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NEAR-WALL HYDRODYNAMICS OF A CIRCULATING FLUIDIZED BED

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The available experimental data on the velocities of phases, concentrations of particles, size of clusters in the wall layer of a circulating fluidized bed, and also on the width of this zone have been generalized within the framework of similarity theory. An analysis of the relationship between the velocity of a cluster and its vertical dimension has made it possible to elucidate the character of gas flow around the cluster.

As is known [1], the flow of a two-phase medium near the walls of a standpipe in a circulating fluidized bed is of rather complex character. In contrast to the main (central) part of the bed, where all the particles move upwards, in the wall region one part moves downward in the form of relatively stable "clogs" (clusters) and the other moves upward, just as in the core. This type of pattern of wall flow is a distinguishing feature of a circulating fluidized bed which reflects the internal circulation of particles in the standpipe and greatly determines the entire specificity of transfer processes in the system. It should be noted that in the general case the size of the wall region is not a constant quantity and depends on different geometric and hydrodynamic factors [2].

In the literature, there are a number of publications devoted to investigations of different aspects of the wall hydrodynamics of a circulating fluidized bed: velocities of phases [3–10], concentrations of particles [3, 11, 12], sizes of clusters [6, 9, 13], and the width of the wall annular zone [1, 10, 14–21]. The experimental conditions of these investigations are listed in Table 1. As a rule, these works cite only primary experimental data and lack any attempt to generalize them and establish relationships between the characteristics noted. In view of this, the available valuable information is of a fragmentary character to some extent, not allowing its justifiable use in engineering practice. At the same time, a new method has appeared recently which, as is evidenced by experience, has turned out to be rather efficient in obtaining extended generalizations of experimental data in such a system. This is the technique, developed in [22, 23], of the similarity theory of transport processes in infiltrated disperse systems. In view of this, the aim of the present work is the analysis and generalization of the available experimental data by the above-mentioned technique of similarity theory.

Descending Velocities of Particle Aggregates (Clusters) near the Walls of the Standpipe. Analysis of experimental data [3–9] has shown that the value of v_c depends substantially on the gas filtration rate in the standpipe and practically is independent of the magnitude of the circulatory flow of particles and of the height above the gas distributor. The correlation was done in accordance with the equation [23]

$$\Gamma' = \varphi\,(\mathrm{Fr_t}, \bar{J}_s, H/D, h/H)\,, \tag{1}$$

that expresses the functional dependence of the arbitrary dimensionless hydrodynamic characteristic of a circulating fluidized bed Γ' on the governing factors. In our specific case, expression (1), with account for the above, is reduced to

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TABLE 1. Condition of the Experiments on the Determination of the Parameters of the Wall Flow in a Circulatory Fluidized Bed

Reference	J_s, kg/(m^2·sec)	u, m/sec	H, m	D, m	ρ_s, kg/m^3	d, mm
[3]	8.7–16.2	1.2–6.0	6.65	0.2	2300	0.046
[4]	4.2	3.0	7.0	0.286×0.176	1500	0.068
[5]	30	3.7	8.4	0.4	2600	0.12
[5]	49	2.9	8.4	0.4	1500	0.085
[6]	11.25; 11.7	1.17–1.29	2.79	0.05	1000	0.06
[7]	16.4; 25.4	4.78; 5.85	3	0.22×0.22	2300	0.53; 0.718
[8]	17–98	24–5.5	8.5; 11.2; 35	0.41; 0.83; 14.7×11.6	2600	0.062
[9]	45	5	11	0.15	2600	0.251
[10]	12.7	2.6	5.1	0.14	1700	0.071
[11]	6.4–30.7	2.99–4.02	3.5	0.2	3217	0.06
[12, 19]	–	3.2–7.75	6.9	0.4×0.4	2470; 1240	0.23; 0.55; 0.7
[13]	2–80	3–5	6.6	0.305	2456	0.075
[14]	55–125	2.3–2.5	8.5	0.41	2600	0.04; 0.06; 0.105
[15]	25–75	8; 9	6.0	0.1	2630	0.093; 0.12
[16]	196	4.6	13.0	0.3	1714	0.076
[17]	49–586	4.6–4.9	13.0	0.3	1714	0.076
[18]	87	2.5	8.5	0.41	2600	0.062
[20]	–	1.0	2.0	0.2×0.2	2400	0.12
[21]	2.0–21.3	2.5	6.2	0.16	2500	0.12

