PHYSICAL AND MATHEMATICAL SIMULATION OF THE PROCESS OF CENTRIFUGAL DUST SEPARATION

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Results are presented of a calculation and experimental simulation of the process of centrifugal dust separation, and a method for calculating the limiting dimension is developed.

In our earlier papers [1, 2] we presented some results of a mathematical simulation of the motion of dust particles in a plane rotating stream, which is realized for example in the plane separation zone of a number of high-efficiency laboratory and commercial dust separators [3, 4]. Recognizing that mathematical simulation inevitably entails a definite abstraction of the real process, it is advisable to carry out a physical simulation of the operation of a plane separation zone, to compare the results of the mathematical and physical simulation, and to develop on this basis a method for calculating the centrifugal separation.

The experimental investigation was carried out with geometrically similar models of a specially developed laboratory separator. The following characteristic quantities were varied: the characteristic dimension of the model, namely the outside diameter of the separation zone (L = 0.25, 0.5, and 1.0 m), the dust density (ρ_2 = 1600, 3980, and 7000 kg/m^3), the characteristic dimension of the similar polydispersed dust [5] (δ_0 = 68-168 μ), and the dust concentration (μ = 0.03-0.5 kg of dust/kg of air). We performed 136 experiments, and used the result of each of them to plot the partial loss curve and determine the limiting dimension δ_{lim} [6]. Plots of δ_{lim} against the experimentally varied defining quantities are shown in Fig. 1.

The motion of polydispersed dust is determined by the following similarity criteria [5]:

$$\mathrm{St},\ R,\ \mathrm{Fr},\ \mathrm{Re}_0,\ \mu, \tag{1}$$

which can be represented in the following form, which is somewhat more convenient for our case:

$$\Delta = \mathrm{St}/R,\quad C = R^2/\mathrm{St},\ \mathrm{Fr},\ \mathrm{Re}_0,\ \mu. \tag{2}$$

The results of the physical simulation are described with sufficient accuracy by the following generalized relation (Fig. 2):

$$\Delta_{lim} = f_6(\mu)\left[\Delta^{f_1(\mu)} C^{f_2(\mu)} \mathrm{Fr}^{f_3(\mu)} \mathrm{Re}_0^{f_4(\mu)}\right]^{f_5(\mu)}, \tag{3}$$

where $\Delta_{lim} = \delta_{lim}\rho_2/L\rho_1$ is the defined criterion; $f_1(\mu), \ldots, f_6(\mu)$ are functions of the dust concentration, which can be approximated by the following expressions:

$$\begin{gathered} f_1(\mu) = 1.5 + 0.45 \lg \mu; \\ f_2(\mu) = -1.3 + 3.78\mu - 3.92\mu^2; \\ f_3(\mu) = 0.6 - 0.7\mu; \\ f_4(\mu) = \frac{0.023}{\mu + 0.033} - 0.29; \\ f_5(\mu) = 0.167 + 0.32\mu; \\ f_6(\mu) = 0.69 + 10.8\mu - 9.5\mu^2. \end{gathered} \tag{4}$$

As a rule, any dust separator is designed under the assumption that μ is constant during its operation. Equation (3), with (4) taken into account, is then greatly simplified.

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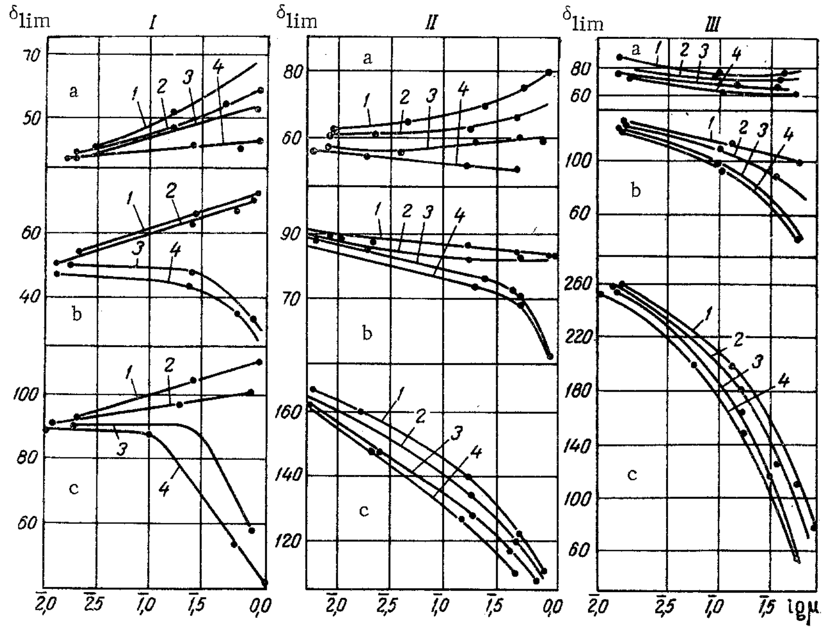

