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CHARACTER OF DUST PARTICLE MOTION IN DIRECT-FLOW CYCLONE WITH INTERMEDIATE DUST EXTRACTION

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The problem of dust particle motion in direct-flow cyclone with intermediate extraction under the influence of centrifugal and aerodynamic force of gas flow resistance has been solved. Dust particle motion paths of different diameters at different points of cyclone input as well as calculation formulas of minimal particle diameter captured by intermediate and basic dust extraction are obtained. Theoretical efficiency of intermediate extraction separation and cyclone in general that are compared with experimental values is calculated. Evaluation of fractional efficiency parameters according to НИИОГАЗ technique is performed.

Swirling two-phase flows found a wide application in technical devices for intensification of mass exchanged and separation processes (dispersed materials drying, air dust-removal, energy separation in Ranque tubes etc.). For design of new ones and effective application of known stirring devices it is necessary to improve methods of calculation of two-phase swirling flows. At present there is no unique idea about proper approach to the calculation of particles motion [1]. The model, based on the concept of «trajectory particles», is considered to be false due to the absence of accounting of Reynolds stress influence on a particle. On the other hand, the advantages of Lagrange approach, being closer to real processes and allowing us to obtain necessary information about particles paths, time of particles being in the device, minimal size of trapped particles are incontestable [2–5].

Let us consider unidimensional motion of a dust particle with a mass at a rate of V in steady gas flow, moving at a rate of W, described by differential equation:

$$\frac{dV}{dt} = \frac{F_a}{m} = \frac{6F_a}{\pi\rho_\delta\delta^3}, \qquad (1)$$

where F_a is the force of aerodynamic resistance, influencing the particle on the side of gas flow, δ, ρ_δ is the equivalent diameter and dust particle density.

As a rule, Reynolds number, calculated by the diameter of a particle and parameters of gaseous medium (ρ_g, μ_g are density and dynamic viscosity of a gas) is not too large: $\mathrm{Re}_\delta = \frac{\delta W \rho_g}{\mu_g} << 100$, therefore, Stokes law may be used for writing down F_a adjusted for particle nonsphericalness:

$$F_a = 3\pi\mu_g\delta\, k_\delta (W - V), \qquad (2)$$

where k_δ is the coefficient of the form, including particle nonsphericalness, equals to $k_\delta = 1/\Phi^2$; $\Phi = \frac{F_c}{F}$ is the factor of the form, equal to the ratio of sphere surface area, having the same volume that the particle under consideration to the area of F surface [6]. It should be noted that at numbers $\mathrm{Re}_\delta \geq 100$ formula (2) gives conservative value of the force of aerodynamic resistance, however at the approximate analysis it is not of decisive importance, as vast particles are separated faster than small ones.

After substitution of (2) into (1) the differential equation in the following form is obtained:

$$\frac{dV}{dt} = \frac{18 k_\delta \mu_g}{\rho_\delta \delta^2}(W - V). \qquad (3)$$

Let us proceed to the dimensionless coordinates, introducing the notations:

$$\bar{V} = \frac{V}{W}; \quad \bar{t} = \frac{t}{T}. \qquad (4)$$

Let us understand by specific time interval T the ratio of specific size L_0 (distance form exit edges of vane twister to dust intermediate bleed holes) to the rate of gas flow: $T = \frac{L_0}{W}$. After substitution of (4) into (3) we obtain:

$$\frac{d\bar{V}}{d\bar{t}} = \beta(1 - \bar{V}), \qquad (5)$$

where the dimensionless group

$$\beta = \frac{18 k_\delta \mu_g L_0}{\rho_\delta \delta^2 W} = 18 k_\delta \frac{L_0}{\delta} \frac{\rho_g}{\rho_\delta} \frac{1}{\mathrm{Re}_\delta}. \qquad (6)$$

After integration we obtain:

$$1 - \bar{V} = (1 - \bar{V}_0) e^{-\beta \bar{t}}, \qquad (7)$$

where $\bar{V}_0$ is the dimensionless initial particle rate.

