Experimental study of the effectiveness of water-air suspension to prevent an explosion

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Abstract. For many countries where mining facilities exist, the importance of the mining sector is steadily increasing. Also, the mining sector is central to the global economy. However, the environment is adversely affected by explosions of finely dispersed coal dust and methane-air mixture in the mine. Dust deposited on the surface of the mine workings is as dangerous as hovering dust. The use of a water suspension system is effective for reducing the concentration of coal dust because dispersion increases. To ensure technological and environmental safety during combustion, release, mixing and distribution of gas impurities in the atmosphere (including in multiply connected areas with complex terrain or in closed spaces), an adequate mathematical description of the processes of creating and maintaining multiphase dispersed structures is required. The creation of such a mathematical model is possible only using the system of unsteady Navier–Stokes equations for compressible gas. For the practical implementation of this mathematical model, experimental studies are needed, which will confirm the possibility to create a water suspension with the necessary dispersion, the area of irrigated surface and at the required distance by the atomizer. The maximum range (in the extreme drops) of the jet was measured from the projection of the atomizer barrel onto the test site using pre-installed beacons. The size of the water droplets was determined by sampling from a stream on small glass slides coated with a thin layer of paraffin. Glass slides were photographed under a microscope and the diameter of the drop was determined using software. It was established experimentally that spraying a liquid with a mass flow rate of 1.0 l/s through square cells measuring 150 μm ensures the formation of a stable water-air dispersed suspension at a distance of 10 m. This is the most effective range where a stable air-dispersed air curtain was formed. By numerical simulation, it was established that the presence of water droplets provides not only complete deposition of coal dust, but also an additional decrease in the overpressure and temperature of the high-temperature cloud of the combustion products of the methane-air mixture. This is due to the transition of the liquid phase to the vapor state. From the analysis of the simulation results it can be seen that the effectiveness of water curtains decreases when extinguishing explosions of only methane-air mixture (that is, without participation in the explosion of coal dust).

Keywords: environmental hazard, hovering coal dust, water-air dispersed suspension
1. Introduction

One of the main factors in the transformation of the environment in industrial regions is the entry into the atmosphere of small toxic dust particles [1, 2] (including nanoparticles) [3, 4], which, if inhaled, are dangerous to human health [5-7]. This aggravates the existing health problems of the respiratory organs and leads to a change in the natural conditions in industrial regions [8-10]. For many countries where mining facilities exist, the importance of the mining sector is steadily increasing [11, 12]. Also, the mining sector is central to the global economy. However, the environment is adversely affected by explosions of finely dispersed coal dust and methane-air mixture in the mine [13, 14]. A key problem in environmental health is atmospheric air protection. This is justified by the fact that atmospheric air realizes different protective environmental functions [15]. Dust deposited on the surface of the mine workings is as dangerous as hovering dust. Dust may begin to hover and, together with dust aerosol, reach explosive concentrations. This is due to an air shock during coal mining, or during the operation of equipment and mining combines, if they are not equipped with dust suppression means, or due to other similar factors. The presence of methane (CH₄) has a significant effect on the coal dust explosion [16]. Using the system of unsteady Navier–Stokes equations for compressible gas makes it possible to adequately mathematically describe the processes of creating and maintaining multiphase dispersed suspensions to ensure technogenic and environmental safety during combustion, emission, mixing and distribution of gas impurity [17, 18]. At present, numerical simulation of turbulent flows is carried out by solving the Reynolds-averaged Navier-Stokes equations supplemented by the turbulence model [19-21]. It has been proven that the use of fine water mist is effective for reducing the concentration of coal dust by increasing the dispersion [5, 22, 23]. For example, in [23], the authors investigate the formulation of suspensions only by the example of liquefied natural gas (LNG) facilities. In the works [5, 22], developed mathematical models for the retention of fine water mist were proposed, but do not take into account the consequences of an accidental explosion. However, in the well-known works, the dynamics of the decrease in temperature and overpressure in the area of fine water mist, which is created by an atomizer, during the propagation of a shock wave from an accidental explosion in the underground mine is not investigated. Therefore, this task is relevant and it is the purpose of this research. Dispersed water mist can be created by atomizers or other spray devices. Atomizers are capable of creating a fine water-air suspension with soaring drops, the characteristic size of which is about 20-40 microns [24, 25]. This water-air suspension is a multi-phase dispersed structure. Consequently, experimental studies will allow us to understand the effectiveness of a fine water mist to reduce the concentration of coal dust and excessive pressure in the shock wave after an accidental explosion.

