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Characteristics of the droplet motion of a liquid antifreeze reagent

Характеристики движения капель жидкого противогололедного реагента

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Key words: anti-icing reagents (AR); airfield and road surfaces; distribution disk; nozzle; mathematical model of the motion of a drop of AR; a drop of AR; air environment; monitoring system of the process of distribution of reagents

Ключевые слова: противогололёдные реагенты (ПГР); аэродромные и дорожные покрытия; распределительный диск; форсунка; математическая модель движения капли ПГР; капля ПГР; воздушная среда; система мониторинга процесса распределения реагентов

Abstract. The object of investigation is the process of spraying of the anti-icing reagent. As an object of research, external forces are selected that affect on each drop of the reagent: counteraction forces, gravity forces, Coriolis force and centrifugal inertial forces, lifting force, frictional forces of the reagent on the surface of the working equipment: disk and blades. It is assumed that the liquid reactant is fed under pressure to the hydraulic nozzles installed in the disk casing, and then falls onto the distribution disk. The tasks solved within the framework of the article: the identification of external forces acting on each drop of the reagent from the moment of flow from the nozzle to the moment when it reaches the coating, the study of the effect of external forces on the characteristics of droplet motion, the mathematical description of the process of formation of the sputtering zone. To refine the droplet motion characteristics under the action of external forces using the already available mathematical description of the droplet motion along a distribution disk, a mathematical model of their motion in the air environment has been developed. The equation of motion of the drops of the reagent, the dependences of the droplet's flight range on the mode and parameters of the working equipment are obtained. Meteorological factors such as wind speed and direction, as well as air environment properties (dynamic and kinematic viscosity, depending on the temperature of the medium) are considered in the simulation. This model will provide an opportunity to the reasonably assignation of the parameters of the distribution equipment during their design and operation and will also serve as a base for mathematical and software systems for the continuous monitoring of the process of applying liquid reagents for road and airfield pavements. Its operation will allow to provide a high-quality treatment of coatings ensuring the preservation of their operational properties and to make a reagent savings.

Аннотация. Цель статьи – формирование комплексной математической модели, описывающей движение капель жидкого реагента при обработке покрытий. Объект исследования – процесс распыления противогололедного реагента. В качестве предмета исследований выбраны внешние силы, воздействующие на каждую, отдельно рассматриваемую, каплю реагента: силы сопротивления среды, сила тяжести, кориолисова и центробежная силы инерции, подъёмная сила, силы трения реагента о поверхность рабочего оборудования: диска и лопаток. Предполагается, что жидкий реагент подаётся под давлением к гидравлическим форсункам, установленным в кожухе диска, а затем попадает на распределительный диск. Задачи, решаемые в рамках статьи: выявление внешних сил, действующих на каждую каплю реагента с момента истечения из форсунки до момента достижения ею покрытия, изучение влияния внешних сил на характеристики движения капель, математическое описание процесса формирования зоны распыления. Для уточнения характеристик движения капель под действием внешних сил с использованием уже имеющегося математического описания движения капель по распределительному диску разработана математическая модель их движения в воздушной среде. Получены уравнения движения капель реагента, выявлены зависимости дальности полета капель от режима (частота вращения диска и давление подачи реагента) и параметров рабочего оборудования (диаметр распределительного диска, радиус его ступицы, наклон лопаток (ребер) диска и его высота над поверхностью покрытия, высота расположения форсунок относительно

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плоскости диска). При моделировании учтены метеорологические факторы, такие как скорость и направление ветра, а также свойства воздушной среды (динамическая и кинематическая вязкость, зависящие от температуры среды). Данная модель предоставит возможность обоснованно назначать параметры распределительного оборудования при их конструировании и эксплуатации, а также будет являться базой для математического и программного обеспечения системы непрерывного контроля над процессом нанесения жидких реагентов на дорожные и аэродромные покрытия. Её функционирование позволит обеспечить качественную обработку покрытий, обеспечивая при этом сохранение их эксплуатационных свойств и экономию реагента.

1. Introduction

Most of the territory of Russia is situated in the temperate continental climatic zones, the northern regions are situated in the Arctic and subarctic areas. The climate of Central Russia is continental, characterized by the presence of hot summer and a prolonged cold winter. Similar climatic conditions are typical for Canada, Mongolia, countries of the Scandinavian Peninsula. With the peculiarity of the geographical location of the country, many problems are related to maintenance and operation of roads and airfields in winter.

The most important is the prevention of the appearance and removal of ice, sleet and snow-ice formations on the covers.

To prevent the icing on roads and airfields, two types of anti-icing reagents (AR) are used: liquid and solid.

There are the distinct designs of aerodrome dispensers of reagents which working organs provide for the use of one type of AR (or both) depending on the task (removal of ice or the adoption of preventive measures for its formation) [1, 2].

The following versions of the design of the distribution equipment (DE) are known: nozzles (injector, fan, side fan), mounted on bars (beams) and distribution disks, treating coatings with both liquid and solid reagents.

The main advantages of the nozzles are the uniformity of the AR application on the surface and the compactness of the workpiece design. Disadvantages are the complexity of adjusting of the height of the arrangement of several nozzles above the coating, the insufficient range of distribution of the AR which poses to complicate the design of the outrigger rods. In addition, such design of the DE imposes the restrictions on the type of AR applied to the surface.

The technology of disk distribution involves the treatment of coatings with both liquid and solid reagents. It is possible to vary the width of the processing strip by changing the speed of rotation of the disks and their height above the surface. Disk distributors allow the high-speed processing of aerodrome coverings (with a speed of up to 40 km/h) with a distribution width up to 40 m. However, when operating this type of DE it is important to take into account the presence of factors and conditions that adversely affect on the uniformity of the AR application. To assess them, it is necessary to consider the design features of the disk DE and to get the conception of the movement of the reagent jet relative to the coating. Automatic monitoring systems for reagent feeds have been developed to monitor the position of remote rods with disks/nozzles [3], the system for monitoring the speed of disks and the flow rate metering AR [4, 5, 6], automated control systems for actuators using the GNSS system [7]. The purpose of such systems is to maintain the consistency of the width and density of the coating regardless of the speed of the machine. However, the algorithm of their functioning does not provide the influence of the external environment on the process of distribution of the AR. The effect of the wind force and the direction on the range and uniformity of processing, the influence of the physical properties of the medium on the nature of the flow of the reagents are not considered. By considering these factors we will able to continue the adjustment of operating modes and parameters of DE ensuring the uniformity and width of the AR application to the coating. In addition to the existing model for the movement of the reagent over the disk, it is necessary to develop a mathematical model of the flow of liquid AR in the air, which can be used to create a system for monitoring the distribution process of the AR, analogous to the systems considered in [8–10]. It will be part of a comprehensive automated system for monitoring and managing the distribution of the reagent. The development of information technologies and software systems [11–13] allows to work on the formation of mathematical and software for such technical means. The urgency of the developed model is also in the scientific justification given to it for the choice of location and modes of operation of the DE at various meteorological conditions (wind speed and direction). Judging by the published literature, in this direction such works were not earlier performed. At the moment, hydrodynamic processes active in viscous fluid flows and contact of a single drop with the

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liquid surface are widely studied [14, 15]. The displacement of a liquid in a gaseous medium is considered in [16, 17, 18]. The jet flow from the nozzle is described in detail in [19, 20, 21, 22]. The mentioned studies, which are the closest to the analyzed processes can be used as a basis for the development of models. However, they require the adaptation to the characteristic design features of the distribution equipment and operational factors associated with the operating mode of the DE and the influence of the external environment on the movement of AR drops. Similar research in the field of agricultural machinery was carried out in [23, 24].