Let us estimate the dimensionless group β for analyzing (7). The following data are taken as an example: dust – KCl has cubic lattice, therefore it forms the particles of the form close to cubic one [7]. The factor of the form is equal F=0,806 for a cube [6]. Then the form coefficient k_δ=1,54. W=9 m/s, δ=10 mkm=10^{-5} m, μ=1,89·10^{-5} Pa·s, ρ_g=1,25 kg/m^3, ρ_δ=2631 kg/m^3 (according to the readings at autopycnometer 1320), L_0=0,276 m. We obtain Re_δ=0,592, β=61,070. Such high value of β means that dimensionless particle rate converges very rapidly to the unity, i.e. independently on initial conditions the rate of a particle V becomes close to the flow rate W. Really, if $\bar{t}$=0,1 is taken, then

$$1-\bar{V}=0{,}0022(1-\bar{V_0})<0{,}01.$$

The presented example shows that the peripheral and axial projections of small particles rate in a dust catcher may be taken as equal to the corresponding projections of gas rate. And only range rate of particles, stipulated by centrifugal forces, should be determined. At increasing the diameter of the particles magnitude β decreases in proportion to square of diameter.

The analysis of twisted adiabatic gas-dust flow in the direct-flow cyclone will be carried out under the following assumptions:

1. The overspeed part of a particle in a twister is completed and it obtains the axial V_z and peripheral V_φ projections of rate, equal to the corresponding projections of gas flow rate W_z and W_φ respectively. The given assumption results in certain calculating errors of motion of the particles with the diameter more than 5 mkm.
2. The axial projection of gas rate changes according to the law W_φ=const$\sqrt{r}$. This law, observed in the experiments [8, 9], allow us to obtain a simple decision, suitable for quantitative analysis of particles motion.
3. Particle does not change its form and diameter with time; it is neither disintegrated nor coagulated. Deviation of particle form of sphere is included by the coefficient k_δ.
4. Particle gas flow is of viscous nature. Gas turbulent pulses are ignored, that coordinates with the conclusion of the paper [4]: turbulent diffusion of particles in direct-flow cyclone influence insignifficantly the dust catching process.
5. Magnus force, buoyancy force, Coriolis force, gravity force, added mass force are ignored as the stated forces are less, by several digits, in comparison with force of aerodynamic resistance and centrifugal force [9–13].
6. Electrostatic, thermophoretic and other forces of non-hydrodynamic nature are neglected.
7. Nonuniform distribution of axial projection of gas rate round radius is neglected that is in compliance with the data of the paper [14], according to which axial projection of particles rate slightly changes round tube radius.

Such a problem is solved in paper [15] in respect to a cyclone with counter swirling flows.

At taken assumptions the differential equation of particles motion in cylindrical coordinates takes on a form:

$$\frac{dV_r}{dt}=\frac{V_\varphi^2}{r}-\frac{18k_\delta\mu_g V_r}{\rho_\delta\delta^2}$$

or in dimensionless form:

$$\frac{d\bar{V}_r}{d\bar{t}}=\frac{\bar{V}_\varphi^2}{\bar{r}}-\beta\bar{V}_r, \tag{8}$$

where

$$V_z=W_z;\ \bar{V}_z=\frac{V_z}{W_z}=1;\ \bar{t}=\frac{t}{T};\ T=\frac{L_0}{W_z};$$

$$\bar{V}_r=\frac{V_r}{W_z};\ \bar{V}_\varphi=\frac{V_\varphi}{W_z};\ \bar{r}=\frac{r}{L_0};\ \beta=\frac{18k_\delta\mu_g L_0}{\rho_\delta\,\delta^2 V_z}. \tag{9}$$

In the concerned case the group β (9) may be considered as constant, as according to the assumptions W_z=const. Equation (8) has an analytical solution:

$$\bar{V}_r=e^{-\beta\bar{t}}\left(\bar{V}_{r0}+\int_0^{\bar{t}} e^{-\beta\bar{t}}\,\frac{\bar{V}_\varphi^2}{\bar{r}}\,d\bar{t}\right),$$

where $\bar{V}_{r0}$ is the radial projection of particle rate at the initial point of time $\bar{t}$=0.