2. Materials and Methods

Before carrying out the experimental investigation, the atomizer was tested for leaks with the latch open and the muffled outlets of the injectors. Holding time at a pressure of 1 MPa for at least 2 minutes. The flow rate was measured with a turbine flowmeter DR-20-60-Ya42A. Before the beginning of the experiment, the flowmeter was calibrated. Accuracy of flow rate determination ±2.5 %. The flow rate of the irrigating water, the amount of water was determined by the measured capacitance, the error 1 %. To measure the range of the jet, the atomizer was fixed at an angle of inclination to the horizon 30°± 1 on high 1 ± 0.01 m. The maximum range (at the last drop) of the jet was measured from the projection of the atomizer barrel to the test site using pre-installed beacons. Accuracy of measurement ± 0.2 m. The angle of the spray of the spray was determined visually by measuring the diameter of the spray at a distance 0.5 m from the cutoff of the atomizer nozzle. Measurement error ± 5 %. The dimensions of the water droplets were determined by sampling from the jet to small subject glasses covered with a thin layer of paraffin. Subject glasses were photographed under a microscope (figure 1, 2) and the software determined the diameter of the drop.
During the experimental studies of the atomizer, the grid was changed, which forms the size of the droplets of the jet of the jet. In this case, the geometrical dimensions of the side of the square cross-section of the grid $a_g$ were varied from 50 to 250 $\mu$m. Mass flow rate $q_f$, which is supplied to the working zone for the formation of droplets, varied within the range of 0.5-2.0 ml/s. Five variants are investigated:

- variant No. 1: $a_g = 50$ $\mu$m, $q_f = 2.0$ ml/s;
- variant No. 2: $a_g = 100$ $\mu$m, $q_f = 1.0$ ml/s;
- variant No. 3: $a_g = 150$ $\mu$m, $q_f = 1.0$ ml/s;
- variant No. 4: $a_g = 200$ $\mu$m, $q_f = 0.5$ ml/s;
- variant No. 5: $a_g = 250$ $\mu$m, $q_f = 0.5$ ml/s.

Knowing the minimum, maximum and average droplet diameters, a distribution diagram of the droplet diameters (figure 3).
To simulate the impact of water curtains on the propagation of a shock wave, a software complex is used that is a computer interactive system of engineering three-dimensional analysis of gas-dynamic processes of mixing two gases. The application is written in the IDE Visual C++ 3.0 Enterprise Edition using the library Microsoft Foundation Classes (MFC). Numerical simulation of nonstationary equations of gas dynamics for a compressible gas in a Cartesian coordinate system [19, 26]. A mathematical description of the processes is presented in the paper [22]. In this case, it is necessary to take into considering the spray quality, the effect of the aerodynamic drag of droplets, the effect of heat release due to a phase transition during the boiling of droplets on the parameters of the motion of the gas mixture.

2.1. The take into considering the spray quality of droplets (or dust particles of solid fractions).
Sputtering quality is characterized by integral and differential curves for the distribution of the volumes (number, surface) of drops by their diameters and various concepts of the average droplet diameter. In most cases, the sprayed liquid used in the technique consists of droplets of various sizes, that is, it has a polydisperse character. To describe the droplet size distribution curves, various dependencies are proposed. The most widely used is the Rosin-Rammler equation:

\[ P = 1 - \exp \left( - \left( \frac{d}{d_+} \right)^n \right), \quad (1) \]

where \( P \) – the volume fraction of droplets whose diameter is smaller \( d \); \( d_+ \) – a characteristic size or an average diameter corresponding to a particular value \( n = 0.3679 \); \( n \) – distribution constant characterizing the degree of heterogeneity of the spray (usually \( 2 > n > 4 \)).

