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Man-made pollution of the environment with coal dust as a result of operation and closure of coal mines

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Abstract. The technological processes of coal mining, enrichment and use, in particular coal combusting is accompanied by formation and release of significant amounts of dust and gases. Atmospheric air protection is one of the most urgent problems of the nowadays technological society, as scientific and technological progress and expansion of production is associated with an increase in negative anthropogenic impacts on the atmosphere. The paper presents a new solution to the current scientific problem of reducing carbon-containing dust content based on the disclosure of the laws of the aerodynamic interaction of dust and water flows in gravitational and electrostatic fields. The authors show in this study the causes of atmosphere pollution with coal-containing dust; main issues of atmospheric air protection at enterprises located in the controlled territory of Ukraine. The data of the first quarter of the 2020 year are presented in the research. The biggest part of the facilities that pollute the atmospheric air are focused in Donetsk and Lugansk regions. It is estimated that the air environment of the underground mine surface complex is filled with exhaust ventilation air of approximately 200.000 m^3 per minute with a dust concentration of approximately (5-7) mg / m^3, which is equal to 1.5 tons of dust per a day. It is here that the possibility of transporting pollutants over long distances is most often realized. Coarse dust discharged through the ventilation systems of mines is intensively deposited in the sanitary protection zones of mines. Fine dust is carried by the wind outside them, polluting the environment on the distance of up to 3500 m from the coal mine. Emissions of carbon dust into the atmosphere are almost always a major part of transboundary environmental pollution. Mine waste also poses an environmental threat. Technologies of reduction air pollution at the source of carbon-containing dust formation should be used in all new industries of economy. The results obtained reveal the mechanism of interaction of the sprayed liquid with coal dust and can be used in the development of new effective means of controlling the carbon-containing dust. The principles and practices of sustainable development, coupled with local research, will help to contain or eliminate health and environmental risks resulting from air pollution by carbon-containing dust.

Keywords: *air pollution, carbon-containing dust, environment, cardiovascular diseases, respiratory tract diseases, human health, dust prevention and control, dust reduction*

Техногенне забруднення довкілля вугільним пилом внаслідок функціонування і закриття вугільних шахт

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Анотація. Технологічні процеси вуглевидобутку, збагачення та використання, зокрема, спалювання вугілля, супроводжуються утворенням і виділенням значної кількості пилу і газів. Захист атмосферного повітря є однією з найактуальніших проблем сучасного технологічного суспільства, оскільки науково-технічний прогрес та розширення виробництва пов'язані зі збільшенням негативного антропогенного впливу на атмосферу. У статті представлено нове рішення актуальної наукової проблеми зменшення вмісту пилу, що містить вуглець, на основі розкриття законів аеродинамічної взаємодії потоків пилу та води в гравітаційному та електростатичному полях. В роботі наведено основні причини забруднення атмосфери вугільним пилом, основні проблеми охорони атмосферного повітря на підприємствах, які розташовані на підконтрольній території України. В роботі представлені дані за 1 квартал 2020 року. Левова частка підприємств-забруднювачів зосереджена у Донецькій та Луганській областях. За підрахунками встановлено, що повітряне середовище підземного шахтного поверхневого комплексу заповнюється витяжним вентиляційним повітрям, близько 200000 м^3 за хвилину з концентрацією пилу (5-7) мг/м^3, що дорівнює 1,5 т пилу на добу. Саме тут найчастіше реалізується можливість транспортування забруднювальних речовин на великі відстані. Грубий пил, що скидається через вентиляційні системи шахт, інтенсивно осідає в санітарно-захисних зонах шахт. Дрібний пил розноситься вітром поза ними, забруднюючи довкілля на відстані до 3500 м від вугільної шахти. Викиди вуглецевого пилу в атмосферу майже завжди є основною частиною транскордонного забруднення навколишнього середовища. Технології зменшення забруднення атмосферного повітря у джерелі вуглевмісного пилоутворення повинні використовуватися у всіх нових галузях промисловості. Отримані результати розкривають механізм взаємодії напилюваної рідини з вугільним пилом і можуть бути використані при розробці нових ефективних засобів боротьби з вуглевмісним пилом. Принципи та практики сталого розвитку в поєднанні з місцевими дослідженнями допоможуть стримати або усунути ризики для здоров'я та навколишнього середовища внаслідок забруднення атмосферного повітря пилом, що містить вуглець.

