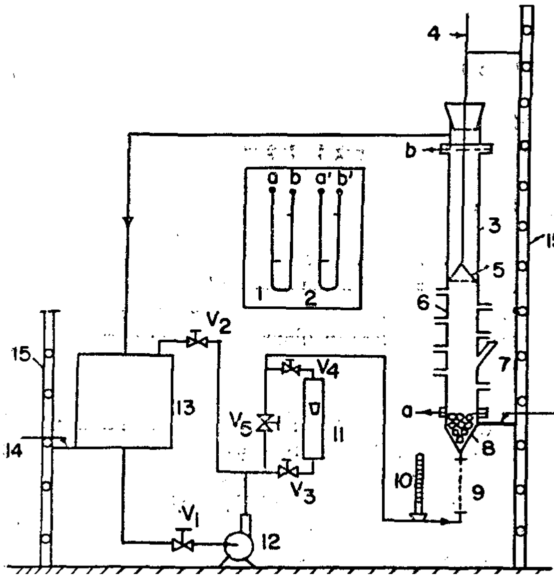


Fig. 1 — Schematic diagram of the liquid-solid semifluidization rset-up t1, & 2, Manometers for bed pressure drop; 3, semifluidizer; 4, movable restraint assembly; 5, top restraint; 6, intermediate pressure tappings; 7, inclined feeder; 8, distributor; 9, flexible •connection; 10, thermometer; 11, rotameter; 12, circulating pump; 13, liquid reservoir; 14, base plate support; 15, supporting structure; a,b, column pressure tappings; and V1-V5, control valves]

removal of materials. A movable restraint made up of 100 mesh stainless steel screen was placed between two perspex rings, the outside diameter of which was very nearly equal to the inside diameter of the column. With the help of a 3 mm diam. brass rod, this restraint was moved to any position within the column. ,A rotameter was included in the liquid line and the fluid was recirculated by a pump. Two pressure taps, one just below the bottom screen and the other at the top of the column, were provided to record the bed pressure drops. . While taking a run, the sample was introduced into the column and the fixed bed height was noted. The movable restraint was adjusted for a particular bed expansion ratio., Pressure drop across the bed was noted with the increase of air flow rate. When semifluidization set in, the top bed formations were constantly recorded.

Results and Discussion

Physical properties of materials and ranges of variables studied are given in Table 1. Typical data showing nature of the variation of pressure drop and packed bed formation with fluid mass velocity are presented in Figs 2 and 3 respectively.

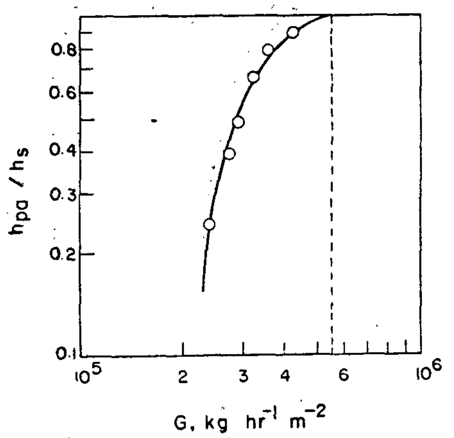
The Correlation

Fan *et at.* reported that the accurate measurement of porosity of the packed and fluidized sections of the semifluidized bed was difficult. This led to a wide -deviation between the calculated and the experimental values of pressure drop. Hence, an attempt has been made to report the semifluidized bed pressure drops

TABLE 1 — PHYSICAL PROPERTIES OF MATERIALS AND RANGES OF VARIABLES STUDIED

$R = 2{\cdot}0, 2{\cdot}5, 3{\cdot}0$ & $3{\cdot}5$

Materials used	Particle size, d_p cm	Density gm/cc	Fixed bed porosity ε_{pa}	h_s cm
Dolomite	0·2435	2·83	0·470	
Dolomite	0·1104	2·83	0·351	6·0, 8·0
Dolomite	0·0550	2·83	0·310	10·0, 12·0
Dolomite	0·0388	2·83	0·256	
Dolomite	0·0273	2·83	0·222	
Chromite	0·1104	3·72	0·500	
Chromite	0·0388	3·72	0·303	
Baryte	0·1104	4·45	0·415	6·0
Baryte	0·0388	4·45	0·316	
Iron ore	0·1104	5·25	0·436	
Iron ore	0·0388	5·25	0·304	