Fig. 1. Limiting dimension (μ) vs dust concentration [I) L = 0.25 m; II) 0.5 m; III) 1.0 m]: a) $\rho_2 = 7000\ kg/m^3$: 1) $\delta_0 = 154\ \mu$, v = 5.75 m/sec; 2) 154 μ, 11.5 m/sec; 3) 77 μ, 5.75 m/sec; 4) 77 μ, 11.5 m/sec. b) $\rho_2 = 3980\ kg/m^3$; 1) $\delta_0 = 136\ \mu$, v = 6.55 m/sec; 2) 136 μ, 13.1 m/sec; 3) 68 μ, 6.55 m/sec; 4) 68 μ, 13.1 m/sec. c) $\rho_2 = 1600\ kg/m^3$: 1) $\delta_0 = 168\ \mu$, v = 5.25 m/sec; 2) 168 μ, 10.5 m/sec; 3) 84 μ, 5.25 m/sec; 4) 84 μ, 10.5 m/sec.

By extrapolating the plots of $\delta_{lim} = f(\mu)$ to values $\mu = 0$ (case of infinitesimally small dust concentration, corresponding to the mathematical simulation conditions), we obtained the following experimental values of the limiting dimension $\delta^e_{lim\,0}$ and $\Delta^e_{lim\,0} = \delta^e_{lim\,0}\rho_2/L\rho_1$; the generalized relation (3) then takes the form

$$\Delta^e_{lim\,0} = 0.695C^{-0.3}Fr^{0.1}Re_0^{0.067}. \tag{5}$$

The profile of the tangential velocities v_φ of pure air along the radius r of a plane separation zone is well approximated by the well-known vortex equation $v_\varphi r^n$ = const at n = 0.7. The value of the swirl on entering the zone (at a radius $r_0 = L/2$) is characterized by the quantity $\tan\alpha_0 = v_{r0}/v_{\varphi 0} = 0.9$; the structural dimensionless radius of the central outlet tube (exhaust)

$$\rho_{out} = r_{out}/r_0 = 0.34.$$

To find the rated value of the limiting dimension $\delta^r_{lim\,0}$ for each combination of the experimental quantities ρ_2, v, and L, several values of the particle diameter δ were assumed and the characteristic parameters in the differential equations of motion of the particle were calculated [1]. By solving the latter with a computer at the experimental values of n, $\tan\alpha_0$, and the initial conditions in [2], we obtained the minimum particle-trajectory radius ρ_{min}, and then, for each combination of ρ_2, v, and L we obtained the values of $\Delta^r_{lim\,0}$ and $\Delta^r_{lim\,0} = \delta^r_{lim\,0}\rho_2/L\rho_1$ for each combination of ρ_2, v, and L from the $\rho_{min} = f(\delta)$ curves at $\rho_{min} = \rho_{out}$.

A comparison of the experimental (for $\mu = 0$) and calculated values of the limiting dimension has shown the following:

1) the value of $\Delta^r_{lim\,0}$ depends to a larger degree on the velocity than $\Delta^e_{lim\,0}$. This is due to the influence of the numbers Fr and Re_0 on the separation process; this influence was not taken into account in the calculation.

2) $\Delta^e_{lim0} > \Delta^r_{lim\,0}$. This is apparently the consequence of a certain disagreement between the "aerodynamic" and structural values of the outlet radius and the disagreement between the initial particle velocities assumed in the calculations and the actual ones.