Ключові слова: забруднення повітря, пил, що містить вуглець, навколишнє середовище, серцево-судинні захворювання, хвороби дихальних шляхів, здоров'я людини, запобігання та контроль пилу, зменшення пилу

Statement of the Problem. The coal industry is a fundamental branch of Ukrainian economy. It is marked by quite complicated technological process, which essentially affect the environment.

The coal mining and coal processing entities are located in various regions of Ukraine. Because of the coal deposits they are located uneven, sometimes there is an excessive concentration of the coal facilities in particular regions.

The production activity in coal mining industry is accompanied by involving new deposits with sometimes-complicated hydrogeological conditions. All the aforementioned features with high concentration of coal mining and coal processing facilities define a continued man-made impact on state change and properties in particular of geological component and the environment in general. Such influence does not concern some production areas, but only overall in the production regions (Lysychenko, 2008).

The technological processes of coal mining, enrichment and use, in particular coal combusting is accompanied by formation and release of significant amounts of dust and gases. This leads the local atmosphere pollution and global negative influence, such as greenhouse effect, ozone depletion, oxidation of sediments, etc. The coal entities emission lots of dust, greenhouse gases (carbon monoxide CO, carbon dioxide CO_2, methane CH_4 and partially nitrogen dioxide NO_2) and acid gases (sulfur dioxide SO_2 and nitrogen oxides NO_x). The main sources of atmosphere pollution in coal industry are mines, enrichment factories, boiler rooms, fuel- combustion power plants, combustion waste dumps, etc. (Rudko, 2016).

The state of the atmosphere in Ukraine is defined as insufficient, in some regions e.g. Donetsk, Kharkiv, Dnipropetrivsk is extremely dangerous. According to statistic the main pollution sources for atmosphere are enterprises of the fuel and energy sector −36% of the total emissions, production companies − 35% and mining companies −25%. The main pollutants are oxides of carbon, nitrogen, sulfur dioxide, ammonia, phenols, formaldehyde, benzopyrene (Kuzin, 2010).

The polluted atmosphere has no boundaries, that is why this problem concerns not only the local inhabitants, but also city, region and even country.

Causes of air pollution:

emissions of toxic substances by industrial enterprises (cities Mariupol and Horlivka, Donetsk region – are so called "leaders" of Ukraine by the content of harmful substances in the air: formaldehyde, nitrogen dioxide, phenol, benz(a)pyrene, hydrogen fluoride, carbon monoxide, suspended solids);

greenhouse gas emissions and particulate emissions (soot) from chimneys;

evaporation of volatile toxic substances from settling tanks;

dust pollution (blowing of toxic substances from ash, slag and sludge dumps, heaps);

air pollution by emissions from stationary and mobile sources (ash from fuel-combustion power plants, formaldehyde, nitrogen dioxide, etc.) taking into account the falling of industrial production;

catastrophic situation with gassiness of cities, where technological equipment has not been updated for a long period (the number of equipment with a service life of 40 years or more exceeds 70%);

air pollution due to the activities of oil and gas companies and during the gas combustion in flares;

transboundary transportation of air pollutants into border areas (almost uncontrolled process due to the lack of sufficient number of mobile and stationary observation points).

The main part of sulfur dioxide (70%), nitrogen oxides (56%) and dust (52%) were released into the atmosphere by enterprises producing electricity, gas and water; hydrocarbons and volatile organic compounds (74%) − mining industry; carbon monoxide (70%) − manufacturing enterprises production companies (Lunova, 2018, 2019, 2020, Yermakov, 2000, 2019, Ulytskyi, 2019).