2. Methods

2.1. Mathematical model of the motion of a drop of AR on the disk

Since the initial conditions of motion and the medium in which the sputtering take place, and the types of acting forces for each drop from the set that make up the stream (jet) of the reagent are the same, the solution of the problem can be reduced to studying the process of motion by the example of one drop of AR. After this, it is necessary to proceed to a more complex problem of considering the moving flow of the reagent. The obtained data should be used to form the process of distribution of AR in different conditions, with different density of air and reagent, with different parameters of DE to determine the most favorable combination of these conditions, factors and parameters from the viewpoint of the quality of coating treatment.

Let us consider the trajectory of the motion of a drop of liquid AR relative to the surface of an airfield cover to determine the influence of the type and parameters of the distribution equipment, its location and operating modes on it.

The mode of operation determines the rotational speed of the distribution disk and the pressure created by the injectors. The main parameters of the distribution equipment are the diameter of the distribution disk, the radius of its hub, the inclination of the blades (ribs) of the disk and its height above the surface of the coating, the height of the nozzles relative to the plane of the disk.

The study of the displacement of a drop of reagent in the air will allow to determine the methods and ways for improving the quality of the distribution of reagents and accordingly the achieved value of the coefficient of adhesion.

In further calculations, the following assumptions are made as follows:

- the drop has the shape of a sphere;
- physical properties of the air environment: temperature T,^{0}C, a density $\rho_{1,}$ kg/m^3, the coefficient Dynamic Viscosity η, kg/m·s;
- density of the liquid reagent ρ_2 is selected based on of Temperatures The surrounding environment and objectives of ongoing works (prevention or deleting the ice);
- type working equipment – distributing disk diameter d, m;
- reagent is sprayed by built in the blade guard nozzles under pressure P_0 MPa, and then discarded by the shoulder of disk blades;
- blade's angle $\varphi_{0;}$
- the calculation takes into account the friction of the PGR on the surface of the blades, the wind speed and direction, the time of motion, the disk height above the coating;
- angle between the direction of the wind and the axis which the velocity vector of the drop of the AR is projected to varies at bounds from 0^0 to 360^0.

The study should begin with a consideration of a drop of AR moving along the disk with the initial flow rate from the nozzle.

To study the motion of the droplet two coordinate systems will be used – xy, to move the drop along the disk and XYZ-to describe its motion relative to the surface of the coating.

When the droplet moves from the nozzle to the periphery of the disk centrifugal forces act on it, the frictional forces on the blade surface of the disk, and the Coriolis force (Figure 1).

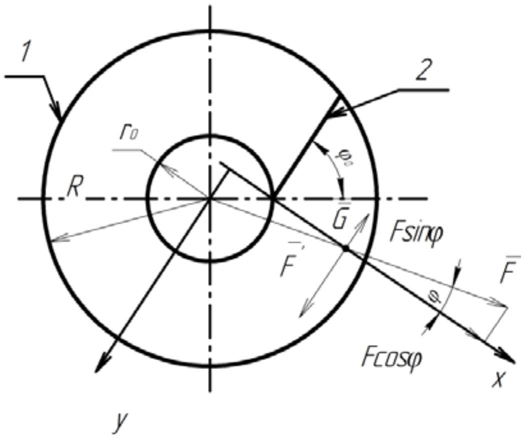

Figure 1. The scheme of the forces acting on a drop of AR on the disk surface

The diagram shows: 1 – distribution disk, 2 – blade (edge) of the disk, R – the radius of the disk, r_0 – radius of the disk hub, φ_0 – tilt angle of disk rib.

The differential equation of motion of a drop of a reagent along with a disk edge located at an angle to the radial position has the form:

$$m\frac{d^2x}{dt^2} = F\cos\varphi(F' - F\sin\varphi)f - G\cdot f,$$

where F is the centrifugal force of inertia, H;

F' is the Coriolis inertia force H;

G is the weight of the drop, H;

f is the friction coefficient of the AR on steel.

In turn, these forces are equal:

$$F = m\cdot r\cdot\omega^2,$$

$$F' = 2m\cdot\omega\frac{dx}{dt},$$

$$G = m\cdot g,$$

where ω is the angular velocity of rotation of the disk;

g – acceleration of gravity, m/s^2.

The solutions of this equation are as follows:

$$x = \frac{K_1 + r_0\cos\varphi_0}{2K}\left((K+f)e^{\omega(K-f)t} + (K-f)e^{-\omega(K-f)t}\right) - K_1,$$

$$K = \sqrt{f^2} + 1,$$

$$K_1 = r_0 \cdot f\cdot \sin\varphi_0 + g\cdot f\frac{1}{\omega^2}.$$

The velocity of the AR drops in the projection onto the x-axis (m/s) can be found by the equation:

$$V_x = \frac{dx}{dt} = \frac{K_1 + r_0\cos\varphi_0}{2K}(K^2 - f^2)\omega(e^{\omega(K-f)t} - e^{-\omega(K-f)t}.$$

The process of motion and the nature of the acting forces are described in detail in [25].

Leaving the nozzle, the flow of liquid formed by individual drops is discarded by the blades of the disk, acquiring additional kinetic energy, and flies off the disk. Then it starts to move in the air.

The velocity of the liquid outflow from the nozzle (the speed of motion in the projection on the y axis) [26, 27]:

$$V_y = \sqrt{\frac{2(P_0+\rho_2 gh)}{\rho_2}},$$

where h is the height of the nozzle relative to the disk, m;

P_0 – AR feed pressure, MPa.

Using the vector addition of velocities, the initial velocity of the droplet is determined at the time of flight from the disk:

$$V = \sqrt{V_x^2 + V_y^2}.$$

According to the XYZ coordinate system, the rotational motion of the disk is portable, and the motion of the AR drop over the disk is a relative motion. Therefore, the droplet velocity at the moment of separation from the disk is calculated according to the classical law of addition of velocities by vector addition of the initial velocity and the linear speed of rotation of the distribution disk:

$$V_1 = \sqrt{V^2 + V_d^2}\ , \qquad (1)$$

where V_d – linear disk rotation speed, m/s.

$$V_d = \omega R,$$

where R is the radius of the disk, m.

