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SOME ASPECTS OF THE STABILITY OF VERTICAL PNEUMOTRANSPORT OF SOLID PARTICLES

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The upper boundary of the critical transition region separating stable (normal) pneumotransport from a through two-phase flow with internal circulation of the particles is determined on the basis of an analysis of pressure losses in a two-phase flow in a vertical channel. Simple dimensionless relations for calculation of the velocities U_{cl} and U_{opt} determining the lower and upper boundaries of the transition region are obtained.

Vertical transport of solid particles by a gas is widely used in industrial installations [1]. A number of works [1-5] performed mainly prior to 1970 are devoted to the study of this process. The problem of pneumotransport stability, which is reduced to the description of the phenomenon of clogging-up of particles and the search for acceptable formulas for calculation of the velocity of clogging-up U_{cl}, has occupied an important place in these studies. The available recommendations for the calculation of U_{cl} [1, 3, 5] are obtained for very narrow ranges of variation of experimental conditions and are presented, as a rule, in dimensional form, and practical application of them is very limited. The whole transition region separating stable pneumotransport from a through two-phase flow with internal circulation of the particles has not been studied in the literature, and recommendations on calculation of the width and location of this zone, which are very important in practice, are absent.

Wide use of new promising technologies on the basis of a circulating fluidized bed [6] and a throughput fluidized system with internal circulation of the particles has served at present as an impetus for continuation of works on the problem of the stability of two-phase flows in vertical channels. A circulating fluidized bed (especially its transport zone) is very similar to a classical pneumotransport system and converts to it with increase in the gas velocity. Here the problem of the stability of these systems can be treated as the study of the laws governing the hydrodynamics of a vertical flow in the transition region separating the mode of stable pneumotransport from the mode of a two-phase flow with internal circulation of the particles (with clogging-up of the particles) of the type of a circulating fluidized bed.

The aim of the present paper is to determine the location of the critical transition region on the basis of an analysis of the pressure losses in a two-phase flow in a vertical channel and to obtain universal dimensionless formulas for the calculation of the lower (U_{cl}) and upper (U_{opt}) boundaries of this zone.

We write an expression for the pressure drop on a stabilized portion of a two-phase flow of length Δl:

$$\Delta p = \rho_s (1 - \varepsilon) g\Delta l + 4\tau \frac{\Delta l}{D} . \qquad (1)$$

We note that in the case of pneumotransport the value of the tangential stress on the riser wall $\tau > 0$ (particles at the wall move vertically upward), and in the case of a circulating fluidized bed $\tau < 0$ (particles at the wall move downward producing internal circulation). Experimental data on the values of τ for both $\tau > 0$ [7, 8] and $\tau < 0$ [8] are available in the literature. It was found that τ depends on the following parameters:

$$\tau = f(U, J_s, d, \rho_s) . \qquad (2)$$

The above-mentioned studies were conducted in air, and therefore, in the general case dependence (2) should be written in the form

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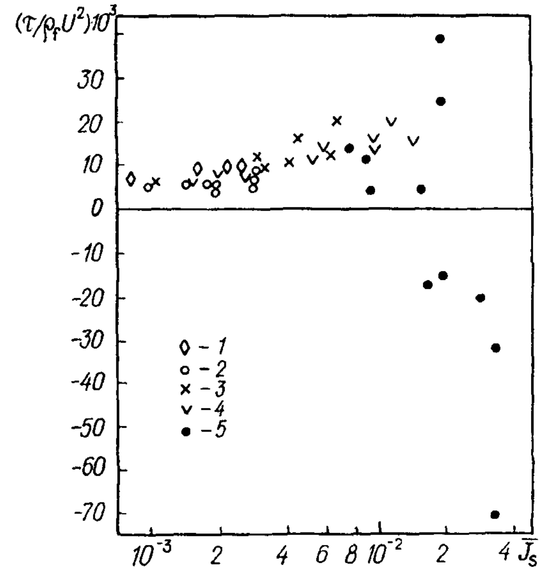