The accepted law of variation of circular velocity provides the independence of the ratio $\frac{\bar{V}_\varphi^2}{\bar{r}}$ on time $\bar{t}$. Then integration gives the following dependence:

$$\bar{V}_r=e^{-\beta\bar{t}}\left[\bar{V}_{r0}+\frac{1}{\beta}\left(\frac{\bar{V}_\varphi^2}{\bar{r}}\right)_{cp}(e^{-\beta\bar{t}}-1)\right]. \tag{10}$$

Knowing the law of variation, the distance traversed by the particle in radial direction may be solved:

$$r-r_0=\int_o^t V_r dt, \tag{11}$$

where r_0 is the initial radius of particle entrance into cyclone separation chamber. Magnitude r_0 may be changed from radius r_1 of central internal insert to radius r_2 of separation chamber.

After substitution $\bar{r}_0=r_0/L_0$, formula for transition to the dimensionless variables (9), dependence (10) into (11) and after integration we get:

$$\bar{r}=\bar{r}_0+\frac{1}{\beta}\left[-\bar{V}_{r0}(e^{-\beta\bar{t}}-1)+\left(\frac{\bar{V}_\varphi^2}{\bar{r}}\right)_{cp}A(\beta,\bar{t})\right], \tag{12}$$

where $A(\beta,\bar{t})=\bar{t}+\frac{1}{\beta}(e^{-\beta\bar{t}}-1)$.

Let us consider the simplest case, when at the exit from the vane swirler the rate projections of the flow W_{r0} and particle V_{r0} are negligibly small and may be ignored, i.e. $\bar{W}_{r0}=\bar{V}_{r0}$=0. In this case the dependence of the following form should be used for calculation of particle path:

$$\bar{r}=\bar{r}_0+\frac{1}{\beta}\left(\frac{\bar{V}_\varphi^2}{\bar{r}}\right)_{cp}A(\beta,\bar{t}). \tag{13}$$

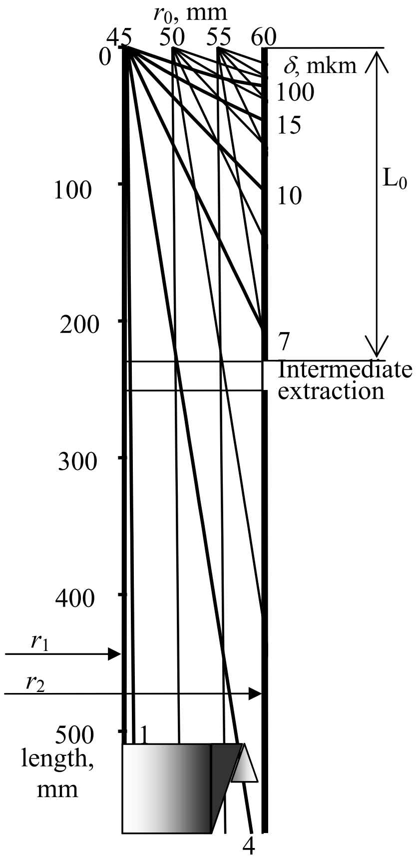

Fig. 1. *Path of motion of the particles with diameter δ with entrance radius r_0*

In fig. 1 the particles paths of different diameter at different entrance radii $\overline{r}_0$ of particles into separation chamber (with sizes r_1=0,045 m and r_2=0,060 m), calculated for a swirler with flow outlet angle at mean radius $\overline{r}_{cp} = \frac{r_1 + r_2}{2L_0} = 0{,}1902$ to the plane, perpendicular to the axis of the device, equal 35° are represented. It is not difficult to determined from the triangle of velocities:

$$\overline{V}_\varphi = \frac{V_\varphi}{V_z} = \mathrm{ctg}35° = 1{,}428; \quad \frac{\overline{V}_\varphi^2}{\overline{r}_{cp}} = 10{,}721.$$

The values of the rest of the parameters are presented above.

