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CALCULATION OF PARAMETERS OF DUST EXTRACTOR OPERATION

The paper deals with the operation parameters of gravity, inertial, porous, wet (rapid) and electric dust extractors such as degree of efficiency and aerodynamic resistance. Theoretical bases of calculation of the parameters are considered.

Keywords: cleaning efficiency, aerodynamic resistance, dust precipitation chamber, cyclone, filter, wet dust extractor, electric filter.

Introduction

Dust air pollution amount is doubled every ten years. The main sources of dust pollution are metallurgy, building material production, local (dust storms) and global (volcanic eruptions) natural phenomena.

Modern dust cleaning devices rarely use only one method of separation (gravitation, inertia, meshing, particle size effect, electric and magnetic field). As a rule, they are designed as diversified devices, for instance, high-speed scrubbers or rotoclones. Consequently, derivation of estimated dependences of dust extractor operation parameters will be useful in evaluation and identification of main forces of separation in complex system of gas dust-cleaning.

It has been shown experimentally that the velocity of aerosol concentration change due to particle precipitation is proportional to the concentration *C* at a given moment of time:

$$-\frac{dC}{d\tau} = kC, \qquad (1)$$

where *k* is the experimental constant, sec^{-1}.

For the case under consideration, i. e. for sedimentation in gravitational field, experimental constant k can be determined as the reciprocal of particle precipitation [1]:

$$k = \frac{1}{h_{oc}/W_{oc}} = \frac{W_{oc}}{h_{oc}}, \tag{2}$$

where h_{oc} is the length of particle precipitation path, m; W_{oc} is the velocity of particle precipitation, m/sec.

Then Eq. (1) has the form

$$-\frac{dC}{d\tau} = C\frac{W_{oc}}{h_{oc}}. \tag{3}$$

Upon integrating (3) from the initial concentration C_0 to C with respect to the time from 0 to τ we obtain

$$C = C_0 e^{-\frac{W_{oc}\tau}{h_{oc}}}. \tag{4}$$

Cleaning efficiency in dust precipitation chamber is greatly influenced by particle residence time in the chamber. The particles in the top part of the chamber are in the most unfavourable conditions; their residence time in the device exceeds precipitation time.

Let us express particle residence time in the chamber in terms of chamber length l, m, and horizontal component of flow velocity W_r:

$$\tau = \frac{l}{W_r}. \tag{5}$$

In view of physical meaning of purification coefficient $\eta = (C_0 — C)/ C_0$, (4), (5), and of the fact that length of particle precipitation path h_{oc} is considered to be equal to the chamber height h, air cleaning efficiency in dust precipitation chamber can be determined by the formula

$$\eta = 1 - e^{\frac{-W_{oc} l}{W_r h}}. \tag{6}$$

Upon solving inverse problem with the use of Stokes formula [1] for precipitation velocity determination $W_{oc} = d^2 \rho g/(18\mu)$, dependence (4) and expressing the velocity in terms of air consumption L, m^3/sec, the diameter of particles of size equal or more than d, m, which will precipitate in the chamber at a given purification coefficient:

$$d = \sqrt{\frac{-\ln(1-\eta)18\mu L}{\rho g l B}}. \tag{7}$$

where B is the width of the chamber, m; ρ is the density of the particle, kg/m^3; μ *is the dynamic viscosity* of the air, kg/(m sec).

Cleaning efficiency depends on uniformity of air flow distribution over the dust extractor cross section, normal to the current line. Degree of uniformity of air flow can be estimated using the momentum coefficient [1]:

$$K_к = \frac{1}{F} \iint_{(F)} \left(\frac{W}{W_{cp}} \right)^2 df\,, \tag{8}$$

where W, W_{cp} are the air velocity in the point in hand and average air velocity over chamber cross-section, m/sec.

The closer coefficient $K_к$ to 1, the more uniform the flow. At $K_к$ = 3 cleaning efficiency can decrease at 25 %.

Aerodynamic resistance of gravity dust extractors can be determined as difference of inlet/outlet air pressure losses:

$$\Delta p = p_{ВЫХ} - p_{ВХ} = \zeta_{вх} W_{вх}^2 \frac{\rho}{2} + \zeta_{вых} W_{вых}^2 \frac{\rho}{2}\,, \tag{9}$$

where $p_{вх}$, $p_{вых}$ are inlet/outlet air pressure losses, Pa; $W_{вх}$, $W_{вых}$ air velocity at inlet and outlet nozzles, m/sec; $\varsigma_{вх}$, $\varsigma_{вых}$ are the coefficients of the local resistances of chamber diffuser and confusor.