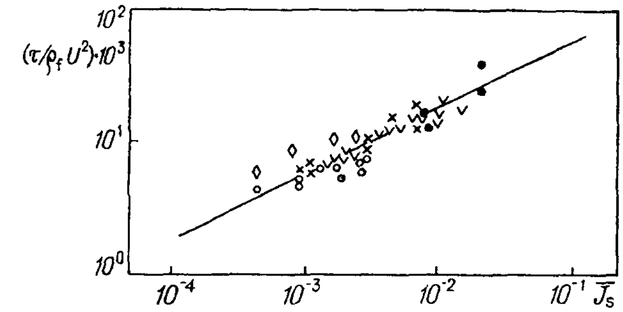


Fig. 1. Tangential friction in vertical two-phase flows: 1) d = 0.113 mm, 2) 0.1, 3) 0.2, 4) 1.18, 5) 0.06; 1-4) [7], 5) [8].

Fig. 2. Generalization of experimental data on the value of tangential friction in vertical pneumotransport. For notation see Fig. 1.

$$\tau = f\,(U, J_s, d, \rho_s, \rho_f, \nu, g)\,, \tag{3}$$

with gas characteristics and the quantity g being added. An analysis of experimental data was made on the basis of similarity theory. Using the π-theorem of dimensionality theory [9], we can present (3) in the dimensionless form

$$\frac{\tau}{\rho_f U^2} = f\left(\frac{J_s}{\rho_s\,(U - U_t)}, \frac{gd^3}{\nu^2}, \frac{\rho_s}{\rho_f}, \frac{Ud}{\nu}\right). \tag{4}$$

The combination $\bar{J}_s = J_s/(\rho_s(U - U_t))$ characterizes the mean value of the particle concentration in the throughput system, and experience in employment of this complex turned out to be very fruitful in the description of the distribution of the particle concentration and the coefficient of heat transfer over the height of the transport zone of a circulating fluidized bed [10]. The velocity of floating $\bar{J}_s$ is unambiguously determined by the second and third combinations on the right-hand side of (4), and the gas velocity enters both $\bar{J}_s$ and Re = Ud/ν. Therefore, the assumption of the following simplified form of (4) is fully substantiated:

$$\frac{\tau}{\rho_f U^2} = f\,(\bar{J}_s)\,. \tag{5}$$

Figure 1 presents data of [7, 8] in coordinates corresponding to (5). It is clearly seen that the test points are divided into two groups that differ in the values of $\bar{J}_s$. When $\bar{J}_s < 1.5\cdot 10^{-2}$, the points are grouped rather regularly, thus indicating the existence of a relation of the type of (5). This is the region of classical pneumotransport, where $\tau > 0$. When $\bar{J}_s > 1.5\cdot 10^{-2}$, a rather considerable scatter of the test points with $\tau > 0$ and $\tau < 0$ is observed; this indicates instability and intermittency of particle motion at the wall. This speaks in favor of the appearance of clogging-up (internal circulation of the particles) in the system and its transition to the mode of a circulating fluidized bed. It is not possible as yet to establish in this transition region any law for describing the values of the tangential stress on the riser wall (5), and therefore in what follows we consider only pneumotransport modes with $\tau > 0$. In Fig. 2 these data are given separately, and the extremely simple formula

