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New Industrial Eco-Technologies Using the Effects of Hydro-vortex Dedusting

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Abstract: The genesis of industrial ecology, the analysis of the main stages in development of technology and eco-technology, allows to confirm that they are not effective enough in ensuring safety and sanitary-hygienic conditions. The introduction of promising innovative technologies, the growth of labor productivity is often limited by parameters of ensuring controllability of technogenic processes, in particular, localization of explosions of aerosol dust mixtures. A method of hydro-vortex dedusting is suggested based on the principle of circulating orthokinetic hetero-coagulation in the system "liquid-solid", graphical-analytical model of hydro-vortex inertial orthokinetic hetero-coagulation. Expressions for effective values of the Stokes and Reynolds criteria under conditions of hydro-vortex hetero-coagulation were modified. Equations are obtained for calculating the amount of decrease in the total energy consumption required for absorption of dust particles, the effective wetting contact angle and minimum diameter of dust particles to be absorbed during hydrovortical heterocoagulation in a function of angular velocity of liquid droplet rotation. A decrease in the energy barrier under conditions of hydro-vortex coagulation is established, being caused by an increase in the effective values of the Stokes criterion in comparison with the values obtained without taking into account rotation of the liquid drops. It is shown that hydro-vortex dedusting increases efficiency of dust suppression, localization of dust mixture explosions, significantly reducing the size of dispersed dust composition, ensures the growth of resource efficiency of eco-technology due to reducing of water consumption.

1. Introduction

In industrial ecology, industrial dust is one of the most common causes of man-made accidents and occupational hazards, which can cause dust diseases occupying the first place in the world among occupational diseases [1].

The problem of air purification and elimination of accumulations of explosive dust mixtures at enterprises is very important for ensuring safe working conditions, sanitary norms, limiting the growth of labor productivity [2,3].

The density of sprinkling and specific water consumption have a significant effect on efficiency of dust suppression in technological processes. In this case low-pressure sprinkling does not catch small dust fractions, which cause silicosis and increase the probability of technogenic uncontrolled processes. [4].

The effect of dust suppression essentially comes to overcoming the energetic barrier and transferring the "solid-liquid" system to a more stable state, i.e., it is determined by the degree of coagulation and capability of liquid droplets to capture dust particles [5].

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With high-pressure hydro-dusting, the energy consumption for aeration is significantly increased, reducing the energy efficiency of processes ensuring safe sanitary-hygienic conditions and results in decrease of competitiveness of the environmental technology [6].

The urgency of the task of improving the technology of high-pressure hydro-dusting as an integral part of the program for introduction of ecological subsoil use requires a new approach to construction of a grapho-analytical model of inertial orthokinetic hetero-coagulation in the "liquid-solid" system.

Technically, coagulation is the result of a collision of two phases: liquid and solid. Collision occurs when a drop of liquid and a dust particle contact, while the very fact of coagulation, that is, the absorption of dust by liquid, may not occur, since it is necessary for the final capture and transition into a single system of "drop of liquid - dust particle" it is necessary that inertia force of the liquid drop in relation to dust particle was higher of forces of adhesion and wetting [7].

The degree of mutual penetration of the two phases, especially in respect to the micro-size particles, corresponding to hydrophobicity, that is, the coagulation efficiency depends on the nature of the surface phenomena taking place in the contact zone being caused by the relative velocity of the water drop and the dust particle, their size, and surface tension at the interface. It has been experimentally established [8] that dust particles with a diameter less than $5*10^{-6}$m are practically hydrophobic. At the same time in dust structure of industrial enterprises particles $(1{,}5\div250)10^{-6}$m prevail [2]

Thus, a significant part of the most explosive and harmful for the human body dust suspension is not capable to effective wetting, i.e. due to its small size it is hydrophobic, which significantly reduces the effectiveness of high-pressure hydrodynamic dust suppression systems.

The article is devoted to the investigation of the mechanism of kinematic hetero-coagulation under the action of an attached vortex in the contact zone induced by a droplet of liquid rotating at a velocity ωж and modeling of the kinematic and dynamic parameters of "drop of liquid - dust particle" system in the process of the proposed hydro-vortex inertial orthokinetic hetero-coagulation [9, 10].

The mechanism of the purposeful control of the contact angle θ and the kinetic energy of interaction between liquid droplets and dust particles Wk under conditions of hydro-vortex coagulation is considered.