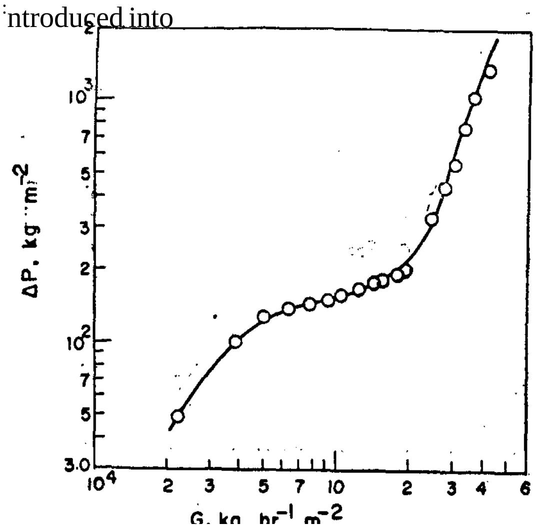


Fig. 3 — Variation of pressure drop with fluid mass velocity [System: dolomite-water; particle size: 14/16 BSS; bed expansion ratio: 2.0; static bed height, h_s : 6-0cm]

as a dimensionless ratio and relate it to various system parameters.

A relation between the group, $\Delta p_T / \Delta p_{osf}$ and the other parameters can be written as follows :

$$\frac{\Delta p_T}{\Delta p_{osf}} = f\left[\frac{D_c}{d_p}, \frac{\rho_s}{\rho_f}, R, \frac{h_s}{D_c}, \frac{h_{pa}}{h_s}\right] \quad ...(6)$$

We observe that the height of initial static bed has no appreciable effect on the semifluidized pressure drop. Also the column diameter has not been altered. Hence, the effect of h_s/D_c is not relevant. Eq. (6), therefore, reduces to :

$$\frac{\Delta p_T}{\Delta p_{osf}} = A\left(\frac{D_c}{d_p}\right)^{a_1}\left(\frac{\rho_s}{\rho_f}\right)^{a_2} R^{a_3}\left(\frac{h_{pa}}{h_s}\right)^{a_4} \quad ...(7)$$

where A is a constant and a_1, a_2 a_3 and a_4 are exponents of the system variables.

The effect of individual parameters can be seen from Table 2. By plotting the pressure drop ratio against each of the system variables on log-log coordinates, the exponents of Eq. (7) are evaluated. After substitution of these exponents, the equation becomes:

$$\frac{\Delta p_T}{\Delta p_{osf}} = A\left[\left(\frac{D_c}{d_p}\right)^{-0.218}\left(\frac{\rho_s}{\rho_f}\right)^{0.610}(R)^{0.354}\left(\frac{h_{pa}}{h_s}\right)^{1.130}\right]^B \quad ...(8)$$

where A is the coefficient and B is the exponent of the overall product. The pressure drop has been plotted against the overall product in Fig. 4. A straight line fit has been obtained by the method of least squares as[12]

TABLE 2a — EFFECT OF VARIOUS SYSTEM VARIABLES ON THE PRESSURE DROP RATIO (INFLUENCE OF WALL EFFECT)

No.	Operating parameter, D_c/d_p	ΔP_{osf} kg/M²	ΔP_T kg/M²	$\Delta P_T / \Delta P_{osf}$	Constant parameters
1	10·42	60·4	734·0	12·15	ρ_s/ρ_f =2·83
2	23·00	73·6	639·0	8·68	R =2
3	46·15	74·7	630·0	8·43	h_s/D_c =2·36
4	65·50	85·6	694·0	8·11	
5	93·00	80·2	620·0	7·73	h_{pa}/h_s = 0·5