Supposing that the particle slides on the wall of the cyclone, when having reached it, and it is bled through the intermediate bleed holes and annular slot of the second extraction into isolated bins, let us plot the dependences of minimal diameter $\delta_{\min}$ of the particles, caught by the intermediate bleed holes (curve 1, fig. 2), and cyclone in whole (curve 2, fig. 2) for various radii $\overline{r}_0$ of particle entrance into cyclone. In theory, all particles, having size more than $\delta_{\min}$, should precipitate in the cyclone, and those which size is $\delta<\delta_{\min}$ should be removed from the cyclone.

The main assumption that particle should reach the wall of a dust catcher, while gas flow being in it, for being collected is also taken as a principle of numerous methods of calculation of particles minimal critical diameter for cyclones of different types [9, 16, 17 et al.]. In this case the distribution of dust-laden flow by the area of input cross-section is not taken into consideration, as the particle is supposed to enter into separation space along the device axis or at its mean radius. The formula for defining $\delta_{\min}$ obtained in this way are not accurate, as particles with the diameter less than $\delta_{\min}$ may be caught in dust catchers if they were close to the wall when entering the cyclone. The dependences $\delta_{\min}=f(\overline{r}_0)$ presented in fig. 2 have no such disadvantage. However, as the dispersed analysis of the dust, set at a cloth filter, showed the overshoot of rather large particles at the exit from the cyclone is observed. Moreover, dust dispersed composition, collected in the intermediate extraction, indicates the presence of particles with the size $\delta<\delta_{\min}$ in it. Therefore, dependences $\delta_{\min}=f(\overline{r}_0)$ may serve for approximate estimate of efficiency of cyclone separation.

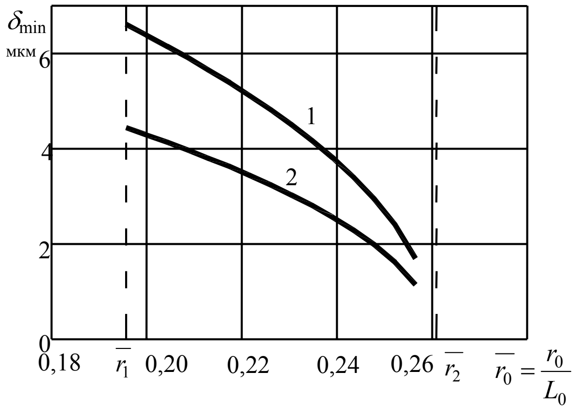

Fig. 2. *Minimal diameter of collected dust with: 1) intermediate, 2) main extractions depending on entrance radius $\overline{r}_0$*

The theoretical efficiency of dust catching η_T according to the known paths of motion of dust particles and dependences $\delta_{\min}=f(\overline{r}_0)$ may be calculated in the following way. Let us suppose dust uniform distribution by the cyclone input cross-section. According to the dispersion composition of dust coming to the cyclone entrance, we plot the integral function $D(\delta)$ of particles distribution by mass on double logarithmic scale. Function $D(\delta)$ may be presented in the form of Rosin-Ramler-Bennett formula [18]:

$$D(\delta) = 1 - e^{(\delta/\delta_e)a}, \tag{14}$$

where δ_e presents, by its physical meaning, such diameter, at which mass of particles larger than δ_e is 36,8 %, and of those which are less is 63,2 %. For the dust under consideration δ_e=23 mkm. Finding the logarithm of the formula (14) twice, we get:

$$\lg\left(\lg\frac{1}{1-D(\delta)}\right) = \lg\lg e + a(\lg\delta - \lg\delta_e).$$

Then $a = \dfrac{\lg\lg\left(\dfrac{1}{1-D(\delta)}\right) - \lg(\lg e)}{\lg\delta - \lg\delta_e} = 2{,}6224.$

Therefore: $D(\delta) = 1 - e^{-(\delta/23)^{2,62}}$.

