https://doi.org/10.31713/m1307

SIMULATION OF COAL AND GAS OUTBURSTS IN OUTBURST-PRONE ZONES OF COAL SEAMS

Viktoriia KRUKOVSKA
Senior Researcher, Doctor of Technical Sciences, Senior Researcher in Department of Control of Dynamic Effects of Rock Pressure, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Ukraine

Oleksandr KRUKOVSKYI
Corresponding member of NAS of Ukraine, Doctor of Technical Sciences, Deputy Director of the Institute, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Ukraine

Abstract

The problem of mining safety in outburst-prone coal seams has not yet been fully studied and resolved, so research related to outbursts continues to be relevant for many coal-mining countries. The purpose of this work is to study the coupled processes of elastoplastic deformation of a coal seam, methane filtration and desorption, which occur in the outburst-prone zone of the coal seam, and to establish the regularities of their joint flow. Numerical simulation methods were used to solve this problem.

Simulation of the joint flow of geomechanical and filtration processes in the outburst-prone zone, on its border and beyond it was made. The regularities of changes in geomechanical and filtration parameters in the near-face zone of the coal seam, as well as the regularities of the influence of moisture on the outburst hazard, were established. The developed numerical model allows to identify a safe limit of moisture saturation, at which the nature of geomechanical and filtration processes in the coal seam are quasi-stationary but not dynamic for the specific geological conditions. The influence of the unloading chink on gas-dynamic processes was studied. It was shown, when using an unloading chink, a zone completely unloaded from rock pressure is formed near the mine face, in which the occurrence of cracking and destruction processes is excluded. The use of the unloading chink significantly slows down the process of fracturing, which prevents the onset of dynamic phenomena.

Key words: coal and gas outburst, coupled processes, elastoplastic deformation, methane filtration, mining safety, moistening, numerical simulation, unloading chink.

1 Introduction

Coal and gas outbursts threaten the safety of mining operations in the coal mines and are one of the main obstacles to the intensification of underground mining and the introduction of new technologies for mining coal seams [1-4]. In the process of outburst, a large amount of gas and fractured coal mass is thrown into the roadway. Rapidly released energy can cause serious damage to mine personnel and production equipment. This problem has not yet been fully studied and resolved, so research related to outbursts continues to be relevant for many coal-mining countries [5-8], including China, Australia, the USA, Ukraine, etc.

Coal and gas outbursts occur in gas-bearing coals, which have a certain composition and physical and mechanical properties, under the influence of static and dynamic stress fields [9, 10]. Both the properties and stress state are the result of the influence of geological and technological factors [11-14].

These dynamic phenomena occur under conditions of rapidly increasing permeability, which depends on the change in stressed state of the medium and gas pressure in its pores and cracs. On the other hand, the change in gas pressure and its desorption depend on gas permeability. This two-way relationship significantly affects both gas filtration in the fractured porous medium and the occurrence and flow of coal and gas outbursts. The complex interrelation of these processes has not yet been fully studied, and the negative consequences of gas-dynamic phenomena continue to complicate mining operations in outburst-prone coal seams.

The purpose of this work is to study the coupled processes of elastoplastic deformation of a coal seam, methane filtration and desorption, which occur in the outburst-prone zone of the coal seam, and to establish the regularities of their joint flow, which will allow us to significantly approach the understanding of this very complicated phenomenon.

To achieve the goal, the following tasks were set:

- to develop a mathematical model of coupled processes of elastoplastic deformation of coal, filtration and desorption of methane in a disturbed zone near a tectonic fault;
- to study the conditions for occurrence of gas-dynamic processes in the near-face zone of a coal seam;

- to study changes in geomechanical and filtration parameters in the near-face zone of a coal seam;
- to study the impact of some technological influences (moistening and unloading of the near-face zone using unloading chink) on the occurrence and flow of outbursts.

Modern computer technologies make it possible to solve complex problems associated with mining, rock mechanics, and, in particular, with coal and gas outbursts [12, 15-18], therefore numerical simulation is the best suited to achieve the above goal.