Once being left from the distribution disk, the drop in the relation to the coating will have a speed:

$$\overline{V_2} = \overline{V_1} + \overline{V_m}, \qquad (2)$$

where V_m – machine speed.

The velocity values V_2 in the projection on the axis will be the initial conditions for further consideration of the droplet moving in the XYZ coordinate system. The X axis is perpendicular to the machine's axis of motion, the Z axis is parallel to it. The Y axis is parallel to the axis of rotation of the distribution disk.

This analysis is necessary for specifying the initial conditions for the equations of motion of drops of reagent in the air.

2.2. Mathematical model of the motion of a drop of AR in the air

At the time of gathering the disk (Figure 2), and on further movement droplet in air on it are: gravity $\overline{G}$, since there is a drop near the ground, the force of the air resistance of the medium $\overline{F_V}$ [28] and the lift force $\overline{R}$ directed opposite to the force of gravity [29]. In scheme arbitrarily, specified wind speed vector $\overline{V_V}$ acting in the XZ plane and directed at an angle α to the X axis.

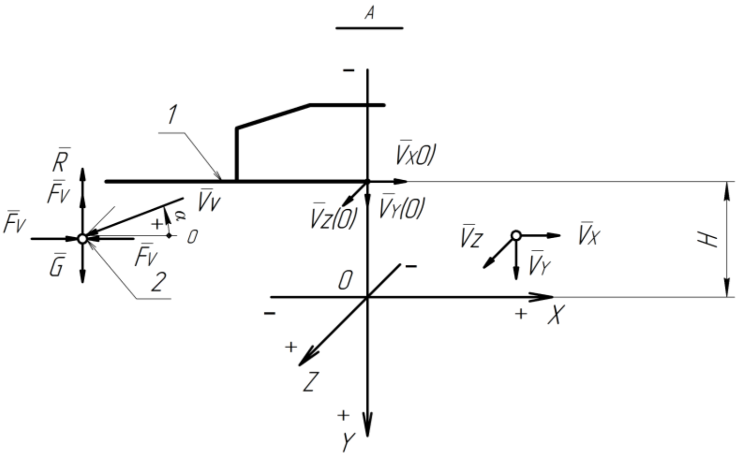

Figure 2. Scheme of the direction of velocity vectors and forces acting on a drop of AR in the process of its movement

In the diagram shown: 1 – the distribution disk 2 – a drop PGR (shown in phantom), $\overline{V_V}$ – wind velocity vector, H – disk height above coated (0), $\overline{V_X}(0)$ – vector initial drop velocity at the time of the gathering from the disk at an angle of 0^0 to the X axis, $\overline{V_Z}(0)$ – initial velocity vector of droplets at the time of a meeting with the disk at an angle of 0^0 to Z axis, $\overline{V_Y}(0)$ – vector initial drop velocity at the time of the gathering from the disk at an angle of 0^0 to Y axis, $\overline{V_X}$,$\overline{V_Y}$,$\overline{V_Z}$ – the vectors drop rate at arbitrary moment of time.

The force of gravity is determined by the formula $G = m \cdot g$, the lifting force, which is a part of the total aerodynamic force is determined by the formula

$$R = \rho_1 \cdot V_k \cdot g,$$

where V_k – drop's amount m^3 ;

ρ_1 is the density of air in kg/m^3.

The strength of the air environment resistance characterizes its viscous properties and is calculated by the formula $F_V = k \cdot v$ [30, 31],

where $v = V_2$ – PRT speed drops when gathering from the disk, m/s;

k is the coefficient of medium resistance, kg/s.

k depends on the dynamic viscosity of the medium and the geometric shape of the body moving inside. For bodies of spherical shape $k = 6\pi \cdot R \cdot \eta$ [32, 33],

where R is the radius of the drop, m;

η is the coefficient of dynamic viscosity of the medium, kg/m·s. This value is a reference and calculated depending on the temperature of the medium [34].

According to Newton's Second Law, the change in the momentum of a body is equal to the sum of the forces acting on it. Then the equation of motion of the drop in the projection onto the Y axis takes the form:

$$m \cdot \overline{a_Y} = m \cdot \bar{g} - \rho_1 \cdot v_k \cdot \bar{g} - k \cdot \bar{v}, \tag{3}$$

where m is the mass of a drop of liquid PGR, kg;

$\overline{a_Y}$ – drop's acceleration, m/s$^{2;}$

ρ_1 is the density of air, kg/m^3.

At the final moment of the considered time interval (when the drop reaches the coating), the value of the Y coordinate must be zero (Figure 2).

At different times, the droplets will leave the disk, flying off from it at some angle β, analogous to the angle of unloading when the solid particles move on the rotating disk [35]. Using this angle and applying the basic theorem of the vector algebra on the decomposition of a vector along an orthogonal basis [36], we can obtain the projections of the initial velocity vector of the drop on the X, Y, Z axis (Figure 3).

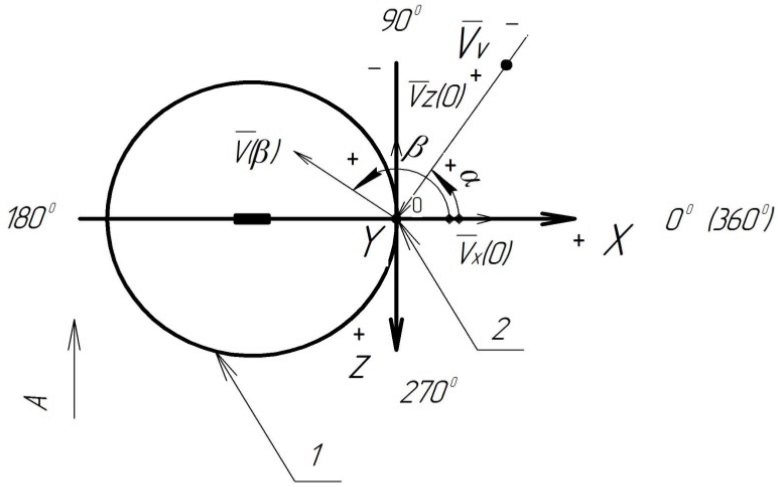

Figure 3. Scheme of the direction of the initial velocity vector of the drop of the PGR at flight from the disk surface

The diagram shows: 1 – the distribution disk, 2 – the drop of the PGR, β – the angle of the drop of the PGR drop from the disk, $\overline{V}(\beta)$ – the vector of the initial velocity of the droplet upon the flight from the disk at the angle, $\overline{V_V}$ – wind velocity vector directed at an angle to the X axis, $\overline{V_X}(0)$ – initial vector of drop's velocity at the time of the gathering from the disc at an angle of 0^0 to the X axis, $\overline{V_Z}(0)$ – initial vector of drop's velocity at the time of gathering from the disc at an angle of 0^0 to the Z axis, $\overline{V_Y}(0)$ – initial vector of drop's velocity at the time of the gathering from the disc at an angle of 0^0 to the axis Y.