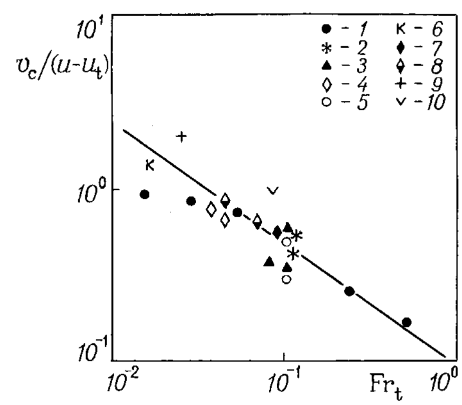

Fig. 1. Comparison of experimental values of the cluster velocity with those calculated by Eq. (3): 1) [3]; 2) [4]; 3) [5]; 4) [6]; 5, 6) [7], d = 0.53 and 0.718 mm; 7–9) [8], H = 8.5; 11.2, and 35 mm; 10) [9].

$$\frac{v_c}{u - u_t} = \varphi\,(\mathrm{Fr}_t, H/D)\,. \tag{2}$$

A standard processing of the experimental data of [3–9] by Eq. (2) yielded the simple relation

$$\frac{v_c}{u - u_t} = 0.1\,\mathrm{Fr}_t^{-0.7}\,, \tag{3}$$

which is shown in Fig. 1. The mean-squared scattering of experimental points about (3) comes to 18%. The region of checking Eq. (3) is seen from Table 1 and Fig. 1.

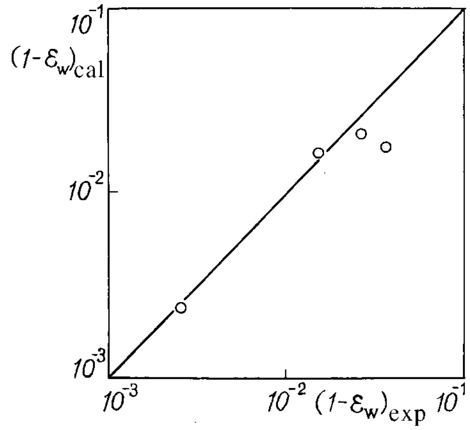

Fig. 2. Comparison of the experimental data of [11] on the value of the wall concentration of particles with the results calculated by Eq. (10).

Concentration of Particles near the Standpipe Wall. An expression for the unknown quantity can be obtained if we use its relationship with the flow of particles near the standpipe wall and cluster velocity:

$$\Phi_w = A\rho_s (1 - \varepsilon_w)\, v_c \,. \tag{4}$$

Here, the relationship between the concentration $1 - \varepsilon_w$ and concentration of clusters $1 - \varepsilon_c$ is assumed to be linear:

$$1 - \varepsilon_w = (1/A)\,(1 - \varepsilon_c)\,. \tag{5}$$

In [24], for the magnitude of the descending flow of particles the following expression was obtained:

$$\frac{\Phi_w}{\rho_s (u - u_t)} = 0.8\,\bar{J}_s\,\mathrm{Fr}_t^{-1.2}\,(h/H)^{-0.8}\,(D/H)^{0.67}\,. \tag{6}$$

With Eqs. (3) and (6) taken into account, for $1 - \varepsilon_w$ from Eq. (5) we have

$$1 - \varepsilon_w = (8/A)\,\bar{J}_s\,\mathrm{Fr}_t^{-0.5}\,(h/H)^{-0.8}\,(D/H)^{0.67}\,. \tag{7}$$

In [25] a simple formula was suggested to calculate the concentration of particles which is mean over the standpipe cross section:

$$1 - \varepsilon = \bar{J}_s\,(h/H)^{-0.82}\,. \tag{8}$$

With the use of Eq. (8), expression (7) is simplified to

$$\frac{1 - \varepsilon_w}{1 - \varepsilon} = (8/A)\,\mathrm{Fr}_t^{-0.5}\,(D/H)^{0.67}\,. \tag{9}$$