The fixation of particles approaching the drop at the distance when adhesion forces act depends on the value of the contact angle θ. To capture hydrophobic particles of dust, a drop of liquid must perform the work of external inertial forces, which corresponds to the kinetic energy Wk of the interaction during their contact. The capture of dust particles by a droplet of liquid occurs under the condition that its kinetic energy Wk is greater or equal to the energy of absorption Пж − г corresponding to the sum of the adhesion energy WAD (F_{AD} − is the adhesion force) determined by the specific energy of detachment and the wetting energy Wп-г (F_{z-g} − is the surface tension force), determined by the specific spreading energy [7,8].

The inertia Stokes (Stk)and Reynolds (Re) criteria, which characterize the ratio of inertia and viscosity in a three-phase "liquid-solid-gaseous" environment, determine the identity of kinematic, inertial and aerodynamic coagulation phenomena. [6,7]

In the work [6], the existence of critical values of the Stokes criterion is experimentally established at which the capture of dust particles is impossible.

To reduce the energy barrier, i.e. the energy capacity of high-pressure hydrodynamic dust suppression it is necessary to change the kinematics of the interaction of a drop of liquid and dust particles in the contact zone, changing the effective value of the Stokes criterion at a fixed speed of translational motion of the dust particle Vп and liquid drop Vz . In view of the foregoing, it is possible due to the rotation of the liquid drop with the velocity ω_z around its axis coinciding with the velocity vector Vz. [8,9]

With hydrovortical kinematic coagulation, the effective values of the Stokes and Reynolds criteria, taking into account their expression for classical coagulation [8], have the form:

$$\mathrm{Stk}_{\omega} = \frac{d_p{}^2(\rho_p - \rho_g)\sqrt{(V_z - V_p)^2 + 0{,}25\omega_z^2 d_p{}^2 \sin\theta}}{18\mu_g d_z}; \quad \mathrm{Re}_{z\omega} = \frac{d_z \rho_z \sqrt{(V_z - V_g)^2 + 0{,}25\omega_z^2 d_p{}^2 \sin\theta}}{\mu_g}, \qquad (1)$$

where: dj – diameter of liquid drop, m; ρ_j – density of liquid drop, kg / m^3; μ_g – coefficient of dynamic viscosity of gas, kg/ms .

Thus, the rotational motion of the liquid droplet increases the actual effective value of the Stokes criteria Stk_{ω} and Reynolds $\mathrm{Re}_{z\omega}$ in the contact zone, contributing to a decrease in the surface-adhesion energy barrier and the critical level of the aerodynamic energy barrier [6].

Based on the well-known graphical model of the kinetic coagulation of a dust particle with a drop of liquid at ω_z=0 [6, 7], a grapho-analytical model of hydrovortical kinematic coagulation is proposed, in which a drop of liquid rotates with angular velocity ω_z relative to the velocity vector of translational motion, inducing in the contact zone the attached vortex [10, 11].

The analysis of the graphic model of interaction in the contact zone at the moment of collision in the "solid-liquid" system, shown in the Fig. 1, taking into account [7, 10], evidences that the contact area of the liquid drop with the dust particle, determined by the wetting perimeter diameter $d_{см\omega}$, has a direct effect on the value of the wetting contact angle θ. The smaller the radius of curvature of the droplet surface in the contact zone, i.e. its smaller size, the smaller the contact angle θ, and, consequently, the more energy it takes to completely absorb a dust particle of diameter $d_{p\,min}$ by a drop of liquid of diameter d_z, determined by the surface energy of detachment and spreading.

