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HYDRODYNAMICS OF A CIRCULATING FLUIDIZED BED

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Within the framework of similarity theory and using the Fr_t and J_s criteria, which are the generalized characteristics of a circulating fluidized bed, we obtain dimensionless dependences that describe the available experimental data on the wall mass fluxes of particles and the tangential stress on riser walls. The influence of the scale factor and other parameters of the system on the Fr_t and J_s quantities is revealed. A procedure to calculate mass fluxes of particles in the bed core is developed.

The circulating fluidized bed (CFB) has found wide application in power engineering in organizing processes of low-grade solid fuel burning and in the chemical industry in conducting different catalytic reactions. The development of computational methods for apparatuses with a CFB is retarded by the absence in practice of generalized dependences to calculate various transfer characteristics of the system, which in a complicated manner depend on physical and hydrodynamic factors. This situation is largely due to the insufficient development of similarity problems for transfer processes in a CFB, the solution of which could provide practical recommendations for rational generalization of the available experimental data.

In [1], on the basis of similarity theory, a universal method is suggested to generalize experimental data on the hydrodynamics of disperse systems with suspended particles, to which the CFB also belongs. This method is based on application of the excess gas velocity $u - u_t^*$, which is a measure of the kinetic energy of particles. Using this quantity, the generalized criteria for the hydrodynamic similarity $\mathrm{Fr}_t^* = (u - u_t^*)^2/gH$ and $\bar{J}_s^* = J_s/\rho_s(u - u_t^*)$ are introduced, by means of which it turns out to be possible to solve the problem of scale transition and to obtain simple dimensionless formulas for calculating various characteristics of a specific disperse system.

In the present work we set ourselves the following problem: using the above-mentioned method to generalize the available experimental data on the wall mass particle fluxes and tangential stress on the riser surface, and to obtain dimensionless dependences for calculating these parameters with allowance for the influence of the scale factor.

1. Descending Mass Fluxes of Particles Near Riser Wall. In [1], the following functional relations are established for the dimensionless hydrodynamic characteristic of the CFB:

$$\Gamma = \varphi\left(\bar{J}_s, \mathrm{Fr}_t, \frac{h}{H}, \frac{H}{D}\right) \quad (1)$$

i.e., a bed operating by the "chemical reactor" scheme, when the quantity of the circulating particle flux J_s is assigned;

$$\Gamma = \Psi\left(\frac{H_0}{H}, \mathrm{Fr}_t, \frac{h}{H}, \frac{H}{D}\right) \quad (2)$$

i.e., a bed operating by the "furnace" scheme, when in the lower part of the riser the pressure drop $\Delta p = \rho_s(1 - \varepsilon_{mf})H_0 g$ is assigned. In the case of the mass flux near the riser wall (Fig. 1) $\Gamma = \Phi_w/\rho_s(u - u_t)$, and for the "chemical reactor" scheme from Eq. (1) it follows (the dependence on the determining parameters is assumed to be exponential) that:

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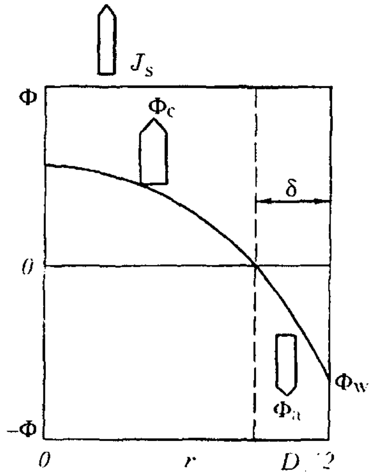

Fig. 1. Diagram of particle fluxes in riser of CFB.

$$\frac{\Phi_w}{\rho_s(u-u_t)} = A\bar{J}_s^{K_1}\mathrm{Fr}_t^{K_2}\left(\frac{h}{H}\right)^{K_3}\left(\frac{H}{D}\right)^{K_4}. \tag{3}$$

