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Mathematical Model of Liquid Droplet Circulating Motion in a Gas Medium

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Математическая модель циркуляционного движения капли жидкости в газовой среде

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A mathematical model of liquid droplet circulating motion in a gas medium has been developed, the use of which makes it possible to create more efficient methods of dust collection. High dustiness of the work space in the collieries, active methane emissions restrain the intensification of coal mining, reducing the competitiveness of mining enterprises. The analysis showed that the occurrence of explosion hazard can be prevented by effective dust collection. The most common method is dust deposition based on wetting dust particles with liquid droplets to form a dust particle – liquid droplet system, which settles on the walls of mine workings. However, with an increase in fluid pressure, energy consumption for dust collection increases significantly, which worsens the parameters of energy efficiency while observing hygiene requirements. Based on study results for physical features of the inertial motion of rotating liquid droplets, a mathematical model of their circulation in a gas medium has been developed to create more efficient dust collection methods. It is proved that the vorticity diffusion equation for a liquid droplet moving along a helical line is identical to the heat conduction equation with a dispersion coefficient of the rotational motion energy of a liquid droplet with a coefficient that is the dynamic viscosity coefficient. It is confirmed that the circulating motion of liquid droplets in both the Nad-Stokes and Stokes motion increases the relaxation time due to a decrease in aerodynamic drag coefficient of the gas medium caused by an increase in the effective Reynold's number with an increase in the angular rotation velocity of liquid droplets. It is shown that averaging the aerodynamic drag coefficient values of the liquid droplet motion makes it possible to use the obtained formulas for calculating hydro-vortex coagulation in a wide range of Reynold's number $1 < \mathrm{Re} < 10^4$.

Ключевые слова:
высоконапорное гидровихревое пылеулавливание, циркуляционное движение, индикаторы и критерии подобия, присоединенный вихрь, дисперсия, диффузия, гетерокоагуляция, коэффициент аэродинамического сопротивления, газовая среда.

Разработана математическая модель циркуляционного движения капли жидкости в газовой среде, применение которой позволяет создать более эффективные способы пылеулавливания. Высокая запыленность технологического пространства угольных предприятий, активные выбросы метана сдерживают интенсификацию добычи угля, снижая конкурентоспособность горнодобывающих предприятий. Проведенный анализ показал, что возникновение взрывоопасных ситуаций можно предотвратить с помощью эффективного пылеулавливания. Наиболее распространенный метод – это осаждение пыли, основанный на смачивании частиц пыли каплями жидкости с образованием системы «частица пыли – капля жидкости», которая оседает на стенках горных выработок. Однако с повышением давления жидкости существенно возрастают энергозатраты на пылеулавливание, что ухудшает показатели энергоэффективности при соблюдении санитарно-гигиенических требований. По результатам исследований физических особенностей инерционного движения вращающихся капель жидкости разработана математическая модель циркуляционного их движения в газовой среде для создания более эффективных способов пылеулавливания. Доказано, что уравнение диффузии завихренности при движении капли жидкости по винтовой линии тождественно уравнению теплопроводности с коэффициентом дисперсии энергии вращательного движения капли жидкости с коэффициентом, являющимся динамическим коэффициентом вязкости. Подтверждено, что циркуляционное движение капель жидкости как при надстоксовском, так и при стоксовском движении увеличивает время релаксации за счет снижения коэффициента аэродинамического сопротивления газовой среды, обусловленного ростом эффективного значения критерия Рейнольдса с увеличением угловой скорости вращения капель жидкости. Показано, что осреднение значений коэффициента аэродинамического сопротивления движения капли жидкости позволяет использовать полученные формулы для расчета гидровихревой коагуляции в широком диапазоне критерия Рейнольдса $1 < \mathrm{Re} < 10^4$.