Then the density of the droplet distribution along the diameters will have the form:

\[ \rho \left( \frac{d}{d_+} \right) = n \left( \frac{d}{d_+} \right)^{n-1} \exp \left( - \left( \frac{d}{d_+} \right)^n \right). \quad (2) \]

2.2. The take into considering the effect of aerodynamic drag of droplets (dust particles of solid fractions) on the parameters of the motion of a gas mixture.
Define the force of resistance acting on a drop (a particle of dust):

\[ \vec{F}_r = -C_d \frac{\rho q^2}{2} \frac{\sigma_k}{|\vec{q}|}, \quad (3) \]

where \( \sigma_k = \frac{\pi d^2}{4} \) – surface area, \( C_d \) – aerodynamic drag coefficient, \( q \) – flow rate. If the drop remains spherical, then to determine \( C_d \), we can recommend the relation:

\[ C_d = 24 / Re + 4.4 / \sqrt{Re} + 0.35, \quad (4) \]

where \( Re = \frac{\rho q d}{\mu} \) – Reynolds number.

Then the aerodynamic drag force averaged over the droplet diameters for the selected reference volume is determined by the formula:
\[ \bar{F}_{fr} = N_k \sum_{i=1}^{\frac{1}{I}} \rho(d_i) \bar{F}_{fr}(d_i), \]  
(5)

where \( N_k = \frac{G_{H_2O} \tau}{m\rho_{H_2O} \sum_{i=1}^{I} \rho(d_i)V_{ki}} \) – number of drops in the control volume, \( G_{H_2O} \) – total water flow (it is assumed that water is continuously fed into the design area), \( \tau \) – time step, \( m \) – quantity of control volumes in the area with sources (droplets, dust particles of solid fractions), \( V_{ki} = (\pi/6)d_i^3 \) – volume of a drop.

The amount of particles of solid fractions in the control volume is determined by the formula:

\[ N_k = \frac{\rho \Delta V}{\rho_C \sum_{i=1}^{I} \rho(d_i)V_{ki}}, \]  
(6)

where \( \rho_{C+} \) – dust concentration in suspension, \( \Delta V \) – control volume, \( \rho_C \) – solid matter density.

The effect of the aerodynamic drag of droplets (dust particles of solid fractions) on the parameters of the motion of the gas mixture was taken into account by introducing into the equations of motion the averaged volume force of resistance: \( \bar{F}_{fr} = \frac{1}{\rho} \bar{F}_{fr}/\Delta V \). It was assumed that the sum of the specific power of the resistance forces and the specific dissipated power is zero \((\rho \bar{F}_{fr}, \bar{q}) + N_\delta = 0\).

### 2.3. The Take into Considering the Effect of Heat Release due to a Phase Transition during the Boiling of Droplets (Chemical Reaction of Combustion of Dust Particles of Solid Fractions) on the Parameters of the Motion of the Gas Mixture

We determine the intensity of the change in the impurity density due to the phase transition during the boiling of water droplets:

\[ \rho_{H_2O_s} = \frac{G_{H_2O}}{m\Delta V}, \]  
(7)

and the intensity of the change in the impurity density due to the chemical combustion reaction:

\[ \rho_s = \frac{G_C}{m\Delta V}, \]  
(8)

where \( G_C \) – the total change in the unit time of the mass of particulate dust particles due to the chemical combustion reaction.