In order to analyze by means of Eq. (3) the data obtained in the CFB operating by the "furnace" scheme, it is first necessary to establish the dependence of the external mass flux J_s on the determining factors

$$\bar{J}_s = \theta\left(\frac{H_0}{H}, \mathrm{Fr}_t, \frac{H}{D}\right), \tag{4}$$

which results from Eq. (2). Generalization of the data of [2, 3] by Eq. (4) gave the equation

$$\bar{J}_s = 0.54\mathrm{Fr}_t^{0.8}\left(\frac{H_0}{H}\right)^{0.8} \tag{5}$$

($0.1 \le H_0 \le 0.5$ m; $0.2 \le d \le 0.32$ mm; $2 \le u \le 6.5$ m/sec; $6.6 \le H \le 13.5$ m). Processing of the experimental data of [4-10] by the quantities Φ_w in accordance with dependence (3) and calculation of J_s in the CFB of the "furnace" type by Eq. (5)* led to the equation

$$\frac{\Phi_w}{\rho_s(u-u_t)} = 0.8\bar{J}_s\mathrm{Fr}_t^{-1,2}\left(\frac{h}{H}\right)^{-0.8}\left(\frac{D}{H}\right)^{0.67}. \tag{6}$$

The experimental points together with correlation (6) are shown in Fig. 2. The mean-square error of approximation is 27%. The range of change in the characteristics of the CFB is as follows: $7 \le H \le 33.5$ m; $0.144 \le D \le 4.7$ m; $0.22 \le h/H \le 0.92$; $4.2 \le J_s \le 42.4$ kg/(m^2·sec); $0.003 \le \mathrm{Fr}_t \le 0.25$. We note that in the case of a boiler with a power of 165 MW [8] and riser cross section 12 × 4.7 m, the quantity 4.7 m was taken as $D = D_e$.

The combination of Eqs. (5) and (6) gives a dependence to calculate Φ_w in beds operating by the "furnace" scheme:

$$\frac{\Phi_w}{\rho_s(u-u_t)} = 0.43\mathrm{Fr}_t^{-0.4}\left(\frac{h}{H_0}\right)^{-0.8}\left(\frac{D}{H}\right)^{0.67}, \tag{7}$$

which is a special case of Eq. (2). As follows from Eqs.(6) and (7), the quantity Φ_w depends rather substantially on the scale of the system, in particular, on the riser diameter.

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* In the presence of secondary blowing, the gas velocity near the gas-distributing lattice was taken as u.

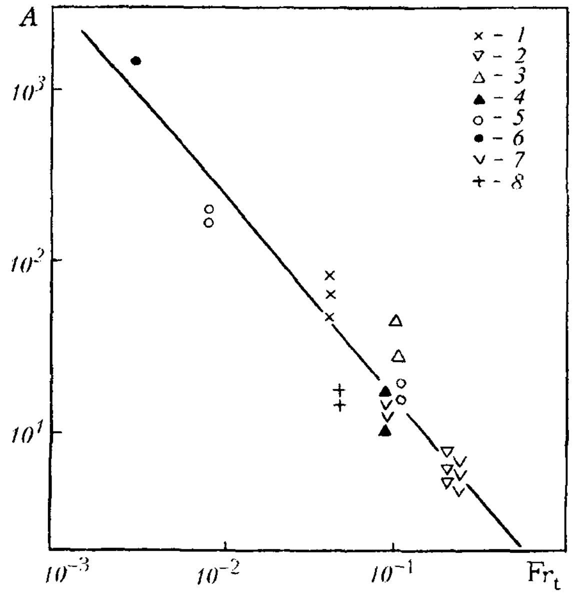

Fig. 2. Descending mass fluxes of particles near riser wall: 1) [4], $S = 0.7 \times 0.118$ m; 2) [5], $D = 0.144$ m; 3) [6], $S = 0.286 \times 0.176$ m; 4) [7], $S = 0.8 \times 1.2$ m; 5) [8], $S = 1.72 \times 1.44$ m; 6) [8], $S = 12 \times 4.7$ m; 7) [9], $D = 0.15$ m; 8) [10], $D = 0.161$ m. $A = \Phi_w / J_s \left(\frac{h}{H}\right)^{-0.8} \left(\frac{D}{H}\right)^{0.67}$.

It is of interest to compare obtained dependence (6) with the experimental data of [11] on measurement of Φ_w for a system closely related to the CFB, i.e., of a vertical pneumatic transport of particles with their pile-up near the riser walls. It is evident that for this system the quantities h and H must be excluded from a number of determining parameters, and then Eq. (2) takes the form

$$\Gamma = \varphi'(\bar{J}_s, \mathrm{Fr}_D). \tag{8}$$

Processing of the data of [11] in accordance with Eq. (8) yields:

$$\frac{\Phi_w}{\rho_s(u - u_t)} = 184 \bar{J}_s \mathrm{Fr}_D^{-1.7}, \tag{9}$$

$$0.018 \le \bar{J}_s \le 0.032;\ 10.5 \le \mathrm{Fr}_D \le 68;\ D = 0.18 \text{ m}.$$

The mean-square deviation of the experimental data calculated from Eq. (9) amounts to 23%. From a comparison of Eqs. (6) and (9), one can see that the dependences of Φ_w on the main parameters are fairly close.