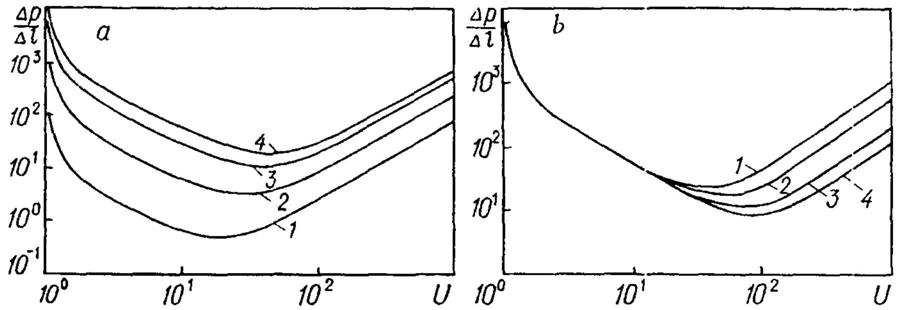


Fig. 3. Pressure losses in a pneumotransport system ($\rho_s = 2500$ kg/m^3, ρ_f = 1.16): a) $D = 0.1$ m: 1) $J_s = 0.5$ kg/(m^2·sec), 2) 5, 3) 25, 4) 50; b) $J_s = 50$ kg/(m^2·sec): 1) $D = 0.05$ m, 2) 0.1, 3) 0.3, 4) 0.5.

$$\frac{\tau}{\rho_f U^2} = 0.17\sqrt{J_s}\,, \tag{6}$$

indicating proportionality of the tangential stress on the riser wall to the square root of the particle concentration, is obtained on the basis of these data. As is known from the literature [1, 10], the coefficient of heat transfer between a gas-suspension flow and the riser wall is also nearly proportional to the square root of the particle concentration. This evidently indicates the existence of an analogy between transport of heat and momentum in these systems. With account for (6) Eq. (2) will have the form (the case of pneumotransport)

$$\frac{\Delta p}{\Delta l} = \rho_s(1-\varepsilon)\,g + \frac{1.36}{D}\sqrt{J_s}\,\frac{\rho_f U^2}{2}\,. \tag{7}$$

The obtained relation (7) allows one to analyze the process of the "pneumotransport–circulating fluidized bed" transition near the upper boundary of the critical region with a smooth decrease in the gas velocity.

We write a relation between the mass flow of the particles and their concentration:

$$J_s = \rho_s(U - U_t^*)\,\frac{1-\varepsilon}{\varepsilon}\,, \tag{8}$$

where U_t^* is the floating velocity of the particles under the conditions of constraint. Using the well-known Todes formula [11] for calculation of U_t^*, we can write

$$\frac{U_t^*}{U_t} = \frac{18 + 0.6\sqrt{\mathrm{Ar}}}{18 + 0.6\sqrt{\mathrm{Ar}\,\varepsilon^{4.75}}}\,\varepsilon^{4.75}\,. \tag{9}$$

We obtained a simpler expression for the right-hand side of (9):

$$\frac{U_t^*}{U_t} = \varepsilon^{5.4\mathrm{Ar}^{-0.05}} \quad (10^1 \le \mathrm{Ar} \le 10^5)\,, \tag{9a}$$

which is a generalization of the well-known Richardson–Zaki formula [3]. The estimates made showed that under pneumotransport conditions $U_t^*/U_t = 0.75$–0.98 and U usually exceeds U_t substantially. This makes it possible to assume in (8) that $U - U_t^* \approx U - U_t$. Due to the sufficient closeness of ε to 1 ($\varepsilon \approx 0.94$–0.99) it is admissible to present (8) in the final simplified form

$$J_s = \rho_s(U - U_t)(1-\varepsilon)\,. \tag{10}$$

With account for (10) expression (7) for $\Delta p/\Delta l$ will be

$$\frac{\Delta p}{\Delta l} = \frac{J_s g}{U - U_t} + \frac{1.36}{D} \sqrt{\left(\frac{J_s}{\rho_s (U - U_t)}\right)^{1/2}} \frac{\rho_f U^2}{2}. \quad (11)$$

A dimensionless form of (11) is

$$\frac{\Delta (p/\rho_f U^2)}{\Delta (l/D)} = \frac{\rho_s}{\rho_f} \frac{\bar{J}_s}{\mathrm{Fr}_u} + 0.68 \sqrt{\bar{J}_s}, \quad (12)$$

where $\mathrm{Fr}_U = U^2/gD$.