We assume that the law is known according to which the burning time of one particle depends on the initial mass of this particle:

\[ t_i = kd_i^2 = k \left( \frac{6M_{0i}}{\pi \rho} \right)^{2/3}, \]  
(9)

where \( k = 6.14 \cdot 10^6 \) and \( M_{0i} = \rho_C V_{ki} \).
Then, according to the transformations known from mathematical analysis and the theory of ordinary
differential equations, a law can be obtained for determining the mass of a particle at an arbitrary
instant of time in the chemical reaction of combustion:
\[
M_i = [M_{0i}^{2/3} - 1.06 \cdot 10^{-7} \rho^{2/3} \cdot t]^{2/3},
\]
(10)
as well as the dependence of the change in unit time of the mass of dust particles of solid fractions due
to the chemical combustion reaction:
\[
G_{Ci} = 1.6 \cdot 10^{-7} \rho^{2/3} \cdot (M_{0i}^{2/3} - 1.06 \cdot 10^{-7} \rho^{2/3} \cdot t)^{1/2},
\]
(11)
where \( t \) – current time.
The total change in the unit time of the mass of dust particles of solid fractions due to the chemical
combustion reaction can be determined by the formula:
\[
G_C = mN_k \sum_{i=1}^{l} \rho(d_i)G_{Ci},
\]
(12)
The effect of the phase transition during the boiling of water droplets (the chemical reaction of
combustion of dust particles of solid fractions) on the parameters of the motion of the gas mixture was
taken into account by introducing into the equation the energy of the heat release intensities in the
control volume:
\[
e_{H_2O_{Os}} = -r(P)\rho_{H_2O_{Os}}, \quad e_{Cs} = \xi H_{uC} \rho_{Cs},
\]
(13)
where \( r(P) \) – specific heat of vaporization, \( \xi \) – coefficient of combustion completeness, \( H_{uC} \) – net
 calorific value.

3. Results and Discussion

The test results showed that it is difficult to obtain a linear dependence of the size of the formed
droplet on the mass flow rate and the geometric size of the mesh. In this experiment it was established
experimentally that the most stable cloud of suspended particles with a characteristic droplet diameter
of 25-50 μm was obtained at a mass flow rate of 1.0 ml/s and a mesh side dimension of 100 μm
(variant No. 3). The share of such drops was about 60-80 %. The formation of a stable cloud with a
water droplet diameter of 25-50 μm and mass-energy characteristics of the formed flare allows to
catch suspended coal dust with its subsequent precipitation.
For variants No. 4 and No. 5, the formation of drops with a larger diameter of 100-120 μm. The share
of such drops was about 65-85 %. In this case, a minimum mass flow of liquid is observed. However,
due to the increase in mass-energy characteristics, the desired effect of trapping suspended particles
was not obtained. The region of formation of the air-drip curtain remained unstable, a scatter of the
compactness of the air curtain.
For variants No. 1 and No. 2, no positive results on the precipitation of the coagulating coal particles
were obtained. These variants are characterized by a low range and characteristic droplet sizes of the
order of 40 μm. Influence on the dust cloud is weak.
Thus, variant No. 3 provided the delivery of dispersed particles and the formation of a stable water-air
dispersed curtain at a distance of \( L = 10 \) m. This is the most effective range, where a stable water-air
dispersed air curtain. Therefore, to further study the dynamics of the reduction in temperature and
excess pressure (consequences from the explosion of methane-air mixture and coal dust) in the area of the water curtain, as the base variant was chosen variant No. 3.

A further study was carried out by three-dimensional mathematical simulation of the impact of water curtains on the propagation of a shock wave caused by an explosion of a methane-air mixture and coal dust in underground mine workings of coal mines.

We simulated the calculated region shown in figure 4. The conditions of the numerical experiment are: length of underground mine $L_x = 31.2$ m, height of underground mining $L_y = 2.2$ m, inlet wind speed $q = 6 \, m/s$, a cloud of methane-air mixture formed at a distance of $L_1 = 10.1$ m from the entrance, cloud radius of methane-air mixture $R_1 = 1.6$ m (figure 5).