The angle β is measured from the X axis in the XZ plane counterclockwise. If we change its value with an arbitrarily chosen step, we obtain the projections of the initial velocity vector V(β) on the X and Z axes. The projection of the vector on the Y axis which lies in the perpendicular plane will be zero.

When studying the drop's behavior in the air traffic, it can be divided into four computational cases:

case I – the angle $\beta = 0^0...90^0$ and $\beta = 270^0…360^0$, II – value of the angle $\beta = 90^0...270^0$, III – the angle $\beta = 0^0...180^0$, IV – the angle $\beta = 180^0...360^0$.

When the angle β is between 0^0 and 360^0 the values of the initial velocity of the reagent droplets in the expansion axis in the chosen coordinate system change and therefore change the value of drop's displacements along the axes X, Y, Z.

The data on these displacements makes it possible to determine the initial and final coordinates of the drop in the XYZ system, visualize the trajectories of the flow of liquid reagents, and calculate the maximum width of the coating strip for the liquid reagent.

In order to take into account the effect of wind on a moving drop, we use the calculation schemes shown in Figures 2 and 3. Figure 2 shows the positions of the reagent drop in the planes XY and ZY, indicating the droplet velocity vectors $\overline{V_X}$ and $\overline{V_Z}$. Let us consider the displacement of a drop relative to the X axis. In this case, there are two possible variants: movement toward the positive direction of the X axis and toward the negative direction. In both cases, the forces of resistance of the air environment are acting. The wind flow, conventionally designated by the vector $\overline{V_V}$ and determined by the strength and direction of the wind, will decrease the velocity of the drop if it moves in the windward zone and increase it if the drop is in the leeward zone [37].

The leeward zone is the zone in which the wind does not exert any influence, that is $\overline{V_V}=0$.

The strength of the air resistance of the medium $F_v = k \cdot V_x$ is directed opposite to the vector of drop's velocity and is effective equally in all directions. Projecting all the forces on the X-axis, we get:

For the first design case:

$$m \cdot \overline{a_x} = k(\overline{V_x} – \overline{V_v}\cos\alpha), \tag{4}$$

For the second design case:

$$m \cdot \overline{a_x} = k(\overline{V_x} \ - \overline{V_v}\cos\alpha) \tag{5}$$

If the drop moves in the leeward zone, the equation of motion takes the form:

$$m \cdot \overline{a_x} = k \cdot \overline{V_x} \tag{6}$$

Similarly, there will be movement in the plane ZY.

A drop from the AR stream can move either in the positive direction along the Z axis (case 3), or in the opposite direction (case IV).

The equation of motion in the projection on the Z axis takes the form:

For the III design case:

$$m \cdot \overline{a_z} = k(\overline{V_z} – \overline{V_v}\sin\alpha), \tag{7}$$

For IV settlement case:

$$m \cdot \overline{a_z} = k(\overline{V_z} – \overline{V_v}\sin\alpha), \tag{8}$$

In the case of movement in the leeward zone:

$$m \cdot \overline{a_z} = k \cdot \overline{V_z}, \tag{9}$$

The obtained equations and dependencies are introduced into the monitoring system software provide an opportunity to accurately estimate the most important quality parameters of the reagent spraying – the width of the processing strip and the uniformity of the AR application under different conditions. If the distributor is equipped with measuring sensors that determine the strength and direction of the wind, as well as the height of the disk above the coating, then by means of the hydraulic drive of the distribution disks, flow regulators and pressure of the reagent feed, it is possible to purposefully change the operating modes and arrangement of the working equipment.

Data on the state of the environment and the performance of the equipment will flow into the control unit of the monitoring system of the reagent dispenser. After their processing and automatic calculations on the above formulas, the system will determine the optimal mode of operation of the equipment (the frequency of disk's rotation, the installation height above the coating, pressure and the value of the AR feed). Data from the sensors will be continuously fed into the control unit in real time. Thus, both external factors related to the environment and internal ones that depend on the working equipment will be considered, and the efficiency and quality of the process of anti-icing processing are ensured.

3. Results and Discussion

1. For the resulting droplet motion equations (3–5, 7, 8), we formulate the initial conditions: the time of motion of the droplet relative to the coating begins in the moment of the droplet's fly off the disk, the maximum time of investigation is the time when the drop reaches the coating. The value of the velocity and acceleration of the drop relative to the Y axis at the initial instant of time is zero. The angle of departure of the β drop from the disk is assumed to be equal zero.

Under the initial conditions for solving the differential equation 3: Y (0) = H, Y '(0) = 0, t the solution of the equation takes the form:

$$Y = \frac{(\mathrm{g}(\mathrm{m} - \rho_1 \cdot \mathrm{v_k}) \cdot (\mathrm{m} - \mathrm{m} \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}} + k \cdot \mathrm{t} \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}}))}{(k^2 \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}})}, \tag{10}$$

$$Y' = \frac{(\mathrm{g}(\mathrm{m} - \rho_1 \cdot \mathrm{v_k}) \cdot (\mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}} - 1))}{(k \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}})}, \tag{11}$$

$$Y'' = \frac{(\mathrm{g}(\mathrm{m} - \rho_1 \cdot \mathrm{V_k}))}{(\mathrm{m} \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}})}, \tag{12}$$

where Y is the coordinate of the drop in the projection onto the Y axis, m. At the initial instant of time t, it is assumed to be equal zero;

Y' is the first derivative of the time coordinate Y, i.e. droplet speed, m/s;

Y'' is the second derivative of the time coordinate Y, i.e. droplet acceleration, m/s^2;

t is the time of motion of the drop, sec;

$\mathrm{V_k}$ is the volume of the drop, m^3.

At the final moment of the considered time interval (when the drop reaches the coating), the value of the Y coordinate must be zero (Figure 2). At the initial moment, Y = H.