2 Methods

The coupled processes of the rock massif deformation and gas filtration in a disturbed area are described by a system of equations [19-21]

$$c_g \frac{\partial u_i}{\partial t} = \sigma_{ij,j} + X_i(t) + P_i(t)\,; \tag{1}$$

$$\frac{\partial p}{\partial t} = \frac{k_g}{2m\mu}\left(\frac{\partial^2 p^2}{\partial x^2} + \frac{\partial^2 p^2}{\partial y^2}\right) + q(t)\,, \tag{2}$$

where c_g - the damping coefficient, kg/(m^3·s); u_i - the displacements, m; t - time, s; $\sigma_{ij,j}$ - the derivatives of the stress tensor components along horizontal axis x and vertical axis y, Pa/m; $X_i(t)$ - the projections of the external forces acting on the volume unit of a solid body, N/m^3; $P_i(t)$ - the projections of forces due to gas pressure in the porous fractured space, N/m^3; p - the gas pressure, Pa; x, y - coordinates, m; k_g - the gas permeability coefficients, m^2; m - porosity; μ - gas viscosity, Pa·s; $q(t)$ - the gas release function, which models methane desorption from a coal seam, Pa/s.

In most cases, gas-dynamic phenomena occur near tectonic faults, where the coal will be ground and has an initial permeability on 10-20 m from both sides of the fault. Technological permeability k_{tech}, which depends on the components of the stress tensor [22], is superimposed on the field of initial, tectonic permeability k_{tect}

$$K = k_{tech} + k_{tect}; \tag{3}$$

$$k_{tech} = \begin{cases} 0 & if \;\; Q^* < 0.4;\;\; P^* > 0.2; \\ k_{\min} & if \;\; 0.4 < Q^* < 0.6; \\ 0.64Q^{*2} - 0.36Q^* + 0.02 & if \;\; 0.6 < Q^* < 1.0;\;\; P^* > 0.1; \\ k_{\max} & if \;\; Q^* > 1.0;\; P^* < 0.1;\ \text{in ZND}; \end{cases} \tag{4}$$

where K - absolute filtration permeability, m^2; $Q^*=(\sigma_1 - \sigma_3)/\gamma H$ – the parameter characterizing the diversity of the stress field components; $P^*=\sigma_3/\gamma H$ - the parameter characterizing the unloading of rocks from the rock pressure; σ_1, σ_3 - maximum and minimum components of the principal stress tensor, Pa; γ - the averaged weight of the overlying mine rocks, N/m^3; H - the mining depth, m; $k_{\min}$ - minimum permeability coefficient sufficient to start the filtration, m^2; $k_{\max}$ - fracture permeability, m^2; ZID - zone of inelastic deformation.

It is known that water affects the phase permeability, the amount of free gas in the crack-pore space and the methane filtration process [23, 24]. In the three-component medium "solid - gas - water" moving components (gas and water) move together in the crack-pore space of the solid with absolute filtration permeability K. On the other hand, the whole without exception the crack-pore space is filled with gas and water, with the content of s_g and s_w, respectively

$$s_g + s_w = 100\%.$$

That is, the permeability for the gas phase k_g depends on the water content

$$k_g = \left(1 - 0{,}01 s_w\right) K\ . \tag{5}$$

In addition, if the gas filtration rates $V_g = \sqrt{V_x^2 + V_y^2}$ become large, then the gas flow expands cracks in coal and gas permeability in areas with high speeds increases by a value that depends on V_g

$$k_g = \left(1 - 0{,}01 s_w\right) K\ + f(V_g). \tag{6}$$

The presence of water in the crack-pore space of coal reduces gas permeability and thus affects the process of gas filtration.

The initial and boundary conditions for the task are

$$\begin{aligned}
&\sigma_{yy}\big|_{t=0} = \gamma H; \quad \sigma_{xx}\big|_{t=0} = \lambda \gamma H;\\
&u_x\big|_{t=0} = 0; \quad u_y\big|_{t=0} = 0;\\
&p\big|_{t=0} = p_0;
\end{aligned} \tag{7}$$

$$
\begin{aligned}
&u_x\big|_{\Omega_1}=0; \quad u_y\big|_{\Omega_2}=0;\\
&p\big|_{\Omega_1}=p_0; \quad p\big|_{\Omega_2}=p_0;\\
&p\big|_{\Omega_3(t)}=p_0; \quad p\big|_{\Omega_4}=0.1\ \text{MPa};
\end{aligned}
\tag{8}
$$

where σ_{xx}, σ_{yy} - components of the stress tensor, Pa; λ - the side thrust coefficient; u_x, u_y - components of the displacement vector, m; p_0 - the methane pressure in the virgin massif, Pa; Ω_1 - the vertical boundaries of the outer contour; Ω_2 - the horizontal boundaries of the outer contour; $\Omega_3(t)$ - the time-varying boundary of the filtering area; Ω_4 - the internal contour (a roadway).