Although the pollutant emissions volumes have decreased recently, primarily due to the shutdown of many enterprises, in some industrial regions (especially in Donetsk-Prydniprovskyi region) they still significantly exceed the maximum allowable norms.

The particular concern is about more than a thousand harmful chemical companies, most of which are located in Donetsk and Luhansk regions. Over the last 10 years, the number of children born here with disabilities has doubled. The poor state of the atmosphere is in the entire Donetsk-Dnieper region, also in Cherkasy, Kyiv and Odessa.

Due to the environmental pollution by the exhaust gases of internal combustion engines with harmful substances, entire regions, especially large cities, become a zone of ecological disaster for the population. The problem of harmful emissions from mobile emission sources is becoming more acute due to the continuous increase of the operated vehicles fleet, the consolidation of traffic network.

The main problems of air protection:

actual emissions of harmful substances into the atmosphere by technological cycles, entities of the mine complex and enterprises in general, performing their quantitative and qualitative assessment;

identification of priority areas for comprehensive work to reduce the harmful emissions;

introduction of new technologies to use the mine gas, degassing and ventilation systems.

intensification of works on reformation, extinguishing and reclamation of waste dumps;

creation of a monitoring system.

The main priorities in the field of air protection

implementation of EU standards and their adaptation to the regulatory system of Ukraine in the field of air quality;

reduction of the harmful effects of air pollution sources;

intensification of the state supervision to comply with the environmental protection legislation during the operation, construction of new and reconstruction of existing industrial enterprises and other facilities;

improvement of ventilation system, purification of indoor air conditioning systems;

improvement of air quality and air quality control in residential and public premises;

improvement of economic methods of air quality management.

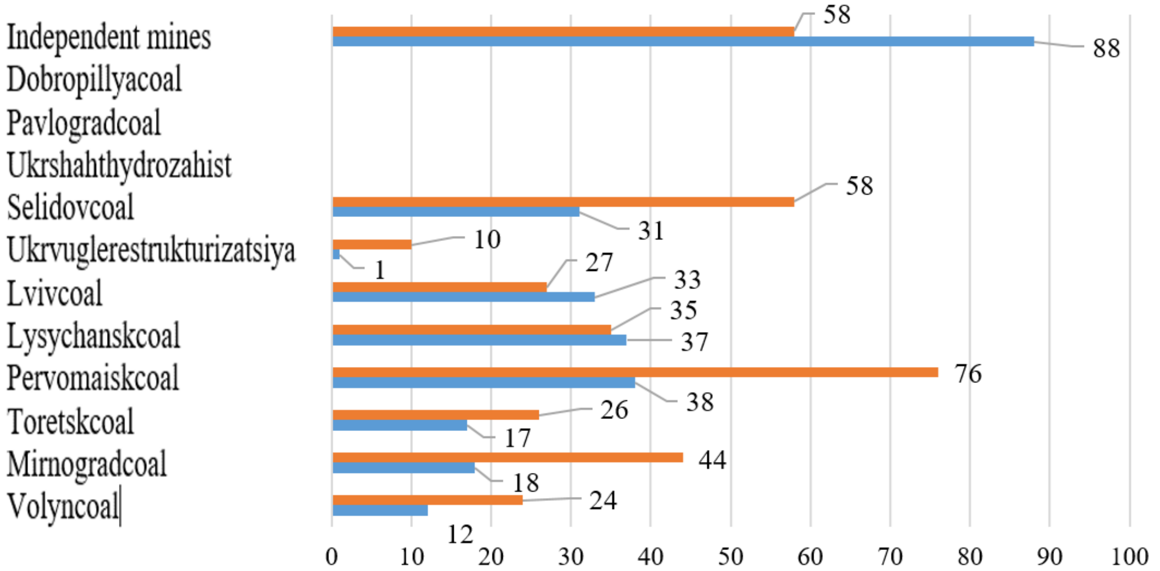

Fig.1. Distribution of organized and unorganized sources of dust pollutants emissions by coal mining enterprises for the first half of 2020 (units)

Number of unorganized emission sources

Number of organized emission sources

At all enterprises located in the controlled territory of Ukraine, for the 1st quarter of 2020 there are 633 sources of pollutant emissions, 314 of which are organized and 358 - unorganized sources of emissions (Fig. 1). The biggest share of the polluting enterprises is concentrated in Donetsk and Luhansk regions (Bondar, 2020, Yermakov, 2020, Lunova, 2020).