![Figure 4. Scheme of calculation area](image.png)

On distance $L_2 = 13$ m a zone filled with a finely dispersed phase begins (depending on the scenario under consideration). It was assumed that the presence of water droplets in this zone ensures complete precipitation of coal dust. Checkpoints $P_1$ and $P_2$, in which the change in the excess pressure and temperature of the gas mixture was controlled, are located on the Z axis at a distance, respectively $L_3 = 14.9$ m and $L_4 = 1.9$ m. The cross-section of the underground mine has such dimensions: width $L_x = 3.2$ m, straight section height $L_y = 0.6$ m, radius of the upper part $R_y = 1.6$ m.

The study was conducted on three possible scenarios for the development of events associated with the process of accidental explosion of a cloud of methane-air mixture in underground mining:
- scenario No. 1 – investigation of the scattering of combustion products along the underground mining with the presence of coal dust in the air;
- scenario No. 2 – investigation of the scattering of combustion products along underground mining without the presence of dispersed phases;
- scenario No. 3 – investigation of the scattering of combustion products along the underground mining with the presence of water droplets (water curtain) in the air.

At the initial moment of time, as a result of the methane-air mixture explosion, a cloud of combustion products with high pressure and temperature. Then the process of dispersion of combustion products was realized, which is accompanied by convective transfer and turbulent scattering of combustion products along the underground mining. Results of numerical modeling at the control point $P_1$ are shown in figure 5 and at the control point $P_2$ – in figure 6.

Analysis of the results of calculations shows that the presence of coal dust in the air leads to an increase in excess pressure and temperature in underground mining (in comparison with the cases when the air does not contain dispersed phases – curves 2, in the presence of a water curtain in air – curves 3 in figure 5), caused by the ignition of this phase (see curves 1 in figure 5a and figure 5b).
The presence of water droplets not only provides complete precipitation of the coal dust, but also an additional reduction in the excess pressure and temperature due to the transition of the liquid phase to the vapor state when a high-temperature cloud of combustion products of the methane-air mixture passes along the drift (see curves 3 in figure 5a and figure 5b).

![Figure 5](image_url)

**Figure 5.** Check point $P_1$. The results of numerical simulation of three possible scenarios for the development of events associated with the explosion of a cloud of methane-air mixture in underground mining: $a$ – change in the excess pressure; $b$ – change in the temperature of the gas mixture; $1$ – scenario No. 1; $2$ – scenario No. 2; $3$ – scenario No. 3

Analysis of the results of calculations shows that the presence of coal dust in the air leads to an increase in excess pressure and temperature in underground mining (in comparison with the cases when the air does not contain dispersed phases – curves 2, in the presence of a water curtain in air – curves 3 in figure 5), caused by the ignition of this phase (see curves 1 in figure 5a and figure 5b).

![Figure 6](image_url)

**Figure 6.** Check point $P_2$. The results of numerical simulation of three possible scenarios for the development of events associated with the explosion of a cloud of methane-air mixture in underground mining: $a$ – change in the excess pressure; $b$ – change in the temperature of the gas mixture; $1$ – scenario No. 1; $2$ – scenario No. 2; $3$ – scenario No. 3

The presence of water droplets not only provides complete precipitation of the coal dust, but also an additional reduction in the excess pressure and temperature due to the transition of the liquid phase to the vapor state when the high-temperature cloud of combustion products of the methane-air mixture...
passes along the underground mine (see curves 3 in figure 6a and figure 6b). For comparison, the results of calculations of the change in the excess pressure and temperature at the reference point are given for the case when the air of underground mining did not contain dispersed phases (see curves 2 in figure 6a and figure 6b). As can be seen from the analysis of simulation results, the efficiency of water curtains decreases when extinguishing explosions of methane-air mixture only (that is without participation in a coal dust explosion).

4. Conclusions

1. It was established experimentally that the most stable cloud of suspended particles with a characteristic droplet diameter of 25-50 μm was obtained at a mass flow rate of 1.0 ml/s and a mesh side dimension of 150 μm (variant No. 3). The share of such drops was about 60-80%. The formation of a stable cloud with a water droplet diameter of 25-50 μm and mass-energy characteristics of the formed flare allows to catch suspended coal dust with its subsequent precipitation.