The calculated dependences $\delta^1_{\min}(\bar{r}_0)$ and $\delta^2_{\min}(\bar{r}_0)$ in the package Statgraphics Plus are approximated by cubic polynomial:

$$\delta^1_{\min}(\bar{r}_0) = 140 - 2178\bar{r}_0 + 12135\bar{r}_0^2 - 23250\bar{r}_0^3, \quad (15)$$

$$\delta^2_{\min}(\bar{r}_0) = 109 - 1702\bar{r}_0 + 9388\bar{r}_0^2 - 17741\bar{r}_0^3. \quad (16)$$

Table 1. *Statistical significance of regressions. Corrected rate of determination is 99,96 %*

Equation	Durbin-Watson criterion	Standard error, mm	Average absolute error, mm
(15)	1,173	0,0307	0,0223
(16)	1,219	0,0193	0,0143

Catching efficiency by the intermediate extraction η^1_T and cyclone in whole η^2_T are determined according to the formulas:

$$\eta^1_T = \frac{100p}{\pi(\bar{r}_2^2 - \bar{r}_1^2)} \int_{\bar{r}_1}^{\bar{r}_2} 2\pi\bar{r}_0[1 - D(\delta^1_{\min}(\bar{r}_0))]\, d\bar{r}_0 =$$

$$\frac{200p}{(\bar{r}_2^2 - \bar{r}_1^2)} \int_{\bar{r}_1}^{\bar{r}_2} \bar{r}_0 e^{-(\delta^1_{\min}(\bar{r}_0)/23)^{2,62}}\, d\bar{r}_0, \%,$$

$$\eta^2_T = \frac{200}{(\bar{r}_2^2 - \bar{r}_1^2)} \int_{\bar{r}_1}^{\bar{r}_2} \bar{r}_0 e^{-(\delta^2_{\min}(\bar{r}_0)/23)^{2,62}}\, d\bar{r}_0, \%$$

where $\delta^1_{\min}(\bar{r}_0)$ and $\delta^2_{\min}(\bar{r}_0)$ are calculated by the formulas (15) and (16) correspondingly, p=0,66 is the expectancy of dust hitting into intermediate extraction, equal to the ratio of holes sum area to the area of lateral surface of a cylinder with the height equal to holes height.

For numerical integration Newton – Cotes sextic quadrature formula, Waddle rule were used [19]. The following values of efficiency of separation were obtained: η^1_T=65,35 % and η^2_T=99,01 %, which were overrated in comparison with the experimental ones.

The accepted flow model is not accurate enough, i. e. it does not allow searching for the separation efficiency of the cycloneas a whole not including such factors as secondary turbulent separated dust loss, ricochet and Magnus effect. The acceptable coincidence η^1_T with the experimental data ($\eta^1_э$=60...62 %) is explained, first of all, by the introduction of dust particles expectancy of hitting into intermediate bleed holes. At dust suction from the second bin together with a part of gas in amount of 5 % from the consumption of $\eta^2_э$ increases from 97,0 to 99,4 %, that differs form η^2_T insignificantly. The observed rise of the efficiency of cyclone separation at the suction of a part of gas is explained by intensity decrease of carrying flow turbulence.

The experiment with the cyclone, scheme of which is presented in fig. 3 was carried out. Muriate salt with density ρ_δ=2631 kg/m^3 (apparent 1950 kg/m^3) and form coefficient k_δ=1,54 is used as the dust. The parameters of gas flow: velocity W=9 m/s, viscosity m=1,89·10^{-5} Pa·s, density ρ_g=1,25 kg/m^3, D=0,12 m. As in NIIOGAS technique the data on fractional efficiency of direct-flow cyclones are absent, then let us estimate them for investigated cyclone according to the method of V.P. Samsonov [18], table 2.