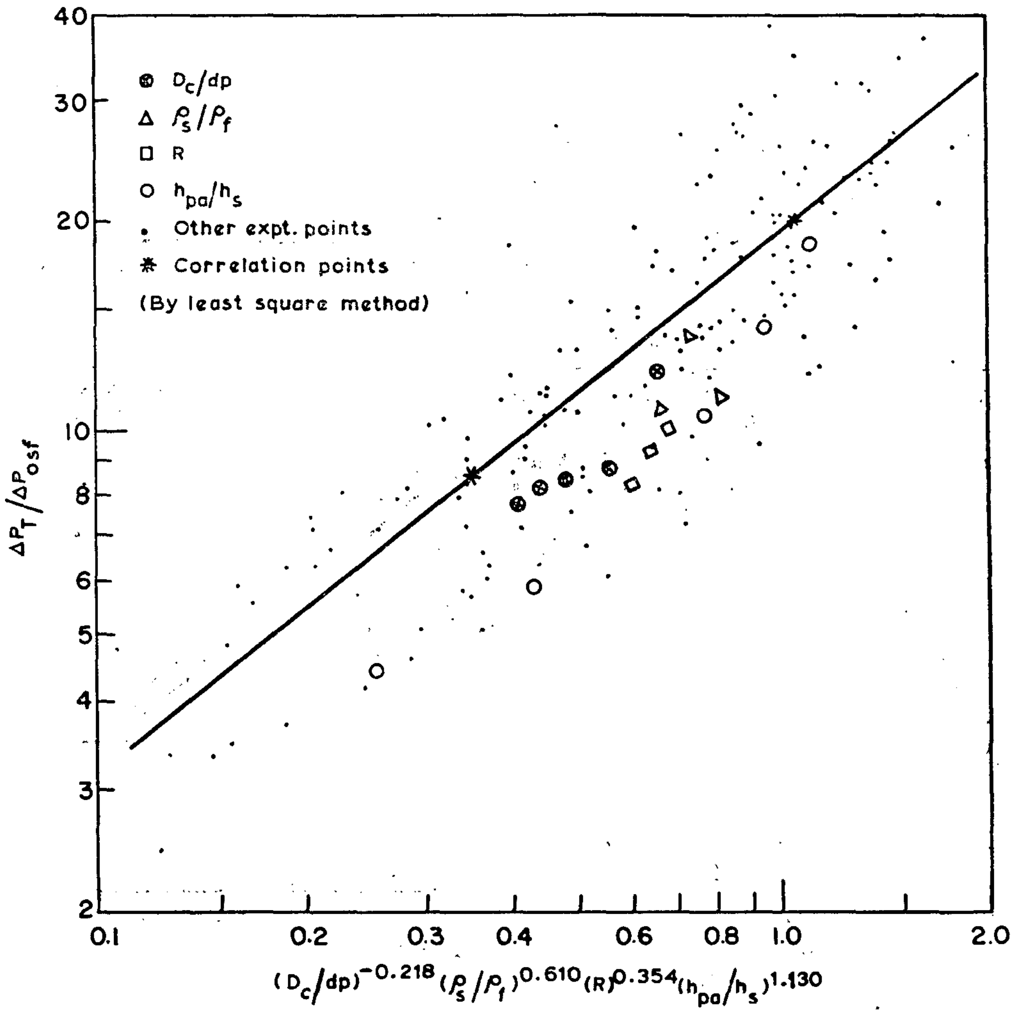


Fig. 4 — Relation of $\Delta P_T/\Delta P_{osf}$ with system variables

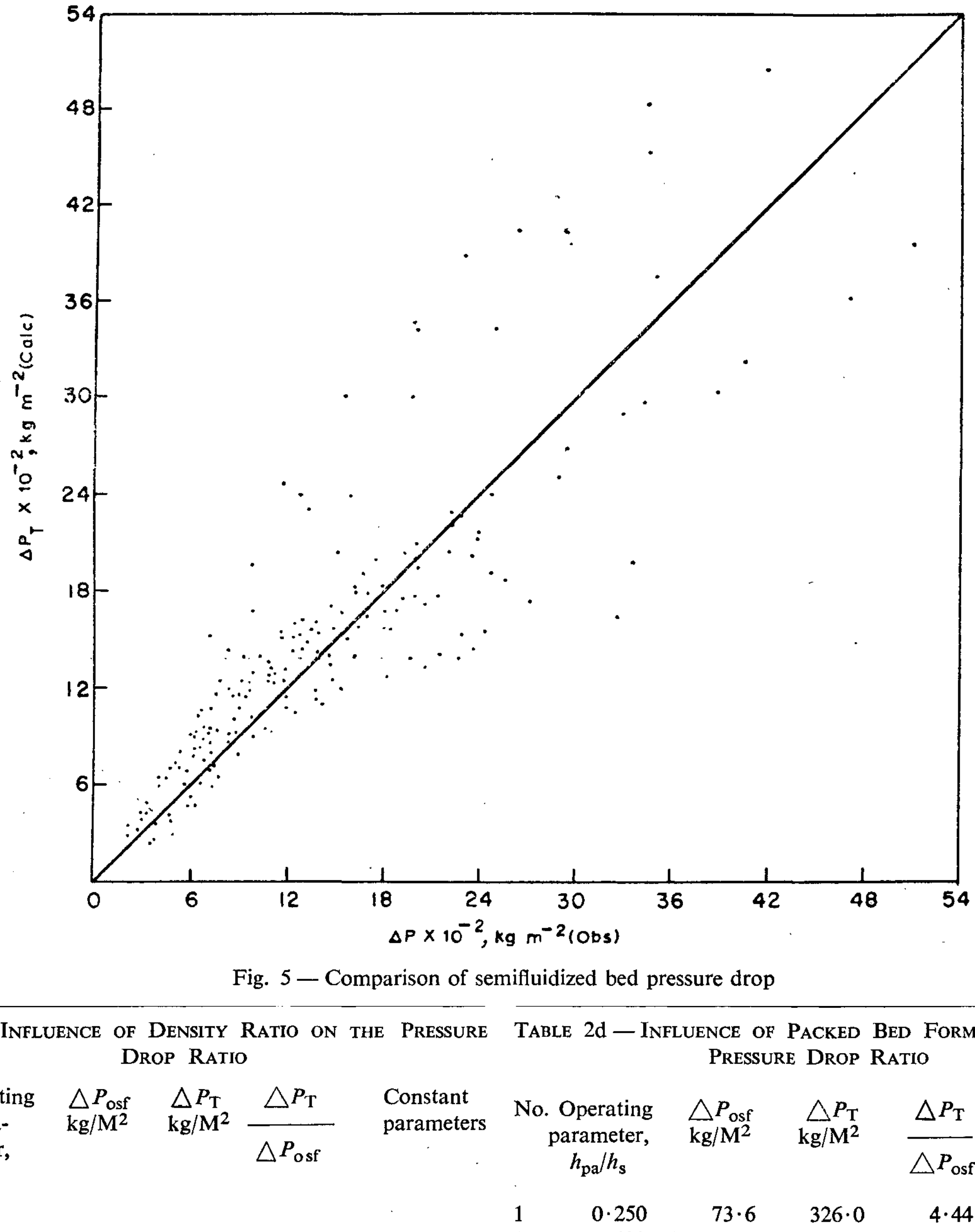


Fig. 5 — Comparison of semifluidized bed pressure drop

TABLE 2b — INFLUENCE OF DENSITY RATIO ON THE PRESSURE DROP RATIO

No.	Operating parameter, ρ_s/ρ_f	ΔP_{osf} kg/M^2	ΔP_T kg/M^2	$\Delta P_T / \Delta P_{osf}$	Constant parameters
1	2·83	73·6	639·0	8·68	D_c/d_p =23
2	3·72	81·6	870·0	10·66	R =2
3	4·45	123·4	1680·0	13·61	h_s/D_c =2·36
4	5·25	143·8	1605·0	11·16	h_{pa}/h_s =0·5