The function in the right-hand side of (11) determines the dependence of $\Delta p/\Delta l$ on the main governing parameters of the two-phase system: J_s, U, ρ_f, ρ_s, U_t, and D. Figure 3 shows sets of curves $\Delta p/\Delta l = f(U)$ constructed by (11) for specific conditions. A characteristic feature of these curves is that each of them has a minimum at a certain gas velocity U_{opt}. It is obvious that this point is the lower boundary of stable pneumotransport and the upper boundary of the transition region characterized by an increase in pressure losses with a decrease in the working velocity of the gas ($\partial \Delta p/\partial U < 0$). To calculate U_{opt} we can use the following equation determining the minimum of $\Delta p/\Delta l$:

$$\frac{\partial (\Delta p/\Delta l)}{\partial U} = 0. \quad (13)$$

Substitution of the expression for $\Delta p/\Delta l$ in the form of (11) into (13) gives an algebraic equation of the fifth order for determining U_{opt}:

$$y^5 + \frac{2}{3} y^3 U_t - \frac{1}{3} y U_t^2 - A = 0, \quad (14)$$

where $A = 0.98 g D \sqrt{J_s \rho_s}/\rho_f$; $y = \sqrt{U_{opt} - U_t}$.

In dimensionless form Eq. (14) will be

$$z^5 + \frac{2}{3} z^3 - \frac{1}{3} z - B = 0, \quad (15)$$

where $z = ((U_{opt} - U_t)/U_t)^{1/2}$; $B = (\rho_s/\rho_f)^{1/2} \sqrt{J_s^*}/\mathrm{Fr}_t$.

Equation (15) has a single positive root z_1 (the Descartes theorem [12]) that determines the sought quantity U_{opt}:

$$U_{opt} = U_t (1 + z_1^2). \quad (16)$$

It turned out to be possible to approximate the numerical solution of (15) within a wide range of values of the parameter B ($10^{-3} \le B \le 10^6$) by simple power-law dependences of z_1 on B, which led to the following expressions for U_{opt}:

a) $B \le 1/3$

$$U_{opt} = U_t \left(\frac{4}{3} + 0.65 B^{0.8}\right); \quad (17)$$

b) $B > 1/3$

$$U_{opt} = U_t (1 + B^{0.4}). \quad (18)$$

The errors of approximation do not exceed 1% for (17) and 3% for (18).

The obtained equations (17) and (18) reflect the dependence of the velocity U_{opt} on the determining factors. The parameter B unambiguously determining U_{opt} can be called the stability parameter of the pneumotransport

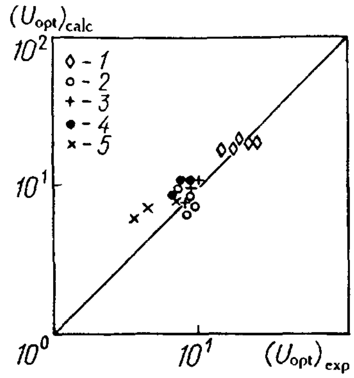


Fig. 4. Generalization of experimental data on U_{opt} (m/sec) in vertical pneumotransport: 1) [5] (d = 3-4 mm), 2) [4] (d = 1.67 mm), 3) [4] (d = 0.93 mm), 4) [4] (d = 0.586 mm), 5) [4] (d_{eq} = 0.168 mm).