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Introduction

High dustiness of the work space in the collieries, active methane emissions restrain the intensification of coal mining, reducing the competitiveness of mining enterprises [1–9]. The analysis confirms that at least 65 % of explosion hazards can be prevented by effective dust collection [10–17]. The most common method is dust deposition based on wetting dust particles with liquid droplets to form a dust particle – liquid droplet system, which settles on the walls of mine workings [10–20]. However, with an increase in fluid pressure, the power consumption for dust collection increases significantly, which worsens energy efficiency indicators while observing sanitary requirements. The studies [21–35] offer a mathematical model of hydro-vortex orthokinetic heterocoagulation which describes the mechanism of rotating liquid droplet interaction with dust particles.

The solution of the problem of unsteady motion of rotating liquid droplets in a gaseous medium with large Reynolds numbers is a major challenge, and until now this problem has not been sufficiently studied. The motion mode of rotating liquid droplets in a gaseous medium in a dynamically active section of high-pressure spraying is determined by a continuous change of Reynolds numbers in the range of $1 < \mathrm{Re} < 10^4$ in an inertial path section in a gaseous medium. Experimental studies confirm that the force of aerodynamic drag to the liquid droplet motion changes nonlinearly when the Reynolds number increases, but if the Reynolds number is $\mathrm{Re} \le 1$ it changes linearly [36, 37]. A significant change in the relaxation time of liquid droplets and dust particles along the inertial path also complicates the solution of the aerohydrodynamics problem of the liquid droplets rotational motion along a helical line.

Problem Setting

In order to study physical features of the liquid droplet inertial motion to build mathematical models of the liquid droplet hydro-vortex circulating motion in a gaseous medium, it is necessary to build equations of the rotating liquid droplets motion taking into account the physical phenomena that determine the role of surface and intra-droplet liquid circulation when interacting with the gas medium in the entire range of Reynolds numbers.

When we study the liquid droplet rotational motion flowing around by a gaseous medium in order to construct a mathematical model of its circulation motion along a helical line in a gaseous medium, we take the following admissions:

– the equilibrium shape of a liquid droplet is maintained throughout the inertial path;

– the gaseous medium tangential velocity on the liquid droplet surface has no discontinuity, i.e. it is continuous;

– the gaseous medium velocity perpendicular to the drop surface is equal to zero;

– the forces with which a liquid drop and a gaseous medium affect each other obey Newton's law, i.e. they are equal in size and opposite in direction;

– the tangential velocity of a gaseous medium on the liquid droplet surface during its steady motion contributes to occurrence of the liquid intra-droplet circulation.

A change in the kinematic parameters characterizing the rotating liquid droplet helical motion in a gaseous medium leads to changes in Reynolds numbers which are determined by the formula [34, 38–40]:

$$\mathrm{Re}_{эф} = \frac{d_ж \rho_ж \sqrt{\left(V_ж - V_г\right)^2 + 0,25\omega_ж^2 d_ж^2}}{\mu_г} \qquad (1)$$

where d_l – the liquid drop diameter, m; ρ_l – the liquid drop density, kg/m^3; μ_g – the dynamic gas viscosity ratio, kg/ms.

The liquid droplet rotation promotes the appearance of an attached vortex around it, which creates a low pressure area and internal liquid circulation in the droplet determined by the Helmholtz – Bernoulli equations [41, 42].

The uniform motion of liquid droplets in a gaseous medium under conditions of equilibrium of forces impacting them is considered steady, while the slowed down or accelerated motion of a liquid droplet is considered incomplete. It is required to establish the relationship between the gaseous medium aerodynamic drag and the liquid droplets motion and their relaxation time in order to determine kinematic and dynamic parameters of the liquid droplets rotating motion in a gaseous medium.

Mathematical Modelling

Let us establish the difference in kinematic parameters of the motion of dust particles and liquid droplets resulting from the impact of the liquid droplet surface layer motion and intra-droplet circulation on the gaseous medium aerodynamic drag coefficient and the velocity relative to it at steady motion of the droplet in the Stokes mode.