As it can be seen from the Fig. 1, the largest number of emission sources are in the independent mines and SE "Pervomaiskcoal" − 146 and 114 units, respectively. During the first half of 2020, the coal industry enterprises released 93023.92 tons of pollutants into the atmosphere, 85118.05 tons of which are from organized and 7906.08 tons − from unorganized sources of emissions. The largest amount of pollutants − 46340.38 tons were produced by Lvivcoal in the first half of 2020. A significant amount of pollutants was produced by independent mines and SE "Mirnogradcoal", 22747.56 and 13364.80 tons, respectively. The lowest amount of pollutants in

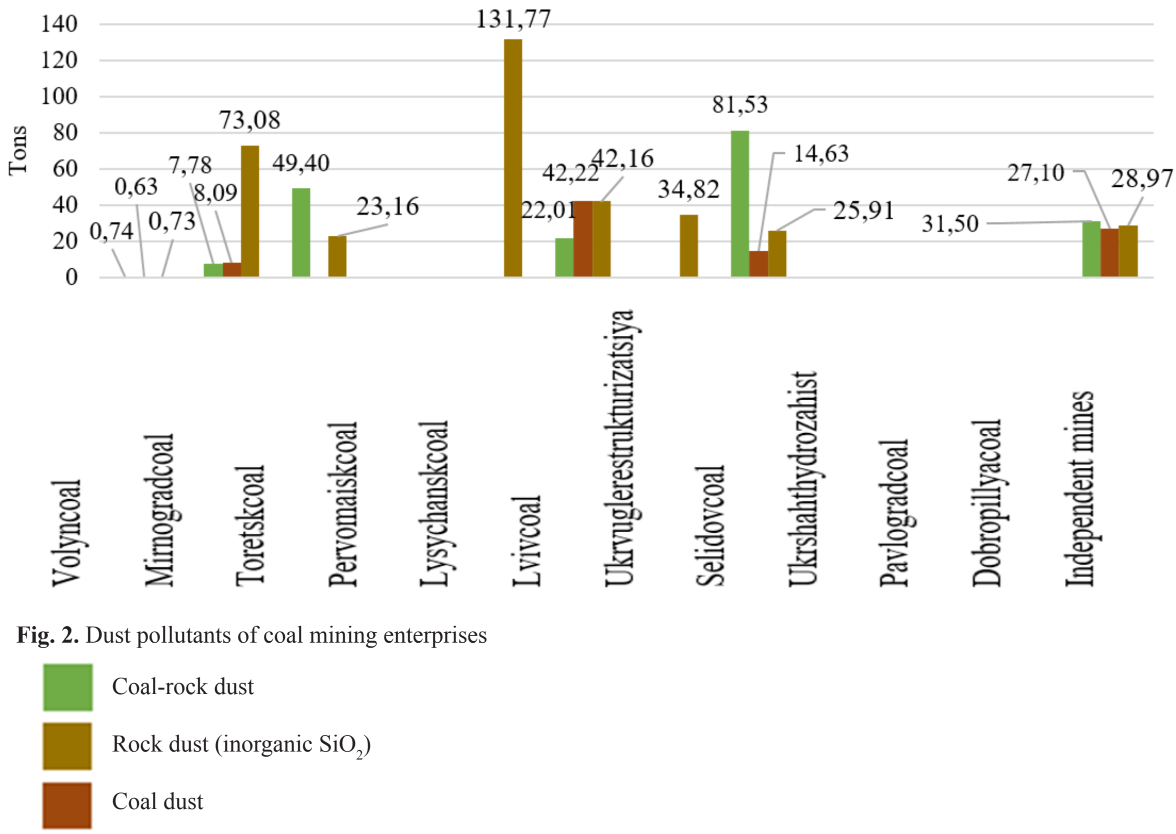

Fig. 2. Dust pollutants of coal mining enterprises

2020 was emitted by SE "Volyncoal" − 12.20 tons. Emissions of coal mining enterprises are shown in the Fig. 2. PJSC "Lysychanskcoal" emits the most solid pollutants − 1137.87 tons, and the least - SE "Volyncoal" – 7.34 tons.