TABLE 2c — INFLUENCE OF BED EXPANSION RATIO ON THE PRESSURE DROP RATIO

No.	Operating parameter, R	ΔP_{osf} kg/M^2	ΔP_T kg/M^2	$\Delta P_T / \Delta P_{osf}$	Constant parameters
1	2·0	73·6	639·0	8·68	D_c/d_p=23·00
2	2·5	80·4	670·0	8·33	ρ_s/ρ_f =2·83
3	3·0	77·1	720·0	9·34	h_s/D_c =2·36
4	3·5	82·2	830·0	10·10	h_{pa}/h_s = 0·5

TABLE 2d — INFLUENCE OF PACKED BED FORMATIONS ON THE PRESSURE DROP RATIO

No.	Operating parameter, h_{pa}/h_s	ΔP_{osf} kg/M^2	ΔP_T kg/M^2	$\Delta P_T / \Delta P_{osf}$	Constant parameters
1	0·250	73·6	326·0	4·44	
2	0·400		435·0	5·91	D_c/d_p = 23·00
3	0·500		639·0	8·68	ρ_s/ρ_f = 2·83
4	0·666		775·0	10·53	R = 2·00
5	0·800		1033·0	14·04	h_s/D_c = 2·36
6	0·916		1360·0	18·48	

$$\frac{\Delta P_T}{\Delta P_{osf}} = 19.50 \left(\frac{D_c}{d_p}\right)^{-0\cdot 17} \left(\frac{\rho_s}{\rho_f}\right)^{0\cdot 48} (R)^{0\cdot 28} \left(\frac{h_{pa}}{h_s}\right)^{0\cdot 89} \quad \ldots(9)$$

The values of the pressure drop calculated using Eq. (9) have been compared with the experimental values in Fig. 5. Though it can be said that in general there is no appreciable deviation of the calculated values from the experimental, a few points deviate considerably from the diagonal line. These refer particularly to particles of large size and of higher density and to the two extreme regions of semifluidization operation, viz. the onset and the maximum semifluidization conditions. Similar discrepancies have been observed by Kurian and Raja Rao[9]. The possible explanations for the discrepancy are:

(i) The screen configuration,
(ii) The orientation of the particles to the screen; opening when they approach the screen;
(iii) The blinding of the screen;
(iv) Influence of particle shape; and
(v) Certain degree of instability existing at the extreme regions of semifluidization operation.

A better explanation cannot be given without making more detailed studies.

Acknowledgement

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Nomenclature

C = correction factor for pressure drop correlation in semifluidization
D_c = diameter of the column, L
d_p = particle diameter, L
f = function
g_c = gravitational constant, $L\theta^{-2}$
G = mass velocity of fluid, $ML^{-2}\theta^{-1}$
G_{sf} = semi-fluidization mass velocity, $ML^{-2}\theta^{-1}$
h = overall height of column (or semifluidizer), L
h_f = height of fully fluidized bed, L
h_{pa} = height of packed section in semifluidization, L
h_s = height of initial static bed, L
$\triangle p_a$ = additional pressure drop in the restraining plate, FL^{-2}
$\left(\frac{\triangle p}{L}\right)_f$ = pressure gradient across fluidized bed (or fluidized section of semifluidized bed), FL^{-3}
$\left(\frac{\triangle p}{L}\right)_{pa}$ = pressure gradient across packed bed (or packed section of semifluidized bed), FL^{-3}
$\triangle P_{osf}$ = pressure drop across bed corresponding to the onset of semifluidization condition, FL^{-2}
$\triangle P_T$ = overall pressure drop across the semifluidized bed, FL^{-2}
R = bed expansion ratio in semifluidization, dimensionless, (h/h_s)
t = average fluid temperature, °C
u = linear velocity of fluid, $L\theta^{-1}$
ρ_s = density of solid, ML^{-3}
ρ_f = density of fluid, ML^{-3}
ε_f = porosity of fluidized bed or fluidized section of semifluidized bed, dimensionless
ε_{pa} = porosity of packed bed or packed section of semi-fluidized bed, dimensionless
μ = viscosity of fluid, $ML^{-1}\theta^{-1}$

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