The gaseous medium resistence to a dust particle moving in it along a helical line is determined by the equation [36]:

$$F_c = \lambda \rho_г \frac{\left(V_ж - V_г\right)^2 + 0,25\omega_ж^2 d_ж^2}{2} S, \qquad (2)$$

where λ – medium aerodynamic drag coefficient; ρ_g – gas medium density, kg/m^3; $S = \frac{\pi d_ж^2}{4}$ – area of a liquid drop projection onto a plane perpendicular to its translational motion direction, m^2.

The steady-state rotational motion of dust particles at Reynolds numbers less than unity is determined by the linear Stokes law for the gaseous medium aerodynamic drag force [36]:

$$F_c = 3\pi\mu_г d_ж \sqrt{\left(V_ж - V_г\right)^2 + 0,25\omega_ж^2 d_ж^2}. \qquad (3)$$

The coefficient of the gaseous medium aerodynamic drag to the dust particles movement taking into account equations (1)–(3) is as follows:

$$\lambda = \frac{24\mu_г}{\rho_г d_ж \sqrt{\left(V_ж - V_г\right)^2 + 0,25\omega_ж^2 d_ж^2}} = \frac{24}{\mathrm{Re}_{эф}}. \qquad (4)$$

Fig. 1 (*a*, *b*) shows the motion kinematics of a liquid droplet with a diameter d_l, density ρ_l and viscosity μ_l with a relative velocity $V_r$in a gaseous medium with a density ρ_g and viscosity μ_g. The center of the coordinate system in which the rotating liquid droplet helical motion is studied is aligned with its center of gravity. The symmetry condition for the liquid droplet motion gives grounds to divide the three-dimensional spatial problem into plane motion of a liquid droplet with velocities V_r, V_n in a cylindrical coordinate system $r\varphi$ and rotational motion with an angular velocity ω_l around the translational velocity vector V_l the velocity of which is determined by the formula:

$$V_в = \frac{\omega_ж \cdot d_ж}{2}. \qquad (5)$$

Since $V_n = 0$, we ensure the coincidence of vortex lines of rotating liquid droplets with streamlines of their motion. A liquid droplet in its instant rotation rotates around a tangent to the streamline, which corresponds to its motion along a helical line. This motion is potential irrotational since the vector product of the translational velocity V_l and the angular velocity ω_l is equal to zero [41].

The liquid movement inside a droplet and a gaseous medium is described by the Navier – Stokes equations and the flow continuity equation [41]. Rotation of a liquid droplet in the process of its translational motion along a helical line

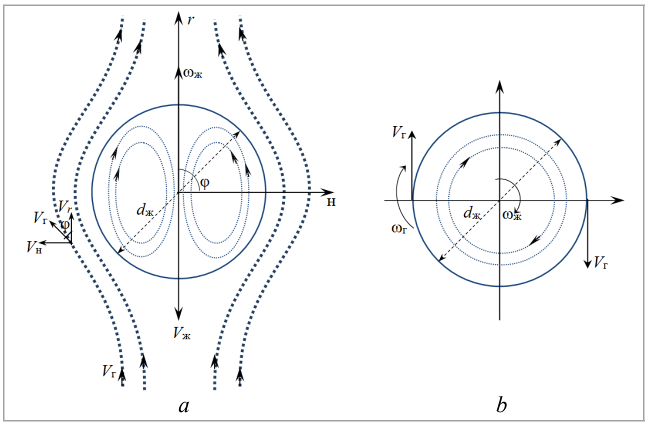

Fig. 1. Kinematics of motion along a helical line of a rotating liquid droplet with its viscous flow by air: translational motion in the plane *гн* (*a*); rotational motion V_l around the vector of translational velocity ω_l (*b*): V_l – the droplet rotation speed relative to a gaseous medium, m/s; V_g – the velocity of flow of the gaseous medium droplet surface, m/s; ω_l – the angular velocity of droplet rotating in a gaseous medium, s $^{-1}$; φ – the angle between vectors of the droplet velocity and droplet surface flow velocity, deg.; V_r and V_n – the tangential and nominal components of the flow velocity around the droplet surface with a gaseous medium, respectively, m/s $^{-1}$

leads to the vorticity dispersion appearance, i.e. the vortex propagation in a gaseous medium due to its viscosity. Taking into account that $\omega_l = \operatorname{rot} V_l$, the Stokes equation for a rotating liquid droplet in a gaseous medium considering its viscosity can be as follows:

$$\rho_г \omega_ж V_ж + \operatorname{grad} P + \mu_г \operatorname{rot} \omega_ж = 0, \qquad (6)$$

where P – volume force potential.

