Prospects for vortex hydrodedusting in coal mines

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Abstract. Efficiency of coal mining and mineral processing is restricted by imperfection of the technology of blasting-generated dust control and mine safety. Using the mechanism of circulating inertia hetero-coagulation in the liquid–solid system, the authors propose the method of vortex high-pressure hydrodedusting. Furthermore, the contact interaction model is adjusted, and the relations are derived for the Stokes and Reynolds criteria, minimized total dust absorption energy, effective wetting angle and minimum diameter of water drops as function of their rotation speed. It is shown that the reduction in the particle size distribution in dispersed dust improves efficiency of dust explosion localization and silicosis control. It is proved that the patented vortex nozzles scale-down both minimum size of absorbed dust by times and water flow rate by 20%.

1. Introduction
Hydrodedusting is one of the most popular tools to prevent explosions of coal dust and create health conditions in mining. As practice shows, intensification of production and introduction of new advanced mining and processing technologies is restricted by imperfection of methods available for localization of coal dust explosions. Low-pressure spraying misses dust fines which are the most explosible and provocative of silicosis [1–3].

A potential for improvement of hydrodedusting efficiency lies in increasing the outlet water pressure as it governs the rate of coagulation and capability of water drops to trap dust particles [2]. At the same time, the increase in the energy consumption by aeration results in lower competitive ability of the eco-technology in mining [3–5].

Regarding micro-size particles showing hydrophobic behavior, the degree of inter-penetration of two phases, i.e. efficiency of coagulation, depends on the nature of surface phenomena in the zone of their contact governed by the relative velocity of water drop and dust particle, their sizes and surface tension at the interface. It I experimentally found that dust particles having diameter less than 5⋅10^{-6} m are hydrophobic [2, 6, 7]. In the meanwhile, dust in coal mines is mainly composed of particles (1.5–250)⋅10^{-6} m in size [1, 4].

Thus, considerable portion of the most explosive-hazards and harmful dust cloud cannot be wetted effectively as it is hydrophobic due to small size of particles, which greatly weakens performance of high-pressure hydrodynamic dedusting.

The objective of modeling kinematics and dynamics of the water drop–dust particle system in the course of the proposed vortex inertia orthokinetic heterocoagulation is studying the mechanism of kinematic coagulation under the action of bound vortex in the zone of contact induced by a water drop with a rotation speed ωω [8, 9].
Fixing of particles approaching the drop at a distance of effective adhesion depends on the value of a wetting angle $\theta$. For a water drop to catch hydrophobic particle, it is required to perform work of external inertia forces, which conforms with a kinetic energy $W_k$ of the particle–drop interaction in their contact zone. A water drop traps a dust particle when the kinetic energy $W_k$ equals or exceeds an absorption energy $\Pi_{w,g}$, coming up to a sum of an adhesion energy $W_{ad}$ ($F_{ad}$—force of adhesion), governed by a detachment energy, and a wetting energy $W_{w,g}$ ($F_{w,g}$—force of surface tension), conditioned by a spreading energy [5, 6].

Based on the known graphical model for the kinetic coagulation of a dust particle by a water drop at $\omega_w = 0$ [5, 6], a model of the vortex kinematic coagulation was constructed such that a water drop rotates at the speed $\omega_w$ and induces the bound vortex in the contact zone.

It is seen in the mode of the contact interaction at the moment of collision in the solid–liquid system in Figure 1 that the water drop–dust particle contact area is governed by the wetted perimeter diameter $d_w$ directly affects the value of the limiting wetting angle $\theta$. With the smaller curvature of the drop surface in the contact zones, i.e. smaller size drop, the limiting wetting angle $\theta$ diminishes, which, consequently, results in the increase in the energy required for the total absorption of a dust particle with a diameter $d_{min}$ by a water drop with a diameter $d_w$ and determined by the surface energy of detachment and spreading.

This study focuses on the mechanism of purposeful control of the limiting wetting angle $\theta$ and the kinetic energy $W_k$ of interaction between water drops and dust particles.

2. Mathematical modeling of vortex kinematic coagulation

As the limiting wetting angle $\theta$ reduces, the absorption energy lowers, which makes it possible to ensure pre-set efficiency of dedusting at reduced energy input, or to push the range of absorption of smaller size particles, i.e. to enhance dedusting at the preset energy consumption.

Figure 1 shows that when a dust particle collides a water drop with the rotation speed $\omega_w$, the wetted perimeter diameter grows up to $d_{weto}$ as against $d_{wet}$ at $\omega_w = 0$, i.e. under classical heterocoagulation (1, 2 in Figure 1).