Inertial separation can occur both in rectilinear and in curvilinear flows. In either case, however, inertial dust precipitation is due to current line curvature during flow over barriers. Under inertia particle paths are curved to a lesser degree than current lines. As a result, certain particles collide with the barrier or contact it and under certain conditions and gravity force drop out of air flow. Different planes, cylindrical surfaces, spherical bodies (grains, drops of liquid) can be barriers. The probability of dust particle precipitation depends on its mass, flow velocity, movement type, and sizes of the barrier. Efficiency of inertial precipitation η_{st} can be expressed by the ratio of cross section area of incident flow from which all the particles are trapped to the projection area of the barrier toward the flow:

– for cylindrical surfaces

$$\eta_{st} = \frac{R_y}{R}\,, \tag{10}$$

– for spherical surfaces

$$\eta_{st} = \left(\frac{R_y}{R} \right)^2, \tag{11}$$

where R_y is the distance from the flow axe to the paths of those particles whose centers contact the cylinder on movement; R is the barrier radius.

Distance R_y can be determined by solving the equation of particle movement [1], however, its analytical solution is impossible for this case. Because of this, efficiency of inertial precipitation is estimated by the Stokes criterion:

$$St = \frac{d_ч^2 W \rho}{18 \mu l}, \tag{12}$$

where *W is the* undisturbed *flow velocity*, m/sec; *l* is the typical size of the barrier (for the cylinder *l* = *R*), m.

The Stokes criterion describes the ratio of inertial forces to the force of medium resistance. Inertial separation is estimated by the critical value of the Stokes number $St_{кр}$, at which particles overcome the force of air flow drag and can settle on the barrier. Values of $St_{кр}$ determine minimal size of the particle d_{min} which can settle on the barrier:

$$d_{\min} = \sqrt{\frac{18 \mu l St_{кр}}{W \rho}}. \qquad 13)$$

The meshing effect plays an important role on inertial precipitation, especially in wet dust extractors and porous layers. Inertial dust separation in curved flows increases time of inertial forces action on the particle and makes it possible to gain small particles separation to the external boundaries of the flow.

Cyclone dust extractors (cyclones) are actively engaged in the case. To determine the air flow velocity affecting the particle in cyclone process W_u, the factor of separation Φ_p or Froude centrifugal criterion is introduced. The latter is the ratio of centrifugal force $P_ц$ to the gravity force P_m:

$$\Phi_p = \frac{P_ц}{P_m} = \frac{M W_ц^2}{rMg} = \frac{W_ц^2}{rg}. \tag{14}$$

Linear velocity $W_ц$ can be replaced by the angular velocity $\omega = W_ц/r$, (*r* is the cyclone radius), thus, the separation factor is equal to

$$\Phi_p = \frac{\omega^2 r}{g}. \tag{15}$$

At known velocity of the particle precipitation under gravity forces ω_{oc} centrifugal velocity is determined by the formula

$$W_ц = \Phi_p \omega_{oc}. \tag{16}$$

The methods for calculating the air cleaning efficiency in cyclones are numerous and varied. The most plausible methods are those based on experimental data on fractional degree of cleaning [2].

The total aerodynamic resistance of cyclones is combined from inlet pressure losses, kinetic energy losses at rotary air motion in downflows and upflows, losses by cyclone wall friction and outlet pressure losses. The theoretical calculations of cyclone resistance are very complicated, which is why in practice cyclone resistance is estimated by the coefficients of local resistance (9) which depend on cyclone diameter and Reynolds criterion.

When passing through the porous filters, dust is held back in them due to particle size effect, inertial, contact, diffusion, gravitational and electric forces.