The value of A is easily determined from the condition of the best agreement between the experimental values of $1 - \varepsilon_w$ and those calculated by Eq. (7). Figure 2 presents a comparison between $(1 - \varepsilon_w)_{exp}$ and $(1 - \varepsilon_w)_{cal}$ for A = 0.67. The result obtained indicates that the concentration of particles near the standpipe wall is 1.5 times higher than the concentration of the particles in clusters. Taking this into account, we can recommend the following formula to calculate $1 - \varepsilon_w$:

$$1 - \varepsilon_w = 12.0\, \bar{J}_s\, \mathrm{Fr}_t^{-0.5}\, (h/H)^{-0.8}\, (D/H)^{0.67} \, . \tag{10}$$

To link the quantities $1 - \varepsilon_w$ and $1 - \varepsilon$ we obtain

$$\frac{1 - \varepsilon_w}{1 - \varepsilon} = 12.0\, \mathrm{Fr}_t^{-0.5}\, (D/H)^{0.67} \, . \tag{11}$$

The dependence $(1 - \varepsilon_w)/(1 - \varepsilon) \sim \mathrm{Fr}_t^{-0.5}$ correctly reflects the tendency of the concentration profile of particles to equalize with an increasing gas velocity, when the system undergoes transition to a pneumotransport one.

Gas Velocity near the Standpipe Wall. The analysis of the experimental data of [3, 10] showed that the value of u_w increases linearly with increase in the excessive velocity of the gas and also it decreases practically linearly with increase in the circulatory flow of particles. The generalization of experimental data with the aid of the general expression (1) led to the formula

$$\frac{u_w}{u - u_w} = 0.001\, \bar{J}_s^{-0.92}\, \mathrm{Fr}_t^{-0.46} \, . \tag{12}$$

The standard error in the determination of u_w by (12) is 12%.

In using the dimensionless group $\tilde{J}_s = J_s^2/\rho_s^2 gH$ that characterizes the relationship between the kinetic energy of circulatory motion of particles and their potential energy, formula (12) is simplified to

$$\frac{u_w}{u - u_w} = 0.001\, \tilde{J}_s^{-0.46} \, . \tag{13}$$

The region of checking Eq. (13) that was obtained on the basis of generalization of the data of [3, 10] is seen in Table 1.

The Vertical Dimension of a Cluster. The experimental data on the vertical dimension of a cluster [6, 9, 13] indicates that this quantity substantially depends on the gas filtration velocity, circulatory flow of particles, and the height above the gas-distributing grating. In generalizing the experimental data within the framework of the general relation (1), the fundamental question arises as to which quantity should be taken as $\Gamma' - L/H$ or L/d, i.e., whether the size of a cluster should be related to the standpipe height or to the diameter of the particles. The processing of the above-mentioned experimental data by relation (1) allowed us to draw an unambiguous conclusion: the height of the whole standpipe H should be taken as the scale of L. This indicates that the cluster represents a macroformation of particles and that its size is determined by the geometric parameters of the setup as a whole. The value of L is calculated from the following simple relation:

$$L/H = 0.024\, \bar{J}_s^{0.5}\, (h/H)^{-0.41} \, , \tag{14}$$

which, together with the experimental data, is given in Fig. 3. The mean-squared scatter of the experimental points about (14) is 7%. Substituting the expression $(1 - \varepsilon)$ from Eq. (8) into Eq. (14), we obtain the relationship between the size of a cluster and the mean concentration of particles in the considered horizontal section of the standpipe:

$$L/H = 0.024 \sqrt{1 - \varepsilon} \, . \tag{15}$$

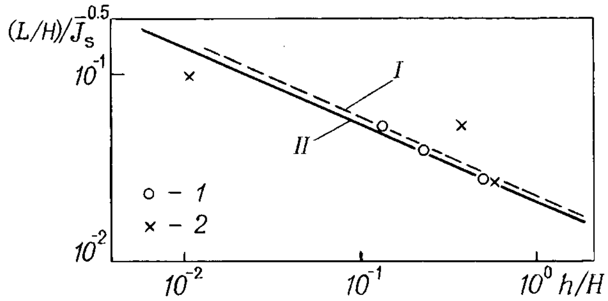

Fig. 3. Generalization of experimental data on the value of the vertical dimension of a cluster: 1) [9]; 2) [6]; I) the line representing the data of [13]; II) the line according to Eq. (14).