After transformation of the equation (6), taking into account that the helical motion of liquid droplets is potential, we write the generalized Helmholtz equation of the gaseous medium rotation caused by the rotational motion of a liquid droplet along a helical line in the following form [41–43]:

$$\rho_г \frac{d\omega_ж}{dt} + \left(\omega_ж \cdot \nabla\right) V_ж = \mu_г \nabla^2 \omega_ж. \qquad (7)$$

The vorticity diffusion is shown on the right side of equation (7), and the diffusion coefficient is the dynamic viscosity coefficient. This confirms the identity of the mechanism of the gaseous medium viscosity impact on the translational motion of a liquid droplet with a velocity V_l in the plane *гн* and on the vorticity diffusion from rotational motion with an angular velocity ω_l around the translational velocity vector V_l. If we consider the motion of the velocity vector V_l in the plane *г*φ, equation (7) can be represented as follows [41, 43, 44]:

$$\frac{\partial \omega_ж}{\partial t} + V_ж \cdot \operatorname{grad} \omega_ж = \nabla^2 \omega_ж. \qquad (8)$$

Equation (8) is presented in the form of a well-known equation of the heat propagation theory by analogy with the vorticity dispersion:

$$\frac{\partial \omega_ж}{\partial t} = V_ж \left(\frac{\partial^2 \omega_ж}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial \omega_ж}{\partial r} \right). \qquad (9)$$

Taking into account the assumptions, velocity components on the surface of a liquid droplet, $V_г^ж$, i.e. boundary conditions, take the following form [36, 45]:

$$V_r^ж = V_r; \quad V_н^ж = V_н = 0. \qquad (10)$$

According to Fig. 1, the distribution of gaseous medium velocities outside the liquid droplet at $d > d_l$ can be represented as:

$$V_н = V_ж \cos\varphi; \quad V_r = V_ж \sin\varphi. \qquad (11)$$

Considering the above and taking into account the data [36, 41], components of the velocity vector of a gaseous medium around a rotating liquid droplet can be represented as:

$$V_н = -\left[1 - \frac{1}{r}\frac{2+3\mu^*}{2\left(1+\mu^*\right)} + \frac{1}{r^3}\frac{\mu^*}{2\left(1+\mu^*\right)}\right]\cos\varphi;$$
$$V_r = \left[1 - \frac{1}{\bar{r}}\frac{2+3\mu^*}{2\left(1-\mu^*\right)} + \frac{1}{\bar{r}^3}\frac{\mu^*}{4\left(1+\mu^*\right)}\right]\sin\varphi, \qquad (12)$$

where $\mu^* = \dfrac{\mu_ж}{\mu_г}$ – relative viscosity; $\bar{r} = \dfrac{2r}{d_ж} > 1$ – relative distance from the rotation axis of a liquid droplet.

Accordingly, the liquid motion inside the droplet at $d < d_l$ has the following form:

$$V_н = \frac{1-r^2}{2\left(1-\mu^*\right)}\cos\varphi;$$
$$V_r = -\frac{1-2r^2}{2\left(1-\mu^*\right)}\sin\varphi. \qquad (13)$$