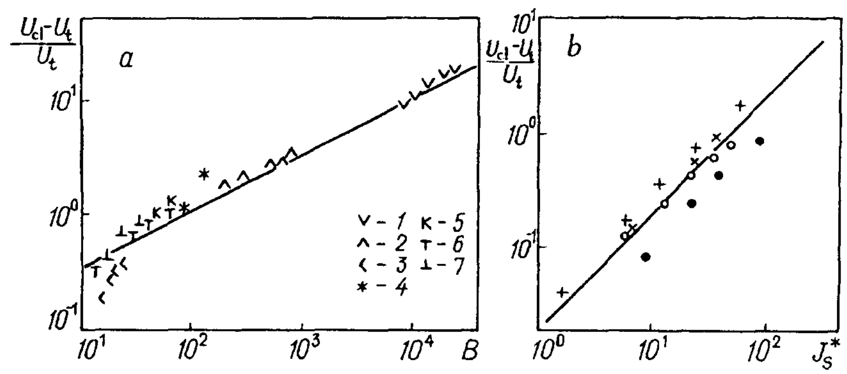


Fig. 5. Generalization of experimental data on velocities of clogging-up U_{cl}: a) small particles: 1-3) [13] (d = 0.04 mm, 0.1, 0.28, respectively); 4-7) [14] (d = 0.12 mm, 0.151, 0.225, 0.256, respectively); b) large particles. For notation see Fig. 4.

system. Figure 4 shows a comparison of data calculated by (17) and (18) and experimental data on U_{opt} [4, 5]. The root-mean-square deviation of the experimental data from the calculated data is 15%.

It is of interest to analyze the dependence of U_{opt} on such an important parameter as the riser diameter. In [5] this problem was studied specially by employing risers of three sizes: 0.055, 0.075, and 0.098 m. The results of the study showed that U_{opt} is virtually independent of D. The obtained recommendations (17) and (18) allow for the effect of this important factor, which as is seen from Fig. 3b, is really rather weak.

The porosity of the two-phase system at the point $U = U_{opt}$ is calculated by a formula following from (10):

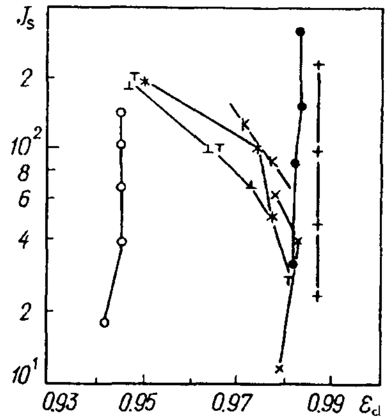
$$\varepsilon_{opt} = 1 - (\bar{J}_s)_{opt}, \tag{19}$$

where $(\bar{J}_s)_{opt} = J_s / (\rho_s(U_{opt} - U_t))$.

Now we analyze the available literature data on the position of the lower boundary of the transition region, i.e., on the values of the velocity of clogging-up of the particles [4, 13, 14]. By analogy with formula (18) (for the data of [4, 13, 14] the value of B is always larger than 1/3) a generalization of the experimental data on U_{cl} was sought in the form of the dependence

$$\frac{U_{cl} - U_t}{U_t} = kB^n. \tag{20}$$

Processing of the mentioned data showed that a function of the form of (20) adequately generalizes only the experimental data [13, 14] for small particles ($d \le 0.28$ mm) (Fig. 5a):



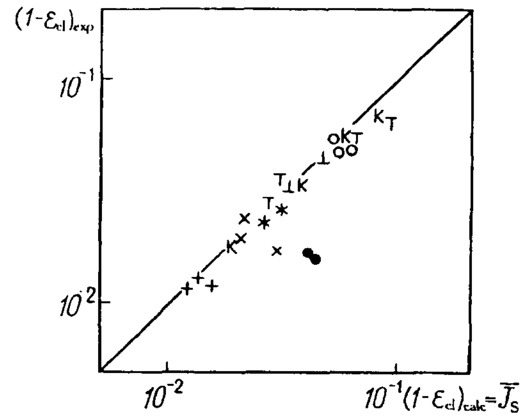


Fig. 6. Influence of the mass flow of the particles on the value of the porosity at the velocity of clogging-up. For notation see Figs. 4, 5. J_s, kg/(m^2·sec).