![Figure 1](image)

**Figure 1.** Graphical model of vortex kinematic coagulation of dust particle and water drop: 1, 2—respectively, models of classical and vortex orthokinetic heterocoagulation at $\omega_w = 0$ and $\omega_w > 0$.

The Strokes and Reynolds numbers Stk and Re, characteristic of the ratio of inertia and viscosity in the three-phase system of liquid–solid–gas, determine identity properties of kinematic, inertia and
aerodynamic phenomena of coagulation [6]. The experimental research in [6] found the critical values of the Stokes number when catching of dust particles becomes impossible.

To push down the energy limit, i.e. energy consumption of high-pressure hydrodynamic dedusting, it is necessary to change the interaction kinematics between a water drop and a dust particle in the contact zone by varying rms value of the Stokes number at the constant forward velocities of the dust particle and water drop, \( V_d \) and \( V_w \), respectively. With regard to the aforesaid, this is achievable at the water drop rotation at the speed \( \omega_w \) around its axis coinciding with the vector of the velocity \( V_w \) [7–9].

In the vortex kinematic coagulation, rms values of the Stokes and Reynolds numbers are given by:

\[
\begin{align*}
\text{Stk}_{\omega} &= \frac{d_w^2 (\rho_d - \rho_g) \sqrt{(V_w - V_d)^2 + 0.25 \omega^2 d^2_w}}{18 \mu_g d_w} , \\
\text{Re}_{\omega} &= \frac{d_w \rho_w \sqrt{(V_w - V_g)^2 + 0.25 \omega^2 d^2_w}}{\mu_g},
\end{align*}
\]

where \( d_w \) is the water drop diameter, m; \( \rho_w, \rho_g, \rho_d \) are the densities of water, gas and dust, respectively, kg/m\(^3\); \( \mu_g \) is the dynamic viscosity of gas, kg/ms; \( V_g \) is the velocity of gas, m/s.

In this fashion, rotation of water drop increases the actual rms numbers \( \text{Stk}_{\omega} \) and \( \text{Re}_{\omega} \) in the drop–particle contact zone and favors reduction in the surface–adhesion energy barrier and critical level of the aerodynamic energy barrier [6].

When a water drop rotates at a speed \( \omega_w \), around it surface and in the contact zone, according to the Helmholtz–Bernoulli condition, a zone of rarefaction by the value of the specific energy \( \Delta W_k \) of the bound vortex is created; the vortex velocity is determined from the Biot–Savart law from electrodynamics. Accordingly, the bound vortex, governed by the water drop rotation, reduced the static pressure in the contact zone with the dust drop, increases the limiting wetting angle down to \( \theta_w \) and contributes to lowering of the hydrodynamic energy barrier [11].

Drawdown in the energy required for the total absorption of dust particle by rotating water drop by the value of the potential rarefaction energy, i.e. work of the force of depression in the contact zone in the dust particle section equal to its diameter can be given by:

\[
\Delta \Pi_{w-gw} = \Delta F_{w-gw} d^2_d = \frac{1}{2} \rho_w \Gamma_{\omega} \omega_w d_d \cos \theta \frac{S_c}{S_s},
\]

where \( \Gamma_{\omega} \) is circulation of gas in the contact zone of dust particle and water drop, m\(^2\)/s; \( S_c \) is the area of the contact zone conforming with the wetting area, m\(^2\); \( S_s \) is the surface area of dust particle, m\(^2\); \( \Delta F_{w-gw} \) is the force of rarefaction pressure (depression) in the contact zone of dust particle and water drop due to the bound vortex effect, equal to the reduction in the surface tension, N.

The equation of extra kinetic energy to push down the aerodynamic barrier of absorption, or actually to reduce the kinetic energy equal to the bound vortex energy, with regard to (2) as well as equations by Bernoulli and Ostrogradsky–Gauss [10, 12] are:

\[
\Delta W_{kw} = \Delta \Pi_{w-gw} = \frac{\pi}{8} \rho_w d^3_d \sin^4 \theta \omega_w^2.
\]

For the vortex inertia orthokinetic heterocoagulation, the minimum energy of total absorption, considering (3), by analogy with the classical heterocoagulation at \( \omega_w = 0 \), is written as [5, 13, 14]:

\[
\Pi_{w-gw} = \Pi_{w-g} - \Pi_{w-g0} = 2 \delta_{w-g} \cos \theta_w\omega,
\]

where \( \delta_{w-g} \) is the surface tension coefficient at the liquid–gas interface, J/m\(^2\).