Particle size effect is very rare phenomenon which is observed only if the size of precipitated particles is more than pore size. Consequently, total coefficient of purification of particular filter layer can be expressed by expression [2]:

$$\eta_{сум} = 1 - \left(1-\eta_r\right)\left(1-\eta_{st}\right)\left(1-\eta_D\right)\left(1-\eta_E\right)\left(1-\eta_g\right), \tag{17}$$

where η_r = (1-r)(1+r) is the coefficient of efficiency of particle precipitation through the contact; $\eta_{st} = St^3/(St^3 + 1.54St^2 + 1.76)$ is the coefficient of particle precipitation efficiency through inertia; $\eta_D = 2.16/[2(2 - ln\ (Re))^{0.33}Pe^{0.66}]$ is the coefficient of particle precipitation efficiency through diffusion; $\eta_E = E_o^{\ 2}r^2/(6W_г\mu r_o)$ is the coefficient of particle precipitation efficiency through electrostatic mechanism; $\eta_g = W_{oc}/W_г$ is the coefficient of particle precipitation efficiency through gravity forces; $r^* = r/r_o$ is the ratio between size of the particle r and size of filter solid element r_o; $Pe = W_г\,(2r_o)/D$ is the Peclet criterion; D is the diffusion coefficient; $Re = W\,(2r)/\nu$ is the Reynolds criterion (ν is the coefficient of air kinematic viscosity); E_o is the maximum strength of electric field near the surface of filter solid element.

Mathematically filtration model can be described by the differential equation which expresses dust balance in its passing through the unit of area of porous partition dh in thick:

$$-Wdh = \eta_{сум} F_н W_ф^n \frac{\left(1-\varepsilon\right)dh}{\varepsilon V_{эл}}, \tag{18}$$

where W, $W_ф$ is the velocity of air flow and filtration; n is the number of dust particles; $F_н$ is the filter area normal to air flow direction; ε is the porosity of filter material layer; $V_{эл}$ is the filter element volume.

The physical meaning of equation (18) is that decrease of dust particles in air flow passing through filter layer is equal to the number of particles trapped by all filter elements of the layer. Upon dividing variables in (18) and integrating in the range from n_o (initial concentration) to n and from 0 to h, we obtain

$$\frac{n}{n_o} = e^{-\psi\,\eta_{сум}}, \tag{19}$$

where $\psi = (1 — \varepsilon)\, F_и h/\varepsilon$ is the index of filter layer structure which expresses the ratio between solid fraction of the filter and pore volume; h is the thickness of filter element.

By analogy with mass concentration the ratio n/n_o can be named as breakthrough coefficient $k_{пр}$, in which case the coefficient of air purification from dust in filter element, in view of (19), is expressed as

$$\eta = 1 - k_{пр} = 1 - e^{-\psi\, \eta_{сум}} . \qquad (20)$$

Porous filters are usually multilayer. If breakthrough coefficients for each layer are considered to be equal, i. e. $k_{пр1} = k_{пр2} = k_{пр3} = k_{пр}$, overall coefficient of purification $\eta_{общ}$ is determined by expression

$$\eta_{общ} = 1 - k_{пр}^{z} = 1 - \left(1 - \eta\right)^{z} , \qquad (21)$$

where z is the number of filter layer.

In porous filters air flow is laminar. Consequently, aerodynamic resistance of porous layer can be determined by Poiseuille**'s** law [3]:

$$\Delta p = \frac{8\mu l_{сум} W}{r_{экв}^{2}} , \qquad (22)$$

where $l_{сум} = a^2 h$ is the total pathway taken by the air in pores (a is the coefficient considering pore tortuosity); $W = W_{ср}/\varepsilon$ *is the* actual air velocity in pores; $r_{экв} = \delta r_{ср}$ is the pore equivalent radius (δ is the filter layer structure dependent coefficient; for the medium of spherical particles $\delta = 2\varepsilon/[3(1 — \varepsilon)]$); $r_{ср}$ is the average pore radius).

In view of adopted values dependence (22) has the form

$$\Delta p = \frac{k_o \mu W_ф h}{r_o^{2}} , \qquad (23)$$

where $k_o = 8a^2/(\varepsilon\delta)$ is the coefficient of pore resistance.

Expression (21) descibes monodisperse aerosol precipitation in homogeneous layers of the filter material. In practice, filtration is often attended with particle coagulation, change in precipitation efficiency and aerodynamic resistance.

Wet dust extractor design involves energy method of calculation.