Methodology & Theoretical Orientation. Theoretical and laboratory studies, experimental measurements, calculation for determining the probability of dust formation, mathematical planning (a second-degree D-optimal plan was used for construction the mathematical model), graph-analytical and mathematical planning methods.

Discussion. Coal mining enterprises are powerful sources of pollutant emissions into the atmosphere. As a result of the operation of coal mining and processing plants, significant amounts of carbon-containing dust enter the atmosphere. Researchers estimate that the air environment of the underground mine's surface complex is filled every minute with approximately 200,000 m^3 of exhaust ventilation air having a dust concentration of approximately (5-7) mg/m^3, which equals to 1.5 tons of dust per a day. This is where a long-range transportation of pollutants is most often possible. Coarse dust discharged through the ventilation systems of mines intensively settles within the sanitary protection zones of mines. Fine dust is carried on long distances by the wind beyond their limits, polluting the environment at a distance of up to 3500 m from the coal mine. Carbon dust emissions into the atmosphere are almost always a major part of transboundary environmental pollution. The mine wastes are also an environmental threat.

Coal dust consists of fine coal powder, which is formed during drilling, blasting, crushing, screening, crumbling, taking into account its fragile nature, mechanical and flowing transportation of coal and coal products. Air quality has the potential to be impacted by the coal dust emissions from coal mining activities, the transportation of coal from mines to designated ports and the loading operations at the port's export terminals.

Carbon-containing dust degrades air quality and ruthlessly distresses the natural bio-network and ecosystems and also has a serious impact on human health. Carbon-containing dust is a factor in increasing mortality from heart and respiratory diseases, decrease in pulmonary function of children and adults with the development of obstructive respiratory disease, and the increase in the frequency of symptoms. Health effects are associated with both short-term and long-term impact of dust particles.

The environmental risk of carbon-containing dust emissions necessitates measures to dust off mine ventilation streams and reduce dust emissions into the atmosphere. To reduce the environmental hazard of coal mine dusts (carbon-containing dust), it is recommended that they are localized using dispersed water.

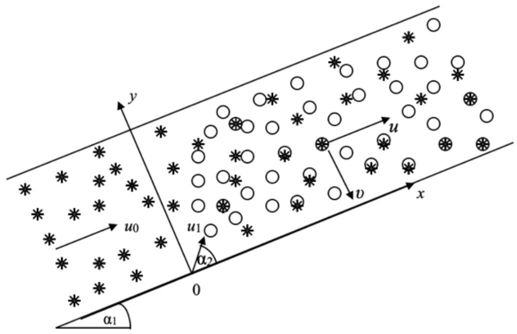

Fig. 3. Scheme of motion and mechanical interaction of the sprayed liquid (circles) with carbon-containing dust (asterisks) in an incline working area

Therefore, the disclosure of the peculiarities of the influence of factors on the effectiveness of the processes of interaction of dispersed water jets with carbon-containing dust in environmental pollution prevention technologies is an urgent problem, the solution of which is a prerequisite for scientific and technological progress in the field of environmental safety.

Theoretical and laboratory studies, experimental measurements, calculation for determining the probability of dust formation, mathematical planning (a second-degree D-optimal plan was used for construction the mathematical model), graph-analytical and mathematical planning methods.

When studying the dynamics of dust and dispersed water flows, we will consider dust particles and droplets of liquid as separate objects moving in the ventilation stream.