This simple formula makes it possible to find the expression of the conductive component of the heat-exchange coefficient in terms of the quantity L. In [26], a relation was obtained to calculate the value of α_{cond}:

$$\mathrm{Nu}_{cond} = 1.65\ \mathrm{Ar}^{0.19}\,(1-\varepsilon)^{0.5}\,. \tag{16}$$

The combination of Eqs. (15) and (16) yields the unknown relationship

$$\mathrm{Nu}_{cond} = 68.75\ \mathrm{Ar}^{0.19}\,L/H\,, \tag{17}$$

which points to the determining role of clusters in the heat exchange of a circulatory fluidized bed with the standpipe walls.

The obtained results on the values of velocities and sizes of clusters make it possible to analyze the character of gas flow past them. The relationship between the velocity of the levitation of the cluster and its vertical dimension is given by the equation

$$(\rho_s^* - \rho_f)\,(1-\varepsilon_{mf})\,S_c L g = \xi\,\frac{\rho_f\,(u_t)_c^2}{2}\,S_c\,, \tag{18}$$

which represents a balance of the forces acting on a cluster in its steady motion. It is assumed that the particles in a cluster are packed to a concentration of $1-\varepsilon_{mf}$ [27]. It follows from Eq. (18) that

$$(u_t)_c = K\sqrt{gL}\,,\quad K = \sqrt{\frac{2\,(\rho_s^* - \rho_f)\,(1-\varepsilon_{mf})}{\xi\rho_f}}\,. \tag{19}$$

On the other hand, the velocity coefficient K can be calculated from the formula

$$K = \frac{v_c + u_w}{\sqrt{gL}} = 6.74\,\bar{J}_s^{-0.25}\,(h/H)^{-0.20}\,(0.1\,\mathrm{Fr}_t^{-0.2} + 0.001\,\tilde{J}_s^{-0.46}\,\mathrm{Fr}_t^{0.5})\,, \tag{20}$$

taking into account that $(u_t)_c = v_c + u_w$ and using the obtained relations (3), (13), and (14) for v_c, u_w, and L. A comparison of relations (19) and (20) gives the following dependence to calculate the effective density of a cluster:

$$\rho_s^* = \rho_f\left(1 + 22.7\,\frac{\xi}{1-\varepsilon_{mf}}\,\bar{J}_s^{-0.5}\,(h/H)^{0.4}\,(0.1\,\mathrm{Fr}_t^{-0.2} + 0.001\,\tilde{J}_s^{-0.46}\,\mathrm{Fr}_t^{0.5})^2\right). \tag{21}$$

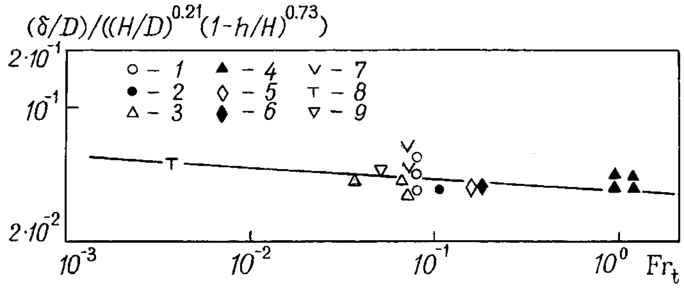

Fig. 4. Generalization of experimental data on the thickness of the annular zone of the wall: 1) [1, Fig. 14.8]; 2) [10]; 3) [14]; 4) [15]; 5) [16]; 6) [17]; 7) [18]; 8) [20]; 9) [21].

Let us make an estimation for the specific case with $\rho_f = 1.2$ kg/m^3; $\varepsilon_{mf} = 0.4$; $J_s = 50$ kg/(m^2·sec); $\rho_s = 2600$ kg/m^3; $u - u_t = 4$ m/sec; and $\xi = 0.003$ [28], considering a cluster as a low-drag body. Calculation by Eq. (21) yields $\rho_s^* = 1.275$ kg/m^3. This seems to indicate that the particles in a cluster are blown through by air and their weight is virtually compensated by resistance forces.