Taking into account (3) and (4), the limiting wetting angle in the contact zone of the liquid and solid phases at the water drop rotation speed \( \omega_w \) is given by:
\[ \theta_d = \arccos \left( \frac{\cos \theta - \frac{\pi \rho_w d_w^3 \sin^4 \theta \omega_w^2}{8 \delta_{w-g} \cos \theta}}{8\delta_{w-g} \cos \theta} \right). \]  

(5)

Thus, with regard to [6], Eq. (5) and the proposed model for the inertial orthokinetic coagulation in the dust particle–water drop system at the water drop rotation speed \( \omega_w \), the minimum diameter \( d_{d\omega_{\min}} \) of a dust particle totally absorbed during capturing and wetting by water drops under the action of surface tension and forward and backward motion inertias is:

\[
d_{d\omega_{\min}} = \frac{\delta_{w-g} \cos \arccos \left( \frac{\cos \theta - \frac{\pi \rho_w d_w^3 \sin^4 \theta \omega_w^2}{8 \delta_{w-g} \cos \theta}}{8\delta_{w-g} \cos \theta} \right)}{(\rho_d - \rho_g)(V_w - V_g)^2}.
\]

(6)

Figure 2 illustrates calculations carried out by the proposed mathematical model of the vortex kinematic coagulation to determine the change in the critical values of the Stokes number \( \text{Stk}_{\omega} \) as function of the rotation speed \( \omega_w \) of a water drop with the diameter \( d_w = 6 \cdot 10^{-6} \text{ m} \) for the perfectly hydrophobic particles of silica. The isolines prove an essential decrease both in the surface–adhesion energy limit preventing particle adhesion and in the critical level of the aerodynamic energy barrier (line 4 in Figure 2).

![Figure 2](image)

**Figure 2.** Isolines of water drop rotation speed as function of critical values of the Stokes and Reynolds numbers: 1—\( \omega_w = 0 \); \( \text{Stk}_{\omega} = 4.1 \cdot 10^{-2} \); \( \text{Re}_w = 20 \); \( d_{d_{\omega_{\min}}} = 6 \cdot 10^{-6} \text{ m} \); 2—\( \omega_w = 1.5 \cdot 10^{-2} \text{ s}^{-1} \); \( \text{Stk}_{\omega} = 9 \cdot 10^{-3} \); \( \text{Re}_w = 15 \); \( d_{d_{\omega_{\min}}} = 3.5 \cdot 10^{-6} \text{ m} \); 3—\( \omega_w = 3 \cdot 10^{-2} \text{ s}^{-1} \); \( \text{Stk}_{\omega} = 5 \cdot 10^{-3} \); \( \text{Re}_w = 6 \); \( d_{d_{\omega_{\min}}} = 1.5 \cdot 10^{-6} \text{ m} \); 4—\( \text{Stk}_{\omega} \) versus \( d_{d_{\omega_{\min}}} \) at \( \text{Stk}_{\omega} = \text{Stk}_{\omega_{\min}} = 4.1 \cdot 10^{-2} \); 5—\( \text{Stk}_{\omega} = 4.1 \cdot 10^{-2} \) versus \( \omega_w \) and \( d_{d_{\omega_{\min}}} \).

At the water drop rotation speed \( \omega_w = 3 \cdot 10^{-2} \text{ s}^{-1} \) the critical values of \( \text{Stk}_{\omega} \) and \( \text{Re}_w \) drop more than 4 and 3 times, respectively, as against their values in the conditions of the forward movement of water drop, i.e. at \( \omega_w = 0 \). Moreover, the rms values of the Stokes and Reynolds numbers calculated from \( (2) \), in the line 4 in Figure 2, conform with their rms values under total adsorption at \( \omega_w = 0 \) from the known criterion equations [6].

The reduction in the Reynolds number for water drops under vortex high-pressure hydrodedusting promotes decrease in the water flow rate and required pressure, which improves efficiency of dust control.

The experimental research sufficiently accurately proved the calculated results from the proposed mathematical model and demonstrated high efficiency of vortex inertia orthokinetic heterocoagulation: the water consumption was lower by 20% and the minimum size of absorption of totally hydrophobic dust particles was decreased to 1.5 \( \cdot \) \( 10^{-6} \text{ m} \) as compared with the classical high-pressure hydraulic dedusting.
3. Conclusions
1. Rotation of water drops under the vortex inertia coagulation raises the rms value of the Stokes number $St_{Kn}$, which promotes an increase in the wetting angle and a decrease in the minimum size of absorbable dust particle down to $1.5 \times 10^{-6}$ m.
2. The vortex kinematic coagulation allows reduction in water flow rate by 20% as against the classical method of high-pressure hydraulic dedusting.

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