Fig. 7. Comparison of experimental values of $1 - \varepsilon_{cl}$ and values calculated by formula (25). For notation see Figs. 4, 5.

$$\frac{U_{cl} - U_t}{U_t} = 0.11 B^{0.5}. \tag{21}$$

The experimental data of Zenz [4] for larger particles ($0.586 \le d \le 1.67$) are generalized by the somewhat different relation (Fig. 5b)

$$\frac{U_{cl} - U_t}{U_t} = 0.02 J_s^* . \tag{22}$$

We note that formula (22) agrees satisfactorily with a relation for calculation of U_{cl} known from the literature [15]:

$$U_{cl} = 32.3 U_s + 0.97 U_t , \tag{23}$$

which was obtained from (8) for $\varepsilon = \varepsilon_{cl} = 0.97$ and $U_t^*/\varepsilon \approx U_t$. In fact, expanding the expression for J_s^* and substituting $\rho_f = 1.2$ kg/m^3, $\rho_s = 2400$ kg/m^3, we obtain from (22) a dimensional formula for U_{cl}

$$U_{cl} = 38.4 U_s + U_t , \tag{24}$$

which is close to (23). This evidently indicates that a generalization of the type of (22) is valid in systems in which the porosity at the clogging-up point does not depend on the value of the mass flow of the particles J_s (formula (23) was obtained under precisely this assumption). Figure 6, where the experimental values of ε_{cl} obtained in [4] are shown, confirms this. The same figure shows the values of ε_{cl} from [14]. As is seen, in this case the dependence $\varepsilon_{cl}(J_s)$ exists and, consequently, in these systems relation (21) is valid.

The porosity at the point of clogging-up is calculated by a formula similar to (19):

$$\varepsilon_{cl} = 1 - (\bar{J}_s)_{cl} , \tag{25}$$

where $(\bar{J}_s)_{cl} = J_s/(\rho_s(U_{cl} - U_t))$. Figure 7 presents experimental values of ε_{cl} calculated by (25). For the data of Zenz [4] obtained in beds of large particles, the values of ε_{cl}, as was noted ealier, do not depend on J_s, and for this case an equation not involving U_{cl} was derived:

$$\varepsilon_{cl} = 0.684 + 0.095 \ln \mathrm{Fr}_t , \tag{26}$$

describing the experimental values of ε_{cl} with an error of ~10%.

The obtained expressions (17), (18), (21), and (22) determine the boundaries and location of the critical transition zone with $\partial \Delta p / \partial U < 0$, where the transition from stable (normal) transport of the particles with $\partial \Delta p / \partial U > 0$ to modes with clogging-up of the particles and formation of inner circulation loops of them (a system of the type of a circulating fluidized bed) occurs with a decrease in the velocity of the gas. These formulas have a dimensionless form, are verified within rather wide ranges of variation of the experimental conditions, and are convenient for practical use in choosing the mode of operation of apparatuses with throughput two-phase systems.

NOTATION

$\mathrm{Ar} = (gd^3/\nu^2)(\rho_s/\rho_f - 1)$, Archimedes number; d, particle diameter; D, riser diameter; $\mathrm{Fr}_t = U_t^2/gD$, $\mathrm{Fr}_U = U^2/gD$, Froude numbers; g, free-fall acceleration; J_s, mass flow of the particles; $\bar{J}_s = J_s/(\rho_s(U - U_t))$, $J_s^* = J_s/\rho_f U_f$, dimensionless flows of the particles; l, length; Δp, pressure drop; U, gas velocity; U_s, velocity of the particles related to an empty cross section of the riser ($U_s = J_s/\rho_s$); U_t, floating velocity of a single particle (at $\varepsilon = 1$); U_t^*, floating velocity of a particle under conditions of constraint; ε, porosity; ν, kinematic viscosity; ρ, density; τ, tangential stress on the riser wall. Subscripts: f, gas; s, particles; t, floating of a single particle; cl, clogging-up; opt, optimum; eq, equivalent.

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