2. It was found experimentally that using a grid with square mesh size of 150 μm and a mass flow rate of liquid supplied to the working zone to form drops equal to 1.0 ml/s, a stable water-air dispersed curtain is created at a distance of 10 m. This is the most effective range where the stable water-air dispersed air curtain. For other investigated variants, the region of formation of the air-dropping curtain remained unstable, a dispersion of the air curtain compactness was observed, and a weak effect on the dust cloud.

3. Numerical modeling has established that the presence of water droplets not only provides complete precipitation of the coal dust, but also an additional reduction in the excess pressure and temperature due to the transition of the liquid phase to the vapor state while passing along the underground mining of the high-temperature cloud of combustion products of the methane-air mixture. As can be seen from the analysis of simulation results, the effectiveness of water curtains decreases when extinguishing explosions of methane-air mixture only (that is without participation in the explosion of coal dust).

5. References

[1] Kolesnyk V, Pavlychenko A, Borysovs’ka O, Buchavyy Y 2018 Formation of physic and mechanical composition of dust emission from the ventilation shaft of a coal mine as a factor of ecological hazard. Solid State Phenomena, 277, 178-187. https://doi.org/10.4028/www.scientific.net/SSP.277.178

[2] Vambol S A, Shakhov Yu V., Vambol V V, Petukhov I I 2016 A mathematical description of the separation of gas mixtures generated by the thermal utilization of waste. Eastern-European Journal of Enterprise Technologies 1/2(79) 35-41. https://doi.org/10.15587/1729-4061.2016.60486

[3] Vambol S, Bogdanov I, Vambol V 2017 Research into regularities of pore formation on the surface of semiconductors. Eastern-European Journal of Enterprise Technologies 3/5(87) 37-44

[4] Vambol S, Bogdanov I, Vambol V 2017 Research into effect of electrochemical etching conditions on the morphology of porous gallium arsenide. Eastern-European Journal of Enterprise Technologies 6/5(90) 22-31

[5] Prostański D 2013 Use of air-and-water spraying systems for improving dust control in mines. Journal of Sustainable Mining 12(2) 29-34. https://doi.org/10.7424/jsm130204

[6] Shmandiy V M, Kharlamova E V, Rigas T E 2015 The study of manifestations of environmental hazards at the regional level. Gigiena i Sanitariya 7 90-92.

[7] Kondratenko O M, Vambol S O, Strokov O P, Avramenko A M 2015 Mathematical model of the efficiency of diesel particulate matter filter. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 6 55-61.
[8] Sundararajan M, Sharma S N, Kumar R, Ansari I, Kumar G 2018 Estimation of SPM Emission in Air Environment through empirical modeling and remedies for dust control in and around coal mining complexes. National Seminar on Environmental Issues: Protection, Conservation and Management (EIPCM), on 26-27, Feb.2016 at Department of Mining & Electrical and Geology BIT Sindri, Dhanbad, Jharkhand. PP, 207-214.

[9] Vambol S, Vambol V, Bogdanov I, Suchikova Y, Rashkevich N 2017 Research of the influence of decomposition of wastes of polymers with nano inclusions on the atmosphere. Eastern-European Journal of Enterprise Technologies 6/10(90) 57–64. doi: 10.15587/1729-4061.2017.118213

[10] Biliaiev M, Rostochil N, Kharytonov M 2014 Expert systems for assessing disaster impact on the environment. Improving disaster resilience and mitigation – it means and tools. NATO Science for Peace and Security Series C: Environmental Security 10 153-165.

[11] Pivnyak G G, Pilov P I, Bondarenko V I, Surgai N S, Tulub S B 2005 Development of coal industry: The part of the power strategy in the Ukraine. Mining Journal 5 14-18.