The essence of the method is that efficiency of wet extractor operation is determined primarily by energy consumptions for air cleaning from dust, and in so doing energy for gas-liquid flow turbulization as well as energy for liquid supply and dispersion should be taken into account. In dynamic scrubbers consideration also must be given to the energy of structure elements rotation. Energy consumptions for wet cleaning of a certain air volume in a unit of time is expressed through the parameter $K_э$, kJ/1000 m^3:

$$K_э = \Delta p + m p_{ж},\tag{24}$$

where Δp is the device aerodynamic resistance, Pa; $m = L_ж/L$ is the specific discharge of liquid, m^3/m^3, ($L_ж$, L are volume consumptions of liquid and air, m^3/sec); $p_ж$ is the pressure of spray liquid, Pa.

The summands of the right side of Eq. (24) are not equivalent and depend on the device type. For instance, aerodynamic resistance is crucial in Venturi scrubber, whereas pressure of liquid dispersion is of great importance in ejection device. Value of $K_э$ considers the method of liquid supply. Dependence between purification coefficient η and energy consumption $K_э$ is expressed by the formula

$$\eta = 1 - e^{-BK_э^s},\tag{25}$$

where B, s are the dust disperse composition dependent constants [3].

Coefficient of gas purification from suspended particles in electric filter can be determined theoretically, with the usy of idealization of separation considering dust to be monodisperse, its concentration in each cross-section equal, gas velocity and drift velocity constant. In the case of tubular electric filter, dust mass dM, settled on precipitation electrode with radius R and length l in time $d\tau$, is equal

$$dM = 2\pi \mathrm{RlW_д Cd\tau},\tag{26}$$

where $W_д$ is the drift velocity, i. e., the velocity of charged particles normal to precipitation electrode, m/sec; C is the dust concentration in electric filter, kg/m^3.

In the volume of electric filter there is dust mass $M = \pi R^2 lC$, which lowers its concentration by dC and decreases by (27) in precipitation time $d\tau$

$$dM = \pi \mathrm{R^2 ldC}.\tag{27}$$

Upon equating right sides of (26) and (27), dividing variables and integrating in the range from C_o to C and from 0 to $\tau = l / W_г$ with consideration for gas velocities in the filter, we obtain

$$-\ln\left(\frac{\mathrm{C}}{\mathrm{C_o}}\right) = \frac{2\mathrm{W_д l}}{\mathrm{W_г R}},\tag{28}$$

hence, coefficient of gas purification is equal to

$$\eta = 1 - \frac{C}{C_o} = 1 - e^{\frac{-2W_д l}{W_г R}},\tag{29}$$

for plate electrodes we obtain (30), substituting *R* for *h*, *h* is the distance between precipitation and corona electrodes

$$\eta = 1 - e^{\frac{-2W_\partial t}{W_r h}} . \qquad (30)$$

Discordances between theoretically determined value of purification coefficient and its practical value are due to the complexity of drift velocity calculation. The drift velocity can be determined by equating the forces of medium resistance (Stokes formula $P = 3\pi\mu Wd$) and force of interaction of electric field and particle charge $P_к$, H, which is equal (Coulomb's law)

$$P_к = q_м E_{oc} = \mathrm{neE_{oc}} = \pi\varepsilon_o E_з E_{oc} d^2 \rho_э , \qquad (31)$$

where $q_м$ is the maximum value of the particle charge, coulomb; E_{oc}, $E_з$ is the electric field tension in precipitation and charge zones, V/m; *n* is the number *of* elementary charge acting on the particle; $e = 16 \cdot 10^{-19}$ coulomb is the value of electronic charge; $\varepsilon_o = 8{,}85 \cdot 10^{-12}$ А/м is the vacuum permittivity; $\rho_э$ is the index of dielectric properties of the particle (on the average, it can be taken as $\rho_э = 1$ for dielectric and $\rho_э = 3$ conducting particle).

The drift velocity

$$W_\partial = \frac{\varepsilon_o E_з E_{oc} d^2 \rho_э}{3\mu} . \qquad (32)$$

Assuming that $\rho_э = 2$, $E_{oc} = E_з = E$, drift velocity for large particle at $d = 2 \div 50$ mcm is equal to

$$W_\partial = \frac{0{,}06 \cdot 10^{-10} E^2 d}{\mu} . \qquad (33)$$

Summary

Air cleaning efficiency in electric filter as well as in dust precipitation chambers is greatly affected by the degree of gas flow uniformity over device cross-section (see Eq. 8).

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