Taking into account formula (9), the equation for calculation of the linear and angular velocity of the gaseous medium rotation due to the vorticity dispersion caused by motion along a helical line of a liquid droplet considering the viscosity, is [41]:

$$V_г = d_ж \omega_ж \left(1 - e^{\frac{r^2 \cdot \rho_г}{4\mu_г t}}\right);$$
$$\omega_г = \frac{d_ж^2 \cdot \omega_ж \cdot \rho_г}{\pi \mu_г P} \cdot e^{-\frac{r^2 \cdot \rho_г}{4\mu_г t}}. \qquad (14)$$

Using equations (12), (13), taking into account equation (3) and boundary conditions (10), (11), the equation for the relaxation time of motion along a helical line of a rotating liquid droplet in the Stokes motion is as follows:

$$\tau_к = \frac{1}{18}\frac{d_ж^2\left(\rho_ж - \rho_г\right)}{\mu_г}\frac{3+3\mu^*}{2+3\mu^*}. \qquad (15)$$

Taking into account equations (3), (15), the aerodynamic drag coefficient for a steady motion of a rotating liquid droplet along a helical line in a gaseous medium in the Stokes motion has the following form [36, 45]:

$$\lambda_к = \frac{24}{Re_{эф}}\frac{3+3\mu^*}{2+3\mu^*}. \qquad (16)$$

By analogy with equation (15) and taking into account equation (5) and the data [36, 41], the formula for the relaxation time of the rotational motion of a liquid droplet during its motion along a helical line is obtained in the form:

$$\tau_{кв} = \frac{1}{90}\frac{d_ж^2\left(\rho_ж - \rho_г\right)}{\mu_г}\frac{3+3\mu^*}{2+3\mu^*}. \qquad (17)$$

Accordingly, by analogy with formula (16) for the coefficient of aerodynamic drag to the liquid droplet rotation in a gaseous medium when it moves along a helical line, we obtain an equation in the form:

$$\lambda_{в} = \frac{4,8}{\mathrm{Re}_{эф}} \frac{3+3\mu^*}{2+3\mu^*}. \qquad (18)$$

The analysis of formulas (4), (16) shows that the coefficient of aerodynamic drag to a motion along a helical line of a rotating liquid droplet in a gaseous medium at the steady Stokes motion is less than the corresponding coefficient for solid spherical particles of the same size, in particular, dust particles. In addition, in contrast to the translational motion of liquid droplets, when they move along a helical line and a liquid droplet rotates with an angular velocity ω_l , the effective value of the Reynolds number increases together with the angular rotation velocity, which also contributes to a decrease in the aerodynamic drag coefficient along the inertial path length during circulating motion of liquid droplets along a helical line in a gaseous medium. In this case, the drag coefficient of a liquid droplet rotational motion in a gaseous medium is five times higher than the drag coefficient of a translational motion. Thus, the decisive factor for the relaxation time when a liquid droplet moves along a helical line is the characteristic of a liquid droplet translational motion with the velocity V_l and the angular rotation velocity ω_l, which together with the liquid droplet diameter determine the effective Reynolds number. An increase in the relaxation time $\tau_к$ due to a decrease in the aerodynamic drag coefficient caused by an increase in the Reynolds number effective value contributes to an increase in the zone of active spraying of rotating liquid droplets and an increase in the energy efficiency of dust collection.

Taking into account the studies [36, 41], the value of the aerodynamic drag coefficient to a rotating liquid droplet motion along an inertial path in the active spraying zone can be represented as

$$\lambda_{к} = \frac{24}{\mathrm{Re}_{эф}}\left(1+0,15\mathrm{Re}_{эф}^{0,687}\right). \qquad (19)$$

Formula (19) shows that the average value of the relaxation time of a liquid droplet motion along a helical line in the section of inertial deceleration has the form

$$\tau_{к\ ср} = \frac{\tau_к}{\left(1+0,15\mathrm{Re}_{эф\ ср}^{0,687}\right)}, \qquad (20)$$

where $\mathrm{Re}_{ef\ av}$ is the average value of the effective Reynolds number over the length of the rotating liquid droplet inertial deceleration.