[12] Sundararajam, Vambol V, Vambol S, Kumari N, Ansari I 2018 Nutrient dispersion modeling of coal overburden dumps for reclamation and sustainable management. Technogenic and ecological safety 4/2(2018) 86–98. doi: 10.5281/zenodo.1433544

[13] Petlovanmi Y, Lozynskyi V, Saik P, Sai K 2018 Modern experience of low-coal seams underground mining in Ukraine. International Journal of Mining Science and Technology. https://doi.org/10.1016/j.ijmst.2018.05.014

[14] Krichevskii S 2015 Evolution of technologies, “green” development and grounds of the general theory of technologies. Philosophy & Cosmology 14 120-139.

[15] Kachurin N, Komashchenko V, Morkun V 2015 Environmental monitoring atmosphere of mining territories. Metallurgical and Mining Industry 6 595-598.

[16] Trubitsyn A A, Popov M Ye, Voroshilov S N, Voroshilov Ya S 2005 Pribor kontrolya pylevyzvyobezposasnosti gornykh yrabotok tipa PKP. Nauchnyye soobshcheniya NNTS GP – IGD im. A.A. Skochinskogo 321 89-103.

[17] Kostyuk V Ye, Kirilash Ye I, Kobrin V N 2013 Matemutcheskaya model’ povedeniya dispersnykh struktur v atmosfere. Tekhnologii tekhnosfernnoy bezopasnosti 4(50) 1-11.

[18] Vambol V 2016 Numerical integration of the process of cooling gas formed by thermal recycling of waste. Eastern European Journal of Enterprise Technologies 6/8(84) 48-53. https://doi.org/10.15587/1729-4061.2016.85455

[19] Belotserkovskiy O M, Andrushchenko S A, Shevelev Yu D 2000 Dinamika prostranstvennykh vikhrevaiek techeniy v neodnorodnoy atmosferе. Vychislitel’nyy eksperiment. Moskva, Yanus-K, 456 s.

[20] Yershov S V 1998 Matemutcheskoye modelirovaniye trekhmernykh vyazkikh techeniy v turbomashinakh – sovreemennyy vzglyad. Problemy mashinostroeniy 1(2) 76-93.

[21] Abramovich G N 1974 Turbulentnoye smesheniye gazovyykh struy. Moskva: Nauka.

[22] Vambol S A, Skob Yu A, Nechiporuk N V, Trukhmayev O A 2013 Modelirovaniye sistemy upravleniya ekologicheskoy bezopasnost’yu s ispol'zovaniem mnogofaznykh dispersnynkh struktur pri vzryve metanovozdushnoy smesi i uglo’noy pli v podzemnykh gornykh yrabotakh. Vestnik kazanskogo tehnologicheskogo universiteta 16(24) 168-174.

[23] Kim B K, Ng D, Mentzer R A, Mannan M S 2012 Modeling of Water-Spray Application in the Forced Dispersion of LNG Vapor Cloud Using a Combined Eulerian–Lagrangian Approach. Industrial & Engineering Chemistry Research 51(42) 13803-13814. https://doi.org/10.1021/ie3003864

[24] Vambol S O, Kobrina N V, Trukhmayev O O 2012 Systema upravlinnya ekologichnoyu bezpekoю pry vykorystanii pylyoprzychnychuyshekh systym zhoshennya u protesi navantazhennya ta rozvantazhennya sypkykh materialiv u portakh. Otkrytye informatsyonne y komp yuternye yntehryrovannye tehnolohyy 55 161-167.
[25] Nechiporuk N V, Kobrina N V, Kostyuk V Ye 2010 Modelirovaniye obespecheniya ekologicheskoy bezopasnosti pri ispol'zovanii orositel'noy sistemy pylepodavleniya v protsesse pogruzki, razgruzki i transportirovki sypuchikh materialov. Yekologichna bezpeka 2/2010(10), 20-22

[26] Loitsianskii L G 1978 Mekhanika zhidkosti i gaza. Moskva: Nauka