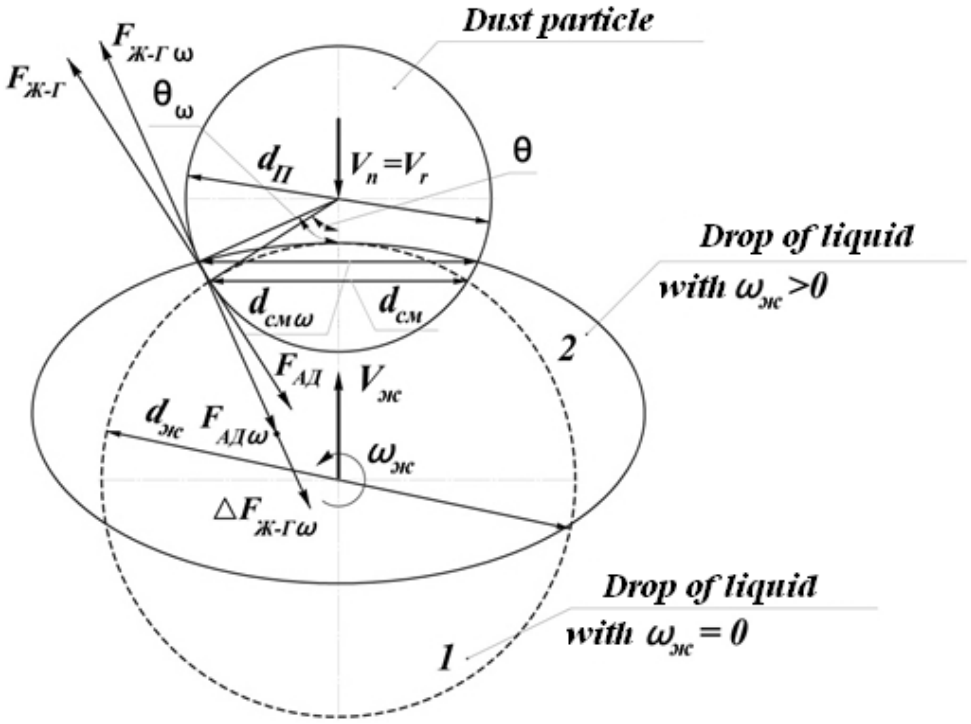


Figure 1. Graphical model of hydrovortical kinematic coagulation of a dust particle liquid droplets:

1, 2 – model of the classical and hydro-vortex inertial orthokinetic hetero-coagulation, respectively for $\omega_z = 0$ and $\omega_j > 0$.

From Fig. 1 it is seen that under the influence of the centrifugal force of inertia the drop of liquid changes the shape, curvature of the surface and, accordingly, the diameter of the wetting perimeter

$d_{w\omega}$, depending on its rotation speed ω_z [10,12].

When a dust particle collides with a droplet of liquid rotating at a velocity ω_z, the diameter of the perimeter of wetting increases to a value $d_{см\omega}$ in comparison with its value $d_{см}$ at $\omega_z = 0$, i.e. with classical hetero-coagulation (see subsection 1.2 of Fig. 1).

From the foregoing it follows that, other things being equal, hydrovortex coagulation requires less energy to completely absorb a dust particle of a given diameter $d_{p\omega min}$, since$\theta_\omega > \theta$ [6-8].

With increasing contact angle θω, the absorption energy is reduced, which makes it possible to expand the absorption range of dust particles of smaller size, that is, to increase the effectiveness of dust suppression at given energy costs, or to provide the given level of dust removal efficiency at lower power consumption [7].

The effect of the kinematic and dynamic parameters of liquid droplet rotation on the energy barrier and contact angle of wetting is shown on the graphical model of hydro-vortex inertial optokinetic hetero-coagulation in the interaction of a dust particle with the droplet of liquid rotating at an angular velocity ω_z, shown in Fig. 1.

When a liquid droplet rotates with an angular velocity ω_z around its surface and in the contact zone, according to the Helmholtz-Bernoulli condition, a rarefaction region is created, i.e. of the reduced static pressure by the value of the specific energy $\Delta W_к$ of the attached vortex and induced by it velocity according to the hydrodynamic analogy is determined by the Bio-Savarra formula known in the theory of electrodynamics. Thus, the attached vortex caused by the rotation of a drop of liquid, decreasing the static pressure in the area of its contact with the dust particle, increases the contact angle of wetting to the value θ_ω and contributes to reducing of the aerodynamic energy barrier [11].

The reduction in the required energy for the complete absorption of a dust particle, taking into account [10,12] may be expressed by the equation:

$$\Delta\Pi_{z-g\omega} = \Delta F_{z-g\omega} d_p = \frac{1}{2}\rho_z G_\omega \omega_z d_p S_к S_p^{-1} \quad , \tag{2}$$

where: Γ_ω −gas circulation in the contact zone of a dust particle and a drop of liquid, m^2/s; S_k −contact area corresponding to the wetting area, m^2; S_p – surface area of a dust particle, m^2; $\Delta F_{z-g\omega}$− depression, that is, the force of the rarefaction pressure in the contact zone of the dust particle and the liquid drop caused by the effect of the attached vortex and equal to the decrease in the surface tension force, n.