Since the aerodynamic drag coefficient and the Reynolds number are functionally related to each other, continuously varying over the length of the inertial path of a rotating liquid droplet in the active spraying zone, the obtained formulas are difficult to apply practically for engineering calculations. In order to build a mathematical model convenient for calculations, we will average kinematic parameters taking into account the continuous change in the kinetic energy of a liquid droplet.

The analysis of formulas (19), (20) shows that the problem is reduced to establishment of the $\mathrm{Re}_{ef\ av}$ value through its known initial value $\mathrm{Re}_{0\ ef}$. According to the data given in [36], 99.8 % of the kinetic energy of a liquid droplet is consumed over a time interval $t = 3\tau$. Thus, the average effective value of the Reynolds number $\mathrm{Re}_{ef\ av} = 0,33\ \mathrm{Re}_{0\ ef}$, $\mathrm{Re}_{0\ ef}$ is the initial effective value of the Reynolds number of a rotating liquid droplet.

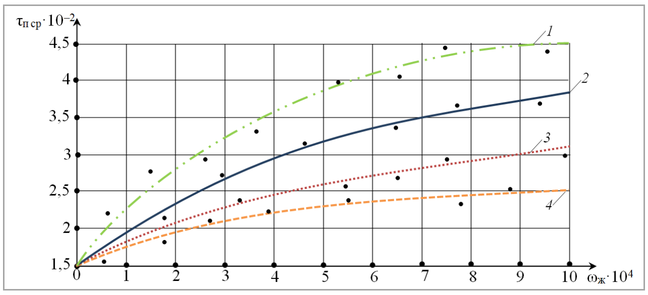

Fig. 2. The dependency graph of the liquid droplet relaxation time and the angular rotation velocity at *1* – $d_к$ = 3·10^{-6} m; *2* – $d_к$ = 2·10^{-6} m; *3* – $d_к$ = 1,5·10^{-6} m; *4* – $d_к$ = 10^{-6} m; V_l = 8 m/s

Taking into account the above, the average values of the relaxation time and aerodynamic drag coefficient to the motion of a liquid droplet in a gaseous medium over the length of inertial braking are determined by the formulas

$$\tau_{к\ ср} = \frac{\tau_к}{1+0,07\mathrm{Re}_{0\ эф}^{0,687}}, \qquad (21)$$

$$\lambda_{ср} = \frac{72}{\mathrm{Re}_{0\ эф}}\left(1+0,07\mathrm{Re}_{0\ эф}^{0,687}\right). \qquad (22)$$

Results and Discussion

In order to verify the obtained mathematical model of aerohydrodynamics of the rotational motion of liquid droplets in a gaseous medium along a helical line, experimental studies were carried out to determine the relaxation time at a given translational velocity, depending on the change in the angular rotation velocity of a liquid droplet.

The research results in Fig. 2 confirm an increase in the relaxation time of rotating liquid droplets with an increase in the angular velocity of their rotation. The analysis of formulas (14), (16), (22) shows that the relaxation time of a rotating liquid droplet along a helical line in a gaseous medium at the inertial path length for both translational and rotational velocities does not depend on the active and inertial forces affecting a liquid droplet but is determined by the viscosity of a gaseous medium and liquid and its geometric parameters.

Conclusion

1. The circulating motion of liquid droplets in both the over-Stokes and Stokes motion increases the relaxation time due to a decrease in the aerodynamic drag coefficient of the gaseous medium caused by an increase in the effective Reynolds number with an increase in the angular rotation velocity of liquid droplets.

2. The vorticity diffusion equation for a liquid droplet moving along a helical line is identical to the heat conduction equation with a dispersion coefficient of the rotational motion energy of a liquid droplet with a coefficient that is the dynamic viscosity coefficient.

3. The averaging of aerodynamic drag coefficient values of a liquid droplet motion by the averaging of the effective Reynolds number over the length of inertial deceleration of a rotating liquid droplet makes it possible to use the formulas obtained for the hydro-vortex coagulation calculation in a wide range of Reynolds numbers $1 < \mathrm{Re} < 10^4$.

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