Let's choose the coordinate axes (Figure 3): x − is the longitudinal coordinate along the movement of the ventilation stream, starting from the place of creation of the dust stream (location of the combine) or from the location of the water flare, y − the transverse coordinate from the bottom to the top starting from the beginning, near the production soil (Gorobei, 2015, 2018, 2020).

The equation of the motion of a solid or liquid body in the field of gravity has the form:

$$m_i \frac{d\vec{U}}{dt} = m_i \vec{g} - \vec{W} \qquad (1)$$

where m_i – mass i – i – dust or liquid droplets, kg;

$\vec{U}$ – vector of relative velocity of a particle or droplet, m / s;

t – the time from the start of the flight of a particle or drop, p;

$\vec{g}$ – acceleration of gravity, m / s^2;

$\vec{W}$ – force of resistance of movement of particles or drops, N.

The equation of motion of the particles of dust and liquid droplets in the projections on the axis of coordinates is as follows:

$$\frac{du}{dt} = -g\sin\alpha_1 - \frac{6}{\rho\pi d_i^3}W_x; \qquad \frac{d\upsilon}{dt} = -g\cos\alpha_1 - \frac{6}{\rho\pi d_i^3}W_y \qquad (2)$$

where u, υ – the projections of the velocity vector on the coordinate axis, m / s;

g – acceleration of gravity (assumed equal to 9.81m/s^2);

α_1 – working angle to the horizon, degrees;

ρ – the density of the particle or droplet (usually assumed equal to 1300 kg/m^3 – for coal dust particles and equal 1000 кг/м^3 – for wate);

d_i – diameter i – particles or drops, m;

W_x, W_y - projections of the vector of the force of motion resistance, N.

It is believed that the resistance forces of the body movement in the air are proportional to the kinetic energy of the relative motion and the area of the midsection of the body. In vector form, this dependency can be represented as follows:

$$\vec{W} = c_n \frac{\pi d_i^2}{4} \frac{\rho_0 |U| \vec{U}}{2}, \qquad (3)$$

where c_n – a drag coefficient that depends on the velocity and diameter of the particles or droplets;

ρ_0 – air density, kg/m^3.

For relative motion in the air flow, the formula (3) in the projections on the coordinate axis, taking into account the sign of the motion direction (on or against the flow) will take the form:

$$W_x = c_x \frac{\pi d_i^2}{4} \frac{\rho_0 |u \pm u_0| (u \pm u_0)}{2}; \qquad W_y = c_y \frac{\pi d_i^2}{4} \frac{\rho_0 |\upsilon| \upsilon}{2} \qquad (4)$$

where c_x, c_y – projection of the drag coefficient on the coordinate axis;

u_0 – ventilation flow velocity, m/s.

By substituting expression (4) into the system of equations (2), we obtain

$$\frac{du}{dt} = -g\sin\alpha - \frac{3\rho_0 c_x}{4\rho d_i}\left|u \pm u_0\right|(u \pm u_0);$$
$$\frac{d\upsilon}{dt} = -g\cos\alpha - \frac{3\rho_0 c_x}{4\rho d_i}\left|\upsilon\right|\upsilon \quad (5)$$

The initial conditions are added to the equations of system (5) on the assumption that particles or droplets at the site of their formation acquire at an angle of inclination to the ground for production a velocity that does not coincide with the velocity of air:

$$1) u(0) = u_1\cos\alpha_2; \quad 2) \upsilon(0) = u_1\sin\alpha_2 \quad (6)$$

where u_1 – initial velocity of dust particles or liquid droplets, m / s;

α_2 – the angle of inclination of the initial velocity of movement of particles or droplets to the production soil, degrees.

Numerous experimental studies show that the coefficient of resistance of a spherical shape obeys the two-term law and can be assumed to be sufficient

$$c_n = 0{,}5 + \frac{24\nu}{|U|d_i} \quad (7)$$

The Fig. 4 shows the calculated curve (7) and the experimental data depending on the coefficient of resistance of motion of bodies of spherical shape from the local Reynolds number during the transition from laminar to turbulent mode.