2. The solution of the differential equations 4,5 with the initial conditions Vx (0) = V_2cos (0), is the velocity of the drop at the initial instant of time, and X (0) = 0 is the coordinate of the drop along the X axis at the initial instant of time,

$$\mathrm{X} = \frac{(\mathrm{m}(\mathrm{V_v} \cdot \cos\alpha - \mathrm{V_2}))}{k} + \mathrm{V_v} \cdot \mathrm{t} \cdot \cos\alpha - \frac{\left(\mathrm{m} \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}}(\mathrm{V_v} \cdot \cos\alpha - \mathrm{V_2})\right)}{k}, \tag{13}$$

$$\mathrm{X}' = \mathrm{V_v} \cdot \cos\alpha - \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}} (\mathrm{V_v} \cdot \cos\alpha - \mathrm{V_2}), \tag{14}$$

$$\mathrm{X}'' = \frac{-(k \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}}(\mathrm{V_v} \cdot \cos\alpha - \mathrm{V_2}))}{\mathrm{m}}, \tag{15}$$

where X' is the first derivative of the time for X coordinate, i.e. droplet speed, m/s;

X'' is the second derivative of the time for X coordinate, i.e. acceleration of the drop, m/s^2.

3. Under the initial conditions, Vz (0) = -V_2 · sin (0), Z (0) = 0.

The solution of equations 7, 8 takes the form:

$$Z = \frac{(\mathrm{m}(\mathrm{V_v}\sin\alpha - \mathrm{Vz}(0)))}{k} + \mathrm{V_v} \cdot \mathrm{t} \cdot \sin\alpha - \frac{(\mathrm{m} \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}}(\mathrm{V_v}\sin\alpha - \mathrm{V_z}(0)))}{k}, \quad (16)$$

$$Z' = \mathrm{V_v}\sin\alpha - \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}}\left(\mathrm{V_v}\sin\alpha - \mathrm{V_z}(0)\right), \quad (17)$$

$$Z'' = \frac{-(k \cdot \mathrm{e}^{k\cdot \mathrm{t}/\mathrm{m}}(\mathrm{V_v}\sin\alpha - \mathrm{Vz}(0)))}{\mathrm{m}}, \quad (18)$$

where Z' is the first derivative of the time for Z coordinate, i.e. droplet speed, m/s; Z'' is the second derivative of the time for Z coordinate, i.e. acceleration of the drop, m/s^2. These equations are derived and based on similar studies [28, 30, 33].

4. The resulting differential equations (3–9) of the AR droplet motion in the air environment in the projections on the X, Y, Z axes allow us to conclude that the acceleration value with which the PGD droplet moves in the air environment is determined by the values of the viscosity coefficient of the medium, mass droplet, travel time and the speed of the AR drop, wind direction and machine speed (equations 12, 15, 18). This confirms and develops the already available results of the study [38–40], since it provides an opportunity to describe the entire process of droplet's motion, starting to fly off the disk and ending with the reaching the coating.

5. The value of the droplet's velocity of a liquid reagent is determined by the droplet's mass, viscosity, travel time, and the departure angle of the droplet from the disk, and by the direction and force of the wind (11, 14, 17). With the change of wind's speed, the deviation of the trajectory of the PGR drop will be observed, the magnitude and direction of which is affected by the force of the wind and its direction relative to the axis of motion of the machine.

6. When wind influences on the flow of reagents, the deviation of the trajectories of the droplets are moving on different sides relative to the rotation axis of the disk will differ in magnitude (equations 4–9).

7. With increasing the wind's strength, it is necessary to reduce the height of the distribution equipment to maintain the range of the AR drop and the required width of the processed strip.

8. As the altitude of the disk increases, the value of the range of the flight of the AR drop increases and consequently the overlapping areas of the coating treatment areas with the liquid reagent in the case of two disks (equations 3, 10, 13, 16). Related results are described in [41], but with reference to the agricultural engineering.

9. The value of the initial velocity of the AR drop at the time of flight from the distribution disk depends on the exhaust velocity of the AR from the injector, that is, not only on the reagent feed pressure, but also on the height of the spray nozzle relative to the distributing disk (formulas 1, 2).

10. The flight range and the width of the processing strip are determined by such parameters of the environment as:

a) the viscosity of the air;
b) direction and speed of the wind.

4. Conclusion

1. A mathematical model of describing the motion of drops of a liquid reagent in the process of treatment with roadside reagents of road and airfield coatings is developed.

2. An analytical solution of the differential equations of AR droplets moving in the air is obtained.

3. Dependences of the trajectory, speed and acceleration of motion on the parameters of the working equipment (the geometrical dimensions of the distribution disk, the mode of operation of the disk and the spray nozzle) and the characteristics of the external environment (viscosity of the air medium, direction and air flow velocity) are determined.

4. Some factors that will allow to maintain the given range continuously and the uniformity of treatment of coatings with liquid reagents are determined. The developed model is recommended to be used in an automatic monitoring system for the distribution of liquid AR.

5. The system should ensure the continuous collection, processing and analysis of environmental data and the distribution equipment in real time. The obtained information will be used to calculate the effectiveness of the coating application process (i.e, the best combination of range, density and uniformity of the AR feed). In the article, the basis of the mathematical support of the work of this system is proposed.

References

1. Glushko A.N, Chelnokov V.V, Bessarabov A.M. Sistema komp'yuternogo menedzhmenta kachestva dlya otsenki ekologicheskogo vozdeystviya protivogololednykh reagentov na vkhode [Computer quality management system for assessing the environmental impact of anti-ice reagents on the environment]. *Mathematical methods in engineering and technology - MMTT.* 2016. No. 10(92). Pp. 176–177. (rus)
2. Vasilyev R.Yu. Protivogololednoye i meteorologicheskoye obespecheniye zimnego soderzhaniya avtomobil'nykh dorog [Anti-ice and meteorological support of winter maintenance of highways]. *Transport and transport-technological systems.* 2017. Pp. 83–86. (rus)
3. Lemchuzhnikov V.E., Masyagin A.V., Novikov V.A., Filatov Yu.V. Mashina dorozhnaya s raspredelitelem protivogololednykh materialov, avtomaticheskim upravleniyem i kontrolem tekhnologicheskogo protsessa, s privodom transportera ot planetarnogo gidromotora, osnashchennogo preobrazovatelem okruzhnoy skorosti gidromotora v chastotu [Road machine with a distributor of de-icing materials, automatic control and monitoring of the technological process, with the drive of the conveyor from the planetary hydraulic motor equipped with a converter of the circumferential speed of the motor to the frequency]. *Patent Russia no. 22263739*, 2005. (rus)
4. Sistema upravleniya mobil'nym raspredelitelem protivogololednykh materialov [Mobile dispenser control system for de-icing materials][Electronic resource] URL: http://russianpatents.com/patent/239/2398929.html (reference date: July 14, 2017). (rus)
5. Belotserkovsky G.M., Ahrameev E.V., Karjakin S.B. Sposob obespecheniya raboty sistem yupravleniya rabochim protsessom mobil'nogo raspredelitelya materialov dlya obrabotki dorozhnykh pokrytiyi ustroystvo upravleniya rabochim protsessom mobil'nogo raspredelitelya materialov [A way to ensure the operation of the workflow control system of a mobile material distributor for the treatment of road surfaces and the device for controlling the workflow of a mobile material distributor]. *Patent Russia no. 2398929*, 2013. (rus)
6. Lukanov N.I. Ustroystvo avtomaticheskogo dozirovaniya khimicheskikh reagentov pri nanesenii ikh na poverkhnost' iskusstvennogo pokrytiya [The device of automatic dosing of chemical reagents when applied to the surface of an artificial coating]. *Patent Russia no. 2487971*, 2013. (rus)
7. *Avtomatizirovannaya sistema upravleniya kommunal'noy dorozhnoy mashinoy. Raspredeleniye zhidkikh protivogololednykh reagentov* [Automated control system for a public road vehicle. Distribution of liquid anti-ice reagents] [Electronic resource]. URL: www.kbkoloss.ru/products/avtomatika-dlya-kommunalnoy-dorozhnoy-mashiny/avtomatika-dlya-peskorazbrasyvatelya-asu2c (reference date: July 19, 2017). (rus)
8. Mandrovskiy K.P. Sistemy upravleniya v upravlenii effektivnost'yu i tekhnicheskim audite dorozhnykh mashin [Control systems in efficiency management and technical audit of road machines]. *Tekhnicheskiyenauki v Rossiiizarubezhom. Materialy V Mezhdunarodnaya konferentsiya konferentsii.* Brynsk. 2016. Pp. 75–78.(rus)
9. Mandrovskiy K.P. Sistemy monitoringa dorozhno-stroitel'nykh, transportnykh mashin i dorozhnykh pokrytiy