By expressing the quantity Φ_w in terms of the local particle concentration ρ, Eq. (6) can be presented in a more compact form. To calculate ρ, the following simple dependence was obtained in [12]:

$$\frac{\rho}{\rho_s} = \bar{J}_s \left(\frac{h}{H}\right)^{-0.82}. \tag{10}$$

With allowance for Eq. (10) relation (6) is reduced to the form

$$\frac{\Phi_w}{\rho_s(u - u_t)} = 0.8 \frac{\rho}{\rho_s} \mathrm{Fr}_t^{-1.2} \left(\frac{D}{H}\right)^{0.67}, \tag{11}$$

which indicates a direct proportionality of the dimensionless mass flux of particles near the riser wall to their mean concentration in the horizontal cross section.

On the basis of analysis of numerous experimental data, in [8] an empirical dependence was established for the width of the descent zone near the riser walls (see Fig. 1) on its diameter

$$\delta = 0.05D^{0.74} \quad (0.07 \le D \le 8\ \text{m})\,. \tag{12}$$

Assuming that δ is independent of the height over the gas distributor and of the gas filtration velocity, we can write the dimensionless analog of (12)

$$\frac{\delta}{D} = 0.025\left(\frac{H}{D}\right)^{0.26} \quad \text{for } H \le 33.5\ \text{m}\,. \tag{13}$$

Taking into account the relative smallness of δ, it is admissible to presuppose a linear dependence of the local descending flux of particles on the radial coordinate:

$$\Phi_a(r) = \Phi_w\left(1 - \frac{D}{2\delta}\right) + \Phi_w\frac{r}{\delta}. \tag{14}$$

Function (14) satisfies the conditions: $\Phi_a(D/2) = \Phi_w$; $\Phi_a(D/2 - \delta) = 0$. For the integral flux near the wall we have

$$\hat{\Phi}_a = 2\pi \int\limits_{D/2-\delta}^{D/2} \Phi(r) r dr = \frac{\pi D\delta}{2}\Phi_w. \tag{15}$$

With allowance for Eqs. (6) and (13), we obtain the following formula to calculate $\hat{\Phi}_a$:

$$\frac{\hat{\Phi}_a}{\frac{\pi D^2}{4}J_s} = 0.04\text{Fr}_t^{-1,2}\left(\frac{h}{H}\right)^{-0.8}\left(\frac{D}{H}\right)^{0.41}. \tag{16}$$

2. Ascending Mass Fluxes of Particles in CFB Core. For an integral ascending flow in the bed core the relation is valid:

$$\hat{\Phi}_c = \frac{\pi D^2}{4}J_s + \hat{\Phi}_a\,. \tag{17}$$

Using Eq. (16), we have

$$\frac{\hat{\Phi}_c}{\frac{\pi D^2}{4}J_s} = 1 + 0.04\text{Fr}_t^{-1,2}\left(\frac{h}{H}\right)^{-0.8}\left(\frac{D}{H}\right)^{0.41}. \tag{18}$$

For the mean specific flux in the bed core

$$\langle\Phi_c\rangle = \frac{\hat{\Phi}_c}{\frac{\pi D^2}{4} - \pi D\delta} = \frac{J_s\left(1 + 0.04\text{Fr}_t^{-1,2}\left(\frac{h}{H}\right)^{-0,8}\left(\frac{D}{H}\right)^{0.41}\right)}{1 - 0.1\left(\frac{H}{D}\right)^{0.26}}. \tag{19}$$

With allowance for Eq. (5) it is easy to calculate the quantities $\hat{\Phi}_a$, $\hat{\Phi}_c$, and $\langle\Phi_c\rangle$ for a CFB operating by the "furnace" scheme.

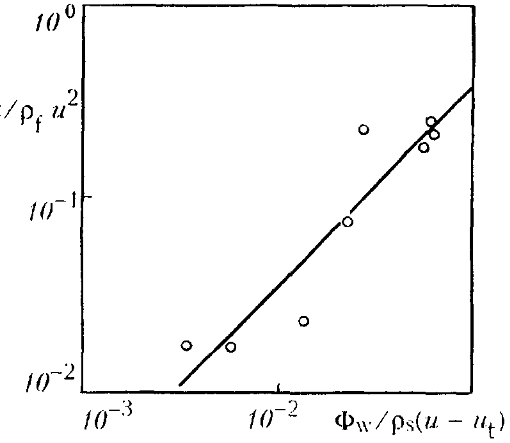

Fig. 3. Tangential stresses on the wall of 0.18-m-diameter riser [11].