The equation for additional kinetic energy, reducing the aerodynamic absorption barrier accounting (2), Fig. 1, the Bernoulli and Ostrogradsky-Gauss equations [10, 13] may be obtained in the form:

$$\Delta W_{к\omega} = \Delta P_{z-g\omega} = \frac{\pi}{8}\rho_z {d_p}^3 \sin^4\theta\omega_z^2 . \tag{3}$$

By analogy with classical hetero-coagulation with $\omega_z = 0$, the equation for calculating the minimum value of the energy of total absorption of a dust particle in the case of hydro-vortex inertial orthokinetic hetero-coagulation, taking into account equation (3), may be written in the form [7]:

$$P_{z-g\omega} = P_{z-g} - \Delta P_{z-g\omega} = 2\delta_{z-g}\cos\theta_\omega . \tag{4}$$

Accounting the equations (3.4), the formula for the wetting contact angle in the contact zone of the liquid and solid phases when the liquid droplet rotates with the angular velocity ω_z under hydrovortic hetero-coagulation conditions is obtained as:

$$\theta_\omega = \arccos\left(\cos\theta - \frac{\pi\rho_z d_p^3 \sin^4\theta\,\omega_z^2}{8\delta_{z-g}\cos\theta}\right) \quad . \tag{5}$$

The minimum diameter $d_{p\,\omega\,min}$ of the dust particle completely absorbed during the capture and wetting by drops of liquid under the action of surface tension forces, inertial forces of translational and rotational motion, we obtain in the form:

$$d_{p\,\omega\,min} = \frac{\delta_{z-g}\cos\ \arccos\left(\cos\theta - \frac{\pi\rho_z d_p^3 \sin^4\theta\,\omega_z^2}{8\delta_{z-g}\cos\theta}\right)}{(\rho_p-\rho_g)(V_z-V_g)^2} . \tag{6}$$

The Fig. 2 shows the calculation results for the proposed mathematical model of hydrovortical

kinematic hetero-coagulation of the dependence of the minimum diameter $d_{п\,\omega\,min}$ of a dust particle completely absorbed during capture and wetting by drops of liquid and the change in the Stokes criterion Stk at a fixed effective critical value of the Stokes criterion $Stk_{\omega кр}$=4.1*10-^{2}, calculated by the formula (1) depending on the angular velocity of water droplets rotation $\omega_{ж}$.