The conditions for the formation of the outburst cavity are the belonging of a finite element to the area of inelastic deformation caused by tensile stresses, and the fulfillment of the criterion for the filtration of methane gradient to exceed the critical value grad $p>P_c$, accepted here $P_c=2\cdot 10^7$ Pa/m.

For the mathematical description of the process of rocks transform into a disturbed state, the Mohr-Coulomb failure theory is applied. To solve the system of equations (1)-(6) with initial and boundary conditions (7) and (8) on a certain time interval, the finite-difference method is used [25].

It is assumed that at the initial time $t=0$ the distribution of stresses and pressure is given, and for sufficiently small values of Δt, we can obtain the distribution of stresses, methane pressure and its filtration rates at time point $t+\Delta t$ by using iterative relations of the finite-difference method.

This process continues from the initial state to any current time point.

The problem is solved by the finite element method embodied in authors' computer program. Fig. 1 shows the numerical calculation scheme.

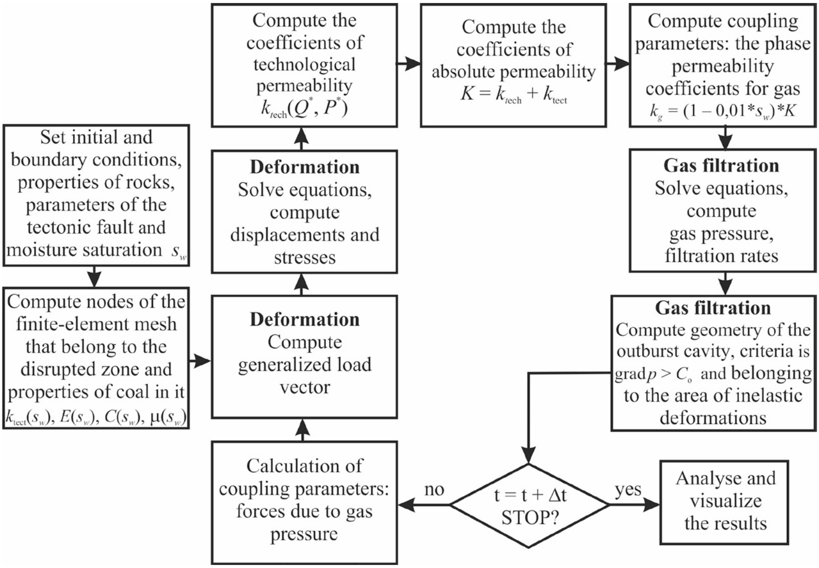


Fig. 1. The scheme of simulating the coupled processes of rock deformation and methane filtration, taking into account the influence of water contained in the fracture-pore space of coal

At each time iteration, in each finite element of the numerical model, the following parameters are calculated: stresses, zones of inelastic deformations, coefficients of technological permeability $k_{tech}(Q^*, P^*)$ caused by mining operations, coefficients of absolute permeability K as the sum of k_{tech} and k_{tect}, gas permeability coefficients k_g, gas pressure and filtration rates.

The most important step in creating complex models of coupled physical processes is their detailed verification. As for this model of the gas-dynamic processes, verification of both its individual modules (deformation and methane filtration) and the entire model as a whole was performed. The developed model of gas filtration in the disturbed area was verified by comparing calculated data on gas release into the well with analytical solutions [26], on the distribution of gas pressure around the well and the change in gas pressure in the undermined coal seam with experimental data [26]. The change in stressed state of rocks was compared with data on the displacement of the roadways contour. The model of coupled geomechanical and filtration processes was verified by comparing calculated parameters and mine data regarding the size of the outburst cavities and the amount of the burst coal [27].

3. Modeling of outburst-hazardous properties of coal near a tectonic fault

A significant part of coal and gas outbursts occurs near geological disturbances [9, 11, 28-31]. On flat coal seams, most of them are confined to disturbances with small amplitudes (up to 5 m), and the most dangerous are areas 10-20 meters wide on both sides of the disturbance [28]. Tectonics of coal seams is the root cause of the manifestation of such physical and mechanical properties of coal, which predetermine its outburst hazard [32].

When the layers were bent into folds and thrusts formed (Fig. 2*a*, 2*b*, 2*c*), stronger rocks moved along the most plastic and less strong coal seams. During layer-by-layer movement, the coal turned into a fine-grained aggregate consisting of fragments rotated relative to their original position and tightly pressed to each other [11].