Let us give an example of calculating the relations $\langle\Phi_c\rangle/\Phi_w$ and $\hat{\Phi}_c/\frac{\pi D^2}{4}J_s$ for specific conditions: $H = 10$ m; $D = 0.10$ m; $u - u_t = 3$ m/sec; $h/H = 0.4$; $\rho_s = 2500$ kg/m^3. From formulas (6) and (19) it follows that $\langle\Phi_c\rangle/\Phi_w = 1.37$; $\hat{\Phi}_c/\frac{\pi D^2}{4}J_s = 1.22$ (formula (18)), i.e., at the given height the internal circulation of particles, $(\hat{\Phi}_c)$ is by about 1.2 times higher than the external circulation $(\frac{\pi D^2}{4}J_s)$. A similar calculation performed for $D =$ 1.0 m gave: $\langle\Phi_c\rangle/\Phi_w = 0.38$; $\hat{\Phi}_c/\frac{\pi D^2}{4}J_s = 1.57$.

3. Tangential Friction on Riser Surface. This quantity is closely associated with the mass flux of particles near the wall. Experimental data on tangential friction in a CFB have not been found. In the above-mentioned work [11], under pneumatic transport conditions with a pile-up of particles, the authors, simultaneously with measurements of Φ_w, also determined the quantities τ. The processing of these experiments carried out by us made it possible to establish a simple functional relation between τ and Φ_w:

$$\frac{\tau}{\rho_f u^2} = 4.0\frac{\Phi_w}{\rho_s(u - u_t)} . \tag{20}$$

A comparison of the experimental points with Eq. (20) is shown in Fig. 3. Assuming the validity of formula (20) also for the CFB, we can recommend the following correlation to evaluate the tangential friction on the riser surface in the CFB:

$$\frac{\tau}{\rho_f u^2} = 3.2\bar{J}_s \mathrm{Fr}_t^{-1.2}\left(\frac{h}{H}\right)^{-0.8}\left(\frac{D}{H}\right)^{0.67} , \tag{21}$$

which follows from Eqs. (6) and (20) and is a particular case for general expression (1).

Conclusion. On the basis of a method developed in [1] for generalizing experimental data on the hydrodynamics of disperse systems with suspended particles, semiempirical dependences are obtained to calculate the important hydrodynamic characteristics of a CFB: the descending circulation flux of particles near the riser walls (Eqs. (6), (7), and (16)); the ascending flux of particles in the bed core (Eqs. (18) and (19)); and the tangential stresses on the riser wall (Eq. (21)). These correlations take into account the influence of the scale factor and can be used for evaluating the corresponding quantities in large-scale apparatuses with a CFB. At the same time, the above-mentioned dependences can be a reliable basis for further investigations of the hydrodynamic characteristics of a CFB and for refinement of the derived semiempirical formulas.

NOTATION

a, diameter of particles; D, diameter of riser; $D_e = \sqrt{4s/\pi}$, equivalent diameter of riser; $Fr_t = (u - u_t^*)^2/gH$, $Fr_t^* = (u - u_t^*)^2/gH$, $Fr_D = (u - u_t)^2/gD$, Froude numbers; g, free fall acceleration; H, height of riser; h, height over gas distributor; $H_0 = \Delta p/\rho_s(1 - \varepsilon_{mf})g$, initial height of a bed; J_s, external specific mass flux of particles; $\bar{J}_s = J_s/\rho_s(u - u_t)$, $\bar{J}_s^* = J_s/\rho_s(u - u_t^*)$, dimensionless mass fluxes of particles; Δp, pressure drop in bed; r, radial coordinate; S, cross section of riser; u, gas velocity near gas distributor; u_t, flotation velocity of single particle; u_t^*, flotation velocity of particles under constrained conditions ($u_t^* \to u_t$ for $\varepsilon \to 1$); δ, width of descending zone near riser walls; ε, porosity; ρ, density; τ, tangential stress on riser wall; Φ, specific flux of particles; $\hat{\Phi}$, flux of particles. Subscripts: a, circular zone near riser wall; c, bed core; e, equivalent; f, gas; mf, fluidization onset; s, particles; t, flotation conditions; w, near riser wall.

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