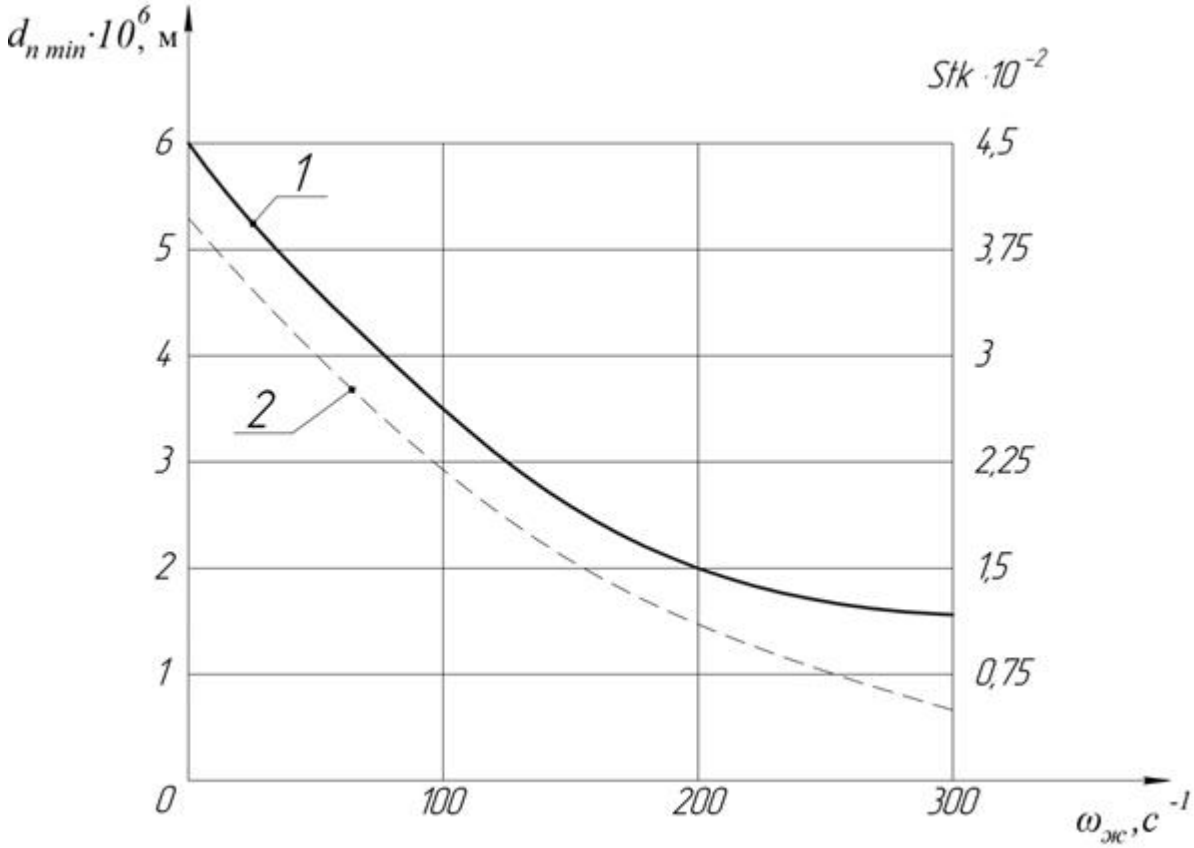


Figure 2. Dependence of $d_{п\,\omega\,min}$(1) and Stk (2) from the change in the angular velocity of rotation of a liquid drop ω_z with $Stk_{\omega kr}$ = 4.1 * 10^{-2}.

It can be seen from the analysis in Fig. 2 that as the particle diameter of the dispersed dust decreases, the constancy of the critical effective value of the Stokes criterion $Stk_{\omega kr}$ = 4.1 * 10^{-2} is achieved kinematically due to the rotational motion of the liquid drop according to equation (1), thereby ensuring complete absorption of dust particles of smaller diameter in comparison with classical hetero-coagulation.

At angular velocity of liquid droplet rotation $\omega_z = 3 * 10^2\ c^{-1}$, the value of Stk_z decreases by more than four, in comparison with their critical values, which ensure complete absorption of dust particles under the translational motion of liquid droplets, that is for $\omega_z = 0$. In this case, the effective values of the Stokes criterion calculated according to formula (1) correspond to their critical values of total absorption at $\omega_z = 0$, i.e. obtained from known criterial equations. [6]

The decrease in the energy barrier under conditions of hydro-vortex coagulation is caused, as shown above (1), by an increase in the Stokes criteria Stk_{ω}, when the liquid droplets rotate compared to their values Stk, calculated without taking into account the rotation of the liquid drop, that is, with $\omega_z = 0$ and $V_z = const$. The constancy of the critical value $Stk_{\omega kr}$ with decreasing diameter of the dust particle $d_{p\,\omega\,min}$ and V_z is provided by increasing the angular velocity of its rotation ω_z.

The decrease in the value of the Reynolds criterion for liquid droplets in hydro-vortex high-

pressure hydro-dusting corresponds to a decrease in the rate of forward motion of a drop of liquid V_z, that is, a decrease in water flow, increasing the resource efficiency of the dust suppression system.

Experimental tests of vortex nozzles have confirmed the results of calculations, have shown high efficiency of hydro-vortex inertial ortokinetic hetero-coagulation, allowing the 20% reduction in water consumption, decrease the size of the absorbed absolutely hydrophobic dust particles up to $1{,}5 * 10^{-6}$m.

The effectiveness of hydro-vortex dedusting is increased due to absorption of fine dust particles, a significant decrease in their medial size at angular velocities up to 300 c^{-1}.

From the analysis of Figure 2 it is seen that by decreasing the particle diameter of dust $d_{p\,\omega\,min}$<6*10^{-6} m criterion value Stk_z <= Stk_{kr}=4.1*10^{-2} which corresponds to power inadequacy for its absorption. With hydro-vortex dedusting, the decrease in the energy of the translational motion of the liquid drop is compensated by the rotational energy, while maintaining the critical value $Stk_{\omega kr}$ =4.1*10^{-2}.

2. Conclusions

1. Circulation motion of liquid droplets, increases the actual effective value of the Stokes criterion $Stk_{\omega kr}$.

2. Hydro-vortex de-dusting reducing the median size of dispersed dust contributes to the effective localization of explosive dust aerosols.

3. Hydrochemical high-pressure dedusting promotes an increase in the wetting angle, a decrease in the minimum absolute hydrophobicity of dust particles, a reduction in level prohibiting of the surface-adhesion energy barrier, it allows the minimum absorption size of absolutely hydrophobic dust particles to be reduced to $1{,}5 * 10^{-6}$ m , that is, to reduce substantially the size of the dispersed composition of dust particles, thereby increasing the efficiency of dust collection**,** adhesion of particles and the critical level of aerodynamic energy barrier.

4. Hydrochemical kinematic coagulation allows to reduce water consumption by 20% compared to the classical high-pressure hydro-dusting.

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