Size of the Annular Zone. An analysis of the experimental data of [1, 10, 14–21] showed that the thickness of the annular zone depends substantially on the height above the gas distributor and, to a much lesser degree, on the gas-filtration velocity and is independent of the magnitude of the mass circulatory flow of particles. According to the data of [21], the quantity δ is independent also of the bed temperature (in the investigated range 20–550^{o}C). The generalization of the data mentioned was made on the basis of the general dependence (1). The resultant formula has the form

$$\delta/D = 0.036\,(H/D)^{0.21}\,(1 - h/H)^{0.73}\,\mathrm{Fr}_t^{-0.06}\,. \tag{22}$$

The experimental points of [1, 10, 14–21] together with relation (22) that describes them are presented in Fig. 4. The mean-squared scatter of points is 21%. The region of checking Eq. (22) is seen from Table 1. Note that Eq. (22) agrees well with the equation

$$\delta/D = 0.55\,(uD/\nu_f)^{-0.22}\,(H/D)^{0.21}\,(1 - h/H)^{0.73}\,, \tag{23}$$

obtained in [2] by processing experimental data empirically for circulatory fluidized-bed boilers and cold models.

CONCLUSIONS

1. On the basis of the technique developed in [22, 23] on the similarity theory of transfer processes in infiltrated disperse systems, the generalizations of the available data on the values of descending velocities of clusters (3), concentration of particles near the standpipe wall (11), wall gas velocity (13), vertical dimension of a cluster (14), and size of the annular zone (22) is performed. These relations have a simple dimensionless form, reflect the influence of the main factors on the characteristics of the wall flow of a two-phase medium, and are convenient for engineering calculations.

2. The relationship between the concentration of particles near the standpipe wall and the concentration mean over its horizontal section (9) has been established.

3. The relationship between the vertical dimension of a cluster with a mean concentration of particles in the horizontal section of the standpipe (15) and also with the conductive component of the heat-exchange coefficient (17) has been established. The latter component points to the determining role of clusters in the heat exchange of a circulatory fluidized bed with the standpipe walls.

4. On the basis of the analysis of the dependence of the levitation velocity of a cluster on its vertical dimension (19), the qualitative character of gas flow past a cluster has been established: along with the flow around the cluster as a whole there is also gas filtration inside the cluster, with the weight of the particles in the cluster being virtually compensated by the hydrodynamic drag force.

NOTATION

A, coefficient introduced into Eq. (5); $\mathrm{Ar} = \frac{gd^3}{\nu_f^2}\left(\frac{\rho_s}{\rho_f} - 1\right)$, Archimedes number; d, diameter of particles; D, diameter of the standpipe; $\mathrm{Fr}_t = (u - u_t)^2/gH$, Froude number; g, free-fall acceleration; h, height above the gas distributor; H, height of the standpipe; J_s, specific mass flow of particles; $\bar{J}_s = J_s/\rho_s(u - u_t)$, dimensionless flow of particles; $\tilde{J}_s = \bar{J}_s^2\,\mathrm{Fr}_t$; K, velocity coefficient introduced in (19); L, vertical dimension of a cluster; $\mathrm{Nu} = \alpha d/\lambda_f$, Nusselt number; S_c, midsection of a cluster; u, gas filtration velocity; u_w, gas velocity near the standpipe wall; u_t, velocity of the levitation of a particle; $(u_t)_c$, velocity of levitation of a cluster; v_c, velocity of a descending motion of a cluster near the standpipe wall; α, heat-exchange coefficient; δ, width of the annular zone; ε, porosity; λ, thermal conductivity; ν, kinematic viscosity; ξ, coefficient of hydrodynamic drag; ρ, density; Φ, specific flow of particles. Subscripts: c, cluster; cond, conductive; f, gas; mf, beginning of fluidization; s, particles; t, levitation conditions; w, near the standpipe wall; cal, calculated; exp, experimental.

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