Table 2. *Estimation of the parameters of fractional efficiency*

Index	Experimental values		Calculated values	
№ of the experiment	1	2	1	2
δ, mkm	20,0	11,0		
σ	1,38	1,50		
δ_e, mkm		23,0	14	
a			2,62	1.52
η, %	89	79	99,01	87.55
x	1,227	0,807	2.34	1.152
d_{50m}	3,02		2,34	
lg$\sigma_{m\eta}$	0,308		0,02	

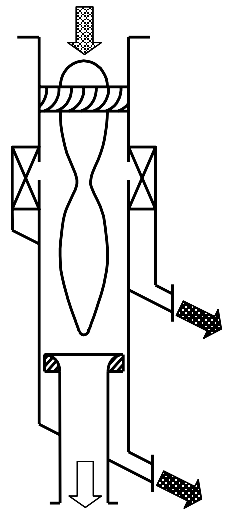

Fig. 3. *Scheme of a direct-flow cyclone with the intermediate dust extraction [21]*

At Novomaltinsk factory of constructional materials (Usolsk region of Irkutsk area) in mineral wool industry top smokes, wasted from the cupola furnaces, were purified in a bag hose, installed on the esplanade. Filter had low purification efficiency and service reliability owing to the hoses freezing and breaks at their regeneration in a cold period of the year. The direct-flow cyclone 0,258 mm with intermediate dust extraction was suggested to be used instead of the filter (fig. 3). Gas temperature at the entrance to the cyclone was 90...97 °C, and at the exit it was 70 °C. Median diameter (by mass) of initial dust of cupola gases at the entrance to the cyclone was 85 mkm, median diameter (by mass) of lost dust was 2 mkm. The diameter of the particles, caught with the efficiency of 50 % equaled to d_{50}=14 mkm. The apparent density of dust was 1008 kg/m^3. Optimal average consumed rate, providing the highest efficiency of dust catching η=86...87 %, was W=5...6 m/s. Gas suction from the bin in the amount of 4...5 % of overall consumption allowed increasing the efficiency of purification on 8...9 % [22].

According to the obtained parameters of fractional efficiency (table 2) the efficiency of tested direct-flow cyclone at purification of cupola gases according to the NIIOGAS technique is estimated (table 3).

Table 3. *Calculation according to НИИОГАЗ technique [20]*

Parameters	According to the experimental data	According to the model
$D=D/D_m$	0,258/0,12=2,15	
$\bar{\rho}=\rho_{\delta n}/\rho_\delta$	1950/1008=1,935	
$\bar{\mu}=\mu/\mu_n$	$1{,}794\cdot10^{-5}/1{,}89\cdot10^{-5}=0{,}949$	
$W=W_m/W$	9/5=1,8	
$d_{50}=d_{50m}\sqrt{\bar{D}\cdot\bar{\rho}\cdot\bar{\mu}\cdot\bar{W}}$	$3{,}02\sqrt{2{,}15\cdot1{,}935\cdot0{,}949\cdot1{,}8}=8{,}0507$	$2{,}34\sqrt{2{,}15.1{,}935.0{,}949.1{,}8}=6{,}2380$
$x=\lg(d_{50}/d_{50m})\sqrt{\lg\sigma^2_{m\eta}+\sigma^2_\eta}$	$\lg(85/8{,}05)\sqrt{0{,}308^2+2{,}17^2}=2{,}2435$	$\lg(85/6{,}23)\times\sqrt{0{,}02^2+2{,}17^2}=2{,}463$
$\Phi_p(x)$, %	98,73	99,31
$\Phi_{эксп}(x)$, %	87	
Error, %	(98,73–87)/0,87=13,48	(99,31–87)/0,87=13,9

The analysis of the results obtained by the NIIOGAS technique shows that proximity of estimates of efficiency according to the experimental and model data indicates the adequacy of model approximation. On the other hand, both estimates have acceptable but rather high error (more than 13 %, at the suction of a part of gas from the bins area the error decreases to 5,0...5,5 %). This shows the urgency of the following tasks of investigation:

- to decrease the volume of analyzed data for providing statistical significance of the estimates of fractional efficiency of direct-flow cyclones;
- to analyze theoretical sufficiency of NIIOGAS technique in respect to direct-flow dust catchers and to develop the new one, more adequate calculation technique of direct-flow cyclones efficiency.

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