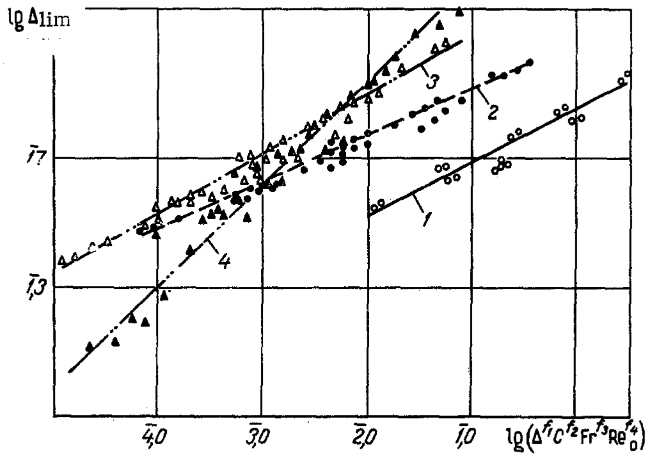

Fig. 2. Generalized plots of $\Delta_{\lim} = f(\Delta^{f_1}C^{f_2}Fr^{f_3}Re_0^{f_4})$ for different values of the dust concentration: 1) $\mu = 0$; 2) 0.0316; 3) 0.1; 4) 0.5.

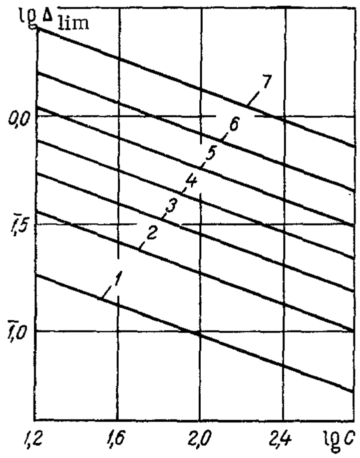

Fig. 3. Dependence of the calculated limiting dimension on the criterion C and on the swirl of the flow: 1) $\tan\alpha_0 = 0.3$; 2) 0.5; 3) 0.7; 4) 0.9; 5) 1.1; 6) 1.3; 7) 1.4.

The average value of $\Delta^{e}_{\lim 0}/\Delta^{r}_{\lim 0} = 1.314$ does indeed take these deviations into account. Since the average value of the indicated difference, amounting to 31.4%, can be easily corrected in the calculations, the scatter of the values of $\Delta^{e}_{\lim 0}/\Delta^{r}_{\lim 0}$ about the value 1.314, which now assumed to be 100%, is an expression of the influence exerted on $\Delta_{\lim}$ by the Fr and Re_0 numbers, which were not taken into account in the calculations, and its average value is 7%. This is a very high degree of agreement between the results of physical and mathematical simulation, in spite of the fact that, on the one hand, assumptions have been made when setting up the mathematical model, and on the other hand, there are errors in the experimental data, in the analysis of the separation products, and in the reduction of the experimental data. The indicated good agreement has served as a basis for developing a method for calculating the limiting dimension.

The calculated value of the limiting dimension is determined only by the criterion C, and at $\tan\alpha_0 = 0.9$ it is approximated by the formula:

$$\Delta^{r}_{\lim 0} = 2.1C^{-0.36}. \tag{6}$$

As a result of the reduction of the results of additional calculations for other values of $\tan\alpha_0$ (Fig. 3), we obtained the more general expression

$$\Delta^{r}_{\lim 0} = 0.265\exp(2.3\operatorname{tg}\alpha_0)\,C^{-0.36}. \tag{7}$$

Taking (5) into account, the formula for the limiting dimension at $\rho = 0$ takes the form

$$\Delta_{\lim 0} = 0.088\exp(2.3\operatorname{tg}\alpha_0)\,C^{-0.3}Fr^{0.1}Re_0^{0.067}, \tag{8}$$

and the general expression, with allowance for (3), is

$$\Delta_{\lim} = 0{,}088\exp(2.3\operatorname{tg}\alpha_0)\frac{f_6}{0.695}\Delta^{f_1f_5}C^{f_2f_5+0{,}3}Fr^{f_3f_5-0{,}1}Re_0^{f_4f_5-0{,}067}. \tag{9}$$

NOTATION

$St = \delta_0^2\rho_2 v/\eta L$ is the Stokes number;
$Fr = v^2/Lg$ is the Froude number;
$Re_0 = vL\rho_1/\eta$ is the Reynolds number for the flow;
$R = v\delta_0\rho_1/\eta$;
$\Delta = \delta_0\rho_2/L\rho_1$;
$C = vL\rho_1^2/\eta\rho_2$ is the similarity criterion;

μ	is the dust concentration, kg of dust/kg of air;
η and ρ_1	are the viscosity and density of the flow;
ρ_2	is the dust density;
δ_0	is the characteristic dimension of polydispersed dust;
v and L	are the characteristic velocity and dimension of the flow;
δ_{lim}	is the limiting dimension;
$v_{\varphi 0}$ and v_{r0}	are the tangential and radial projections of the characteristic velocity.

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