The local Reynolds number is meant to the ratio of the dynamic forces of a particle of dust or a drop of liquid to the forces of air viscosity

$$, \mathrm{Re}_x = \frac{|u - u_0|d_i}{\nu}; \quad \mathrm{Re}_y = \frac{|\upsilon|d_i}{\nu} \quad (8)$$

The maximal error of the calculated data, as shown by the comparison with the experimental data, does not exceed 10 – 20%. An analysis of the possible values of the local Reynolds number implies that it can vary widely. Therefore, taking the minimal diameter d_{min} = 1 μm and the minimal velocity u_{min} = 0.1 m / s, we obtain Re = 0.007. And taking the maximal diameter d_{max} = 1000 μm and the maximal velocity u_{max} = 100 m/s, we obtain Re = 6667.

Thus, the movement of dust particles and liquid droplets will shift from turbulent to laminar mode, capturing the transition mode. Therefore, considering only laminar mode using the Stokes law can lead to gross errors.

Solving second order algebraic equations (6, 7), we find the limit value of velocity projections

$$u_2 = \mp u_0 - \frac{2g\sin\alpha_1}{a_1 + \sqrt{a_1^2 + 4a_2 g\sin\alpha_1}};$$
$$\upsilon_2 = \frac{-2g\cos\alpha_1}{a_1 + \sqrt{a_1^2 + 4a_2 g\cos\alpha_1}} \quad (9)$$

From the formula (9) it follows that at $a_2 = 0$ is the mode of motion is laminar and at $a_1 = 0$ – turbulent.

Figure 5 presents the dependence of the maximal vertical velocity on the diameter of the particles or droplets set by the second formula (9). The Fig. 5 turns out that using Stokes' law when assessing vertical velocity is possible only with a diameter of particles or droplets less than 200 microns.

It is actually hard to believe that a 0.5 mm diameter drop was moving at a speed of 7 m/s. Given the turbulence of the flow, its velocity will be according to the Fig. 5 only 2.5 m/s.

Moreover, it is impossible to use the Stokes law for longitudinal velocity in the active zone of the nozzle plume, where the local Reynolds numbers, as already noted, can be several thousand.

Findings. The mechanism of sedimentation of suspended carbon-containing dust on the working soil due to the action of gravitational and electrostatic forces has been clarified. It lies in the fact that as a result of the natural or forced charge of the dust cloud, its particles are attracted to the droplets of liquid, creating new nuclei, which, falling into the sphere of influence of electrostatic forces are deposited more effectively due to the fact that their mass is equal to the total mass of liquid droplets and particles of dust. As a result of theoretical and experimental studies using existing formulas it was developed a mathematical model of the dynamics of the interaction of dust and dispersed water flows interaction in gravitational and electrostatic fields.

Conclusion & Significance. Air pollutions have major impacts on human health, triggering, and inducing many diseases leading to high morbidities and mortalities. Atmospheric air protection is one of the most urgent problems in modern technological society, as scientific and technological progress and expansion of production is associated with an increase in negative anthropogenic impacts on the atmosphere. The paper presents a new solution to the current scientific problem of reducing carbon-containing dust content based on the disclosure of the laws of the aerodynamic interaction of dust and water flows in gravitational and electrostatic fields.