Литература

1. Глушко А.Н., Челноков В.В., Бессарабов А.М. Система компьютерного менеджмента качества для оценки экологического воздействия противогололедных реагентов на окружающую среду // Математические методы в технике и технологиях – ММТТ. 2016. № 10 (92). С. 176–177.
2. Васильев Р.Ю. Противогололёдное и метеорологическое обеспечение зимнего содержания автомобильных дорог // Транспортные и транспортно-технологические системы. 2017. С. 83–86.
3. Патент РФ № 22263739, 10.11.2005. Машина дорожная с распределителем противогололедных материалов, автоматическим управлением и контролем технологического процесса, с приводом транспортера от планетарного гидромотора, оснащенного преобразователем окружной скорости гидромотора в частоту / Лемчужников В.Е., Масягин А.В., Новиков В.А., Филатов Ю.В. // Патент России № 2263739. 2003. Бюл. № 31.
4. Система управления мобильным распределителем противогололедных материалов [Электронный ресурс] URL: http://russianpatents.com/patent/239/2398929.html (дата обращения: 14.07.2017).
5. Патент РФ № 2398929, 20.07.2013. Способ обеспечения работы системы управления рабочим процессом мобильного распределителя материалов для обработки дорожных покрытий и устройство управления рабочим процессом мобильного распределителя материалов / Белоцерковский Г.М., Ахрамеев Э.В., Карякин С.Б. // Патент России № 2398929. 2009. Бюл. № 25.
6. Патент РФ № 2487971, 20.07.2013. Устройство автоматического дозирования химических реагентов при нанесении их на поверхность искусственного покрытия / Луканов Н.И. // Патент России № 2487971. 2012. Бюл. № 20.
7. Автоматизированная система управления коммунальной дорожной машиной. Распределение жидких противогололедных реагентов [Электронный ресурс]. URL: www.kbkoloss.ru/products/avtomatika-dlya-kommunalnoy-dorozhnoy-mashiny/avtomatika-dlya-peskorazbrasyvatelya-asu2c (дата обращения: 19.07.2017).
8. Мандровский К.П. Системы мониторинга в управлении эффективностью и техническом аудите дорожных машин // Технические науки в России и за рубежом. Материалы V Международной научной конференции. 2016. С. 75–78.
9. Мандровский К.П. Системы мониторинга дорожно-строительных, транспортных машин и дорожных покрытий // ИНТЕРСТРОЙМЕХ – 2015.Материалы международной научно-технической конференции. 2015. С. 310–315.
10. Мандровский К.П. Оценка динамической устойчивости в мониторинговой системе управления технико-экономической эффективностью дорожных машин // Вестник Донского государственного технического университета. 2016. Т. 16. № 2(85). С. 69–76.
11. Kulkarni A., Mohsenin T., Pino Y., French M. Real-time anomaly detection framework for many-core router through

[Monitoring systems in the sphere of road construction, transportation and road surfaces]. *INTERSTROYMEKH - 2015. Materialy mezhdunarodnoy nauchno-tekhnicheskoy konferentsii.* Kazan. 2015. Pp. 310–315.(rus)

10. Mandrovskiy K.P. Otsenka dinamicheskoy ustoychivosti v monitoringovoy sisteme upravleniya tekhniko-ekonomicheskoy effektivnost'yu dorozhnykh mashin [Evaluation of dynamic stability in the monitoring system of management of technical and economic efficiency of road vehicles]. *Vestnik Donskogo gosudarstvennogo tekhnicheskogo universiteta.* 2016. Vol. 16. No. 2(85). Pp. 69–76.(rus)
11. Kulkarni A., Mohsenin T., Pino Y., French M. Real-time anomaly detection framework for many-core router through machine-learning techniques. *ACM Journal on Emerging Technologies in Computing Systems.* 2016. Vol. 13. Pp. 10.
12. Öörni R., Meilikhov E., Korhonen T.O. Interoperability of ecall and era-glonass in-vehicle emergency call systems. *IET Intelligent Transport Systems.* 2015. Vol. 9 No. 6. Pp. 582–590.
13. Lara-Molina F.A., Rosário J.M., Dumur D., Wenger P. Robust, generalized predictive control of the orthoglide robot. *Industrial Robot.* 2014. Vol. 41.No. 3. Pp. 275–285.
14. Ye Y., Li G. Modeling of hydrodynamic cavitating flows considering the bubble-bubble interaction. *International Journal of Multiphase Flow.* 2016. Vol. 84. Pp. 155–164.
15. Ilyinikh A.Yu., Chashechkin Yu.D. Gidrodinamika kontakta padayushchey kapli so svobodnoy poverkhnost'yu zhidkosti [Hydrodynamics of contact of a falling drop with a free surface of a liquid]. *Izvestiya Rossiiskoi Akademii Nauk. Mekhanikazhidkosti i gaza.* 2016. No. 2. Pp. 3–12. (rus)
16. Ibrahim A., Girimaji S.S., Suman S. On air-chemistry reduction for hypersonic external flow applications. International Journal of Heat and Fluid Flow. 2015. Vol. 51. Pp. 298–308.
17. Kim M.-K., Song J., Hwang J., Yoon Y. Effects of canted injection angles on the spray characteristics of liquid jets in subsonic crossflows. Atomization and Sprays. 2010. Vol. 20. No. 9. Pp. 749–762.
18. Eggers J., Villermaux E. Physics of liquid jets. Reports on Progress in Physics. 2008. Vol. 71. No. 036601. Pp. 1–79.
19. Salehi-Shabestari A., Raisee M., Sadeghy K., Ahmadpour A.Flow and displacement of waxy crude oils in a homogenous porous medium: a numerical study. Journal of Non-newtonian Fluid Mechanics. 2016. Vol. 235. Pp. 47–63.
20. Dumouchel C. The experimental investigation on primary atomization of liquid streams. Experiment in Fluid. 2008. Vol. 45. Pp. 371–422.
21. Santangelo P.E. Characterization of high-pressure water-mist sprays: Experimental analysis of droplet size and dispersion. Experimental Thermal and Fluid Science. 2010. Vol. 34. Pp. 1353–1366.
22. Er D.Z., Liew C.V., Heng P.W. Layered growth with bottom-spray granulation for spray deposition of drug. *International Journal of Pharmaceutics.* 2009. No. 377. Pp. 16–24.
23. Onishchenko V.B., Lyubchenko I.S. Review of theoretical studies of process of liquid mineralfertilizers. Науковий Вісник Нубіп України. Серія: Техніка Та Енергетика АПК. 2016. No. 251. Pp. 26.
24. Polishchuk V.N. Irregular movement air-mix for fluids in dispensing system sprayers. Sworldjournal. 2016. Vol. 1110. No. 11. Pp. 221–224.
25. Balovnev V.I. *Mashiny dlya obsluzhivaniya i remonta gorodskikh i avtomobil'nykh dorog* [Machines for maintenance and repair of urban and highways]. Moscow–Omsk: OMSK HOUSE OF PRESS, 2005. 768 p.(rus)
26. Bondarev A., Galaktionov V. Sovremennyye napravleniya razvitiya vizualizatsii dannykh v vychislitel'noy mekhanike