Based on the known theoretical and experimental

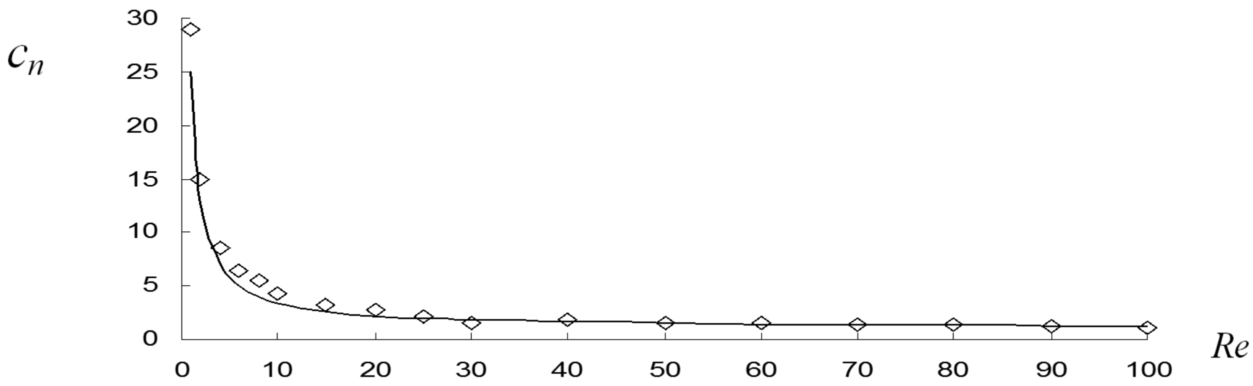

Fig. 4. Dependence of the coefficient of resistance of the motion of globular bodies on the local Reynolds number during the transition from laminar to turbulent mode

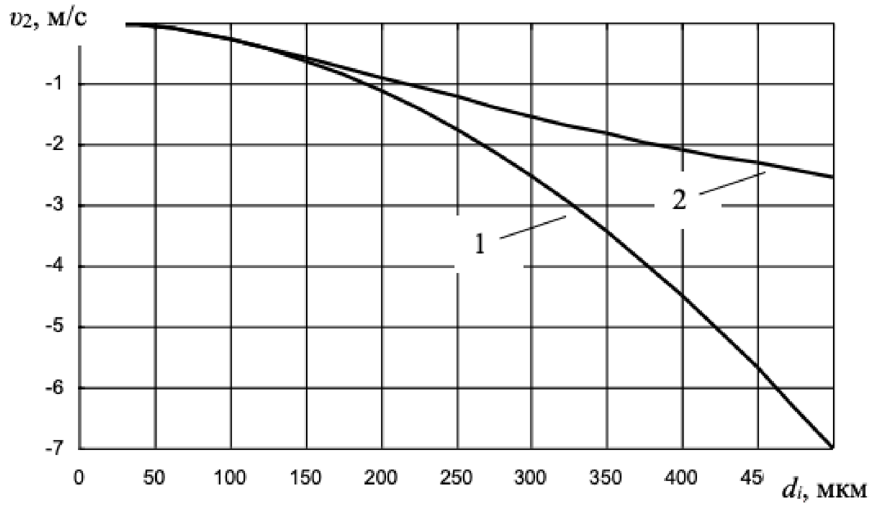

Fig. 5. Dependence of the maximal vertical velocity of a particle or droplet on its diameter during laminar (curve 1) and mixed (curve 2) modes.

data on the interaction of dispersed liquid with air-suspended dust, the mechanism for capturing suspended coal dust by fluid droplets in the ventilation stream has been clarified: dust particles do not have to be wetted and immersed in liquid droplets. This may not be in the case of natural and forced charge of dust and dispersed water flows. Having fallen into the sphere of influence of electrostatic forces, particles rush to drops until they fall on the soil of a mine working area, before they have time to coagulate. After particles of carbon-containing dust get onto the wet soil, the de-dusting effect of the ventilation flow will be achieved.

It has been proved that the movement of dust particles and droplets of fluid will pass from turbulent to laminar mode, capturing also the transition mode. Therefore, considering only laminar mode using Stokes law, as in the works of predecessors, can lead to gross errors. Studies have shown that using the Stokes law when estimating the vertical velocity of motion is only possible with particle or droplet diameters of less than 200 microns. Moreover, its not allowed to use the Stokes law for the longitudinal velocity in the active zone of the nozzle plume, where local Reynolds numbers can reach several thousand.

Technologies to reduce air pollution at the source of carbon-containing dust formation should be used in all new industries of economy. The results obtained reveal the mechanism of interaction of the sprayed liquid with coal dust and can be used in the development of new effective means of controlling the carbon-containing dust. The principles and practices of sustainable development, coupled with local research, will help to reduce or eliminate health and environmental risks resulting from air pollution by carbon-containing dust.

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