machine-learning techniques // ACM Journal on Emerging Technologies in Computing Systems. 2016. Vol. 13. Pp. 10.

12. Öörni R., Meilikhov E., Korhonen T.O. Interoperability of ecall and era-glonass in-vehicle emergency call systems // IET Intelligent Transport Systems. 2015. Vol. 9 № 6. Pp. 582–590.
13. Lara-Molina F.A., Rosário J.M., Dumur D., Wenger P. Robust generalized predictive control of the orthoglide robot // Industrialrobot. 2014. Vol. 41. № 3. Pp. 275–285.
14. Ye Y., Li G. Modeling of hydrodynamic cavitating flows considering the bubble-bubble interaction // International journal of multiphase flow. 2016. Vol. 84. Pp. 155–164.
15. Ильиных А.Ю., Чашечкин Ю.Д. Гидродинамика контакта падающей капли со свободной поверхностью жидкости // Известия Российской академии наук. Механика жидкости и газа. 2016. № 2. С. 3–12.
16. Ibrahim A., Girimaji S.S., Suman S. On air-chemistry reduction for hypersonic external flow applications // International journal of heat and fluid flow. 2015. Vol. 51. Pp. 298–308.
17. Kim M.-K., Song J., Hwang J., Yoon Y. Effects of canted injection angles on the spray characteristics of liquid jets in subsonic crossflows // Atomization and sprays. 2010. Vol. 20. № 9. Pp. 749–762.
18. Eggers J., Villermaux E. Physics of liquid jets // Reports on progress in physics. 2008. Vol. 71. № 036601. Pp. 1–79.
19. Salehi-Shabestari A., Raisee M., Sadeghy K., Ahmadpour A.Flow and displacement of waxy crude oils in a homogenous porous medium: a numerical study // Journal of non-newtonian fluid mechanics. 2016. Vol. 235. Pp. 47–63.
20. Dumouchel C. The experimental investigation on primary atomization of liquid streams // Experiment in fluid. 2008. Vol. 45. Pp. 371–422.
21. Santangelo P.E. Characterization of high-pressure water-mist sprays: Experimental analysis of droplet size and dispersion // Experimental thermal and fluid science. 2010. Vol. 34. Pp. 1353–1366.
22. Er D.Z., Liew C.V., Heng P.W. Layered growth with bottom-spray granulation for spray deposition of drug // International Journal of Pharmaceutics. 2009. № 377. Pp. 16–24.
23. Onishchenko V.B., Lyubchenko I.S. Review of theoretical studies of process of liquid mineralfertilizers // Науковий вісник нубіпукраїни. Серія: техніка та енергетика АПК. 2016. № 251. С. 26.
24. Polishchuk V.N. Irregular movement air-mix for fluids in dispensing system sprayers // SWORLDJOURNAL. 2016. Vol. 1110. № 11. Pp. 221–224.
25. Баловнев В.И. Машины для содержания и ремонта городских и автомобильных дорог. М. - Омск: ОМСКИЙ ДОМ ПЕЧАТИ, 2005. 768 с.
26. Бондарев А., Галактионов В. Современные направления развития визуализации данных в вычислительной механике жидкости и газа // Научная визуализация. 2013. Т. 5. № 4. С. 18–30.
27. Вараксин А.Ю. Гидрогазодинамика и теплофизика двухфазных потоков:проблемы и достижения (обзор) // Теплофизика высоких температур. 2013. Т. 51. № 3. С. 377–407.
28. Шварц К.Г., Шварц Ю.А., Шкляев В.А. Двумерная модель мезомасштабных процессов в нижнем слое атмосферы с учетом неоднородности температуры и влажности воздуха // Вычислительная механика сплошных сред. 2015. Т. 8. № 1. С. 5–15.
29. Kalnay E. Atmospheric modeling, data assimilation and predictability. Cambridge University Press. 2003. Pp. 369
30. Гуськов О.Б. О вращении сферического тела в вязкой суспензии // Физико-химическая кинетика в газовой

zhidkost i igaza [Current trends in the development of data visualization in the computational mechanics of fluid and gas]. *Scientific visualization.* 2013. Vol. 5. No. 4. Pp. 18–30. (rus)

27. Varaksin A.Yu. Gidrogazodinamika i teplofizika dvukhfaznykh potokov:problemy i dostizheniya (obzor)[Hydrodynamics and thermophysics of two-phase flows: problems and achievements (review)]. *Thermophysics of high temperatures*. 2013. Vol. 51. No. 3. Pp. 377–407. (rus)
28. Shvarts K.G., Shvarts Yu.A., Shklyaev V.A. Two-dimensional model of mesoscale processes in the lower atmosphere with allowance for the inhomogeneity of air temperature and humidity. *Computational Mechanics of Continuous Media.* 2015. Vol. 8. No. 1. Pp. 5–15.
29. Kalnay E. *Atmospheric modeling, data assimilation and predictability.* Cambridge University Press. 2003. 369 p.
30. Guskov O.B. O vrashchenii sfericheskogo tela v vyazkoy suspenzii [On the rotation of a spherical body in a viscous suspension]. *Fiziko-khimicheskayakinetika v gazovoydinamike.* 2015. Vol. 16. No. 2. Pp. 7.(rus)
31. Kartushinsky A.I., Mihaelides E.E., Rudy Yu.A., Tisler S.V., Scheglov I.N. Chislennoye modelirovaniye dvumernoy vertikal'noy dvukhfaznoy strui [Numerical simulation of a two-dimensional vertical two-phase jet]. *Izvestiya Rossiiskoi Akademii Nauk. Mechanics of fluid and gas.* 2012. No. 6. Pp. 99–108.(rus)
32. Goncharova O.N. Konvektivnoye dvizheniye zhidkostey pod deystviyem soputstvuyushchikh gazovykh potokov: matematicheskoyemodelirovaniye, chislennyyeissledovaniya [Convective motion of liquids under the action of concomitant gas flows: mathematical modeling, numerical research]. *Omsk Scientific Herald.* 2013. No. 1(117). Pp. 21–24.(rus)
33. Yushkov V.P. Energiyai dissipatsiya turbulentnykh kolebaniy skorosti i temperatury vetra v pogranichnom sloye atmosfery [Energy and dissipation of turbulent fluctuations in wind speed and temperature in the boundary layer of the atmosphere]. *Bulletin of Moscow University*. Series 3: Physics. Astronomy. Moscow. No. 3. Pp. 100–109.(rus)
34. Mukhtorov L.T., Abdumannonov A.A. Opredeleniye koeffitsiyenta vyazkosti sredy metodomkom p'yuternogo modelirovaniya [Determination of the viscosity coefficient of the medium by the method of computer simulation]. *Bulletin of the Tajik National University. Series of Natural Sciences.* 2016. No. 1-2(196). Pp. 121–127.(rus)
35. Zemdikhanov M.M. Gabdullin T.R. Obosnovaniye skhemyi parametrovt sentrobezhnogo razbrasyvatelya peska i reagentov [Justification of the scheme and parameters of the centrifugal sand spreader and reagents]. *Izvestiya KGASU.* 2014. No. 4(30). Pp. 484–489.(rus)
36. Qin Z., Buehler M.J. Computational and theoretikal modeling of intermediate filament networks: structure, mechanics and disease. *Acta Mechanica Sinica.* 2012. Vol. 28. No. 4. Pp. 941–950.
37. Simio E., Scanlan R.H. Wind Effects on Structures: An Introductinon to Wind Engineering. By John Wiley &Sons, Inc.1978. 360 p.
38. Bogdanov V.S, Logachev I.N., Dmitrienko V.G., Zhidkov V.V. Zakonomernosti segregatsii chastits navrashchayushchemsya diske klassifikatora tsentrobezhnogo tipa [Patterns of segregation of particles on a rotary disc of a centrifugal classifier]. *Vestnik Belgorod Technological University V.G. Shukhov.* 2012. No. 1. Pp. 73–78. (rus)
39. Vinogradov A.G. Vrauvannya aeroodinamichnogo koefitsynta matematicheskuyu moduluvanni ruhu krapel voda v pavitriю *News of the National Technical University of Ukraine "Kyiv Polytechnic Institute*". 2011. No. 63. Pp. 264–267.
40. Pshennikova G.V, Mitrakov M.V, Khripin V.A. Vneseniy

динамике. 2015. Т. 16. № 2. С. 7

31. Картушинский А.И., Михаелидес Э.Э., Руди Ю.А., Тислер С.В., Щеглов И.Н. Численное моделирование двумерной вертикальной двухфазной струи // Известия Российской академии наук. Механика жидкости и газа. 2012. № 6. С. 99–108.
32. Гончарова О.Н. Конвективные движения жидкостей под действием сопутствующих потоков газа: математическое моделирование, численные исследования // Омский Научный Вестник. 2013. № 1(117). С. 21–24.
33. Юшков В.П., Энергия и диссипация турбулентных флуктуаций скорости ветра и температуры в пограничном слое атмосферы // Вестник Московского Университета. Серия 3: Физика. Астрономия.2011. № 3. С.100–109.
34. Мухторов Л.Т., Абдуманнонов А.А. Определение коэффициента вязкости среды методом компьютерного моделирования // Вестник Таджикского Национального Университета. Серия Естественных Наук. 2016. № 1–2(196). С. 121–127.
35.Земдиханов М.М., Габдуллин Т.Р. Обоснование схемы и параметров центробежного разбрасывателя песка и реагентов // Известия КГАСУ. 2014. № 4(30). С. 484–489.
36. Qin Z., Buehler M.J. Computational and theoretikal modeling of intermediate filament networks: structure, mechanics and disease // Acta Mechanica Sinica. 2012. Vol. 28. No. 4. Pp. 941–950.
37. Simio E., Scanlan R.H. Wind Effects on Structures: An Introductinon to Wind Engineering.By John Wiley &Sons, Inc, 1978. 360 p.
38. Богданов В.С., Логачев И.Н., Дмитриенко В.Г., Жидков В.В. Закономерности сегрегации частиц на вращающемся диске классификатора центробежного типа // Вестник Белгородского технологического университета им. В.Г. Шухова. 2012. № 1. С. 73–78.
39. Виноградов А.Г. Врахування аеродинамічного коефіцієнта при математичному моделюванні рухукрапель води в повітрі // Вісник Національного технічного університету України «Київський політехнічний інститут». Серія Машинобудування. 2011. № 63. С. 264–267.
40. Пшенникова Г.В., Митраков М.В., Хрипин В.А. Внесение минеральных удобрений центробежными разбрасывателями// Проблемы механизации агрохимического обеспечения сельского хозяйства. 2010. № 2010. С. 68–71.
41. Подшиваленко И.Л., Кузюр В.М.Обоснование рабочей ширины захвата штанги машины для внесения жидких органических удобрений // Конструирование, использование и надежность машин сельскохозяйственного назначения. 2013. № 1(12). С. 18–23.

emineral'nykh udobreniy tsentrobezhnymi razbrasyvatelyami [Introduction of mineral fertilizers by centrifugal spreaders]. *Problems of Mechanization of Agrochemical Provision of Agriculture.* 2010. No. 2010. Pp. 68–71. (rus)

41. Podshivalenko I.L., Kuzyur V.M. Obosnovaniye rabochey shiriny zakhvata shtangi mashiny dlya vneseniya zhidkikh organicheskikh udobreniy [Justification of the working width of the rod of the machine for introducing liquid organic fertilizers]. *Designing, Use and Reliability of Agricultural Machines.* 2013. No. 1(12). Pp. 18–23. (rus)

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