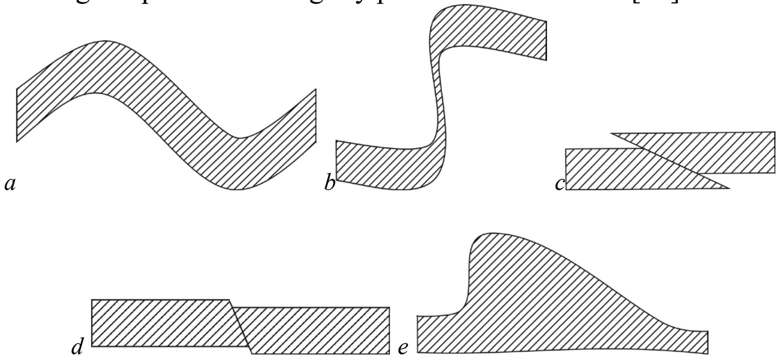


Fig. 2. Types of tectonic disturbances: *a* - fold; *b* - flexure; *c* - thrust; *d* - fault; *e* - swelling

Low-amplitude faults (Fig. 2*d*) arose as a result of shear and tensile stresses. After the formation of the crack zone, a larger rupture occurred in its most weakened part [33]. The formation of tectonic narrowings and swellings in the thickness of coal seams (Fig. 2*e*) is associated with the redistribution of the plastic mass of coal under the influence of tectonic stresses, as a result of layer-by-layer movements in the process of folding. These are particularly dangerous areas of mine fields in terms of coal and gas outbursts.

One of the necessary conditions for mathematical modeling of coupled geomechanical and filtration processes near a tectonic disturbance is to specify the properties of coal in the disturbed zone [34], Fig. 3.

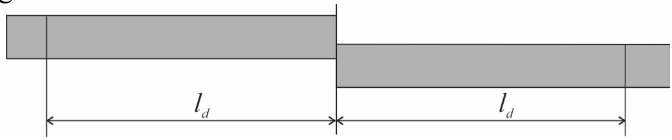


Fig. 3. Coal seam section with tectonic fault

In this work, it was accepted that cohesion C decreases linearly and permeability k_{tect} increases linearly from the boundary of disrupted zone to the tectonic fault; the tensile strength σ_τ is approximately zero

$$
\begin{aligned}
&C = C_0 - \frac{(C_0 - C_{\min})(x_d + l_d - x)}{l_d};\\
&k_{tect} = \frac{k_{\max}(x_d + l_d - x)}{l_d}; \qquad (9)\\
&\sigma_\tau \approx 0; \quad for\ x \in \left[x_d; x_d + l_d\right].
\end{aligned}
$$

where C_0 - the coal cohesion in the unbroken zone, MPa; $C_{\min}$ - the minimum cohesion value in the broken zone, MPa; x_d - x coordinate of the tectonic fault (Fig. 3), м; l_d - the length of the broken zone, м; σ_τ -tensile strength, MPa.

4 Flow of gas-dynamic processes in the near-face zone of a coal seam nearby tectonic faults

For calculations it was taken, that the mine face of 3 m height is at a distance of L from the tectonic fault with a displacement amplitude of 1 m, surrounded by a ten-meter zone of disrupted coal (l_d=10 m). The coal seam thickness is 1.5 m, H=1000 m, m=10%. The gas content in coal is 20 m^3/t, p_0=8 MPa, s_w=1%. The host rock is argillite. Time step is 0.1 s.

If L>10 m and the mine face is located outside the tectonically disturbed zone, relative methane pressure (p/p_0) in the coal seam near the mine face decreases slowly (Fig. 4), the permeability increases evenly here, according to the change in stress, no cavities are formed in the coal seam; all processes are quasi-stationary in nature.

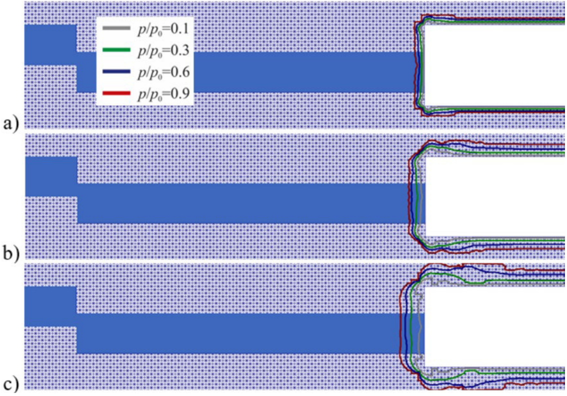


Fig. 4. Isobars of relative methane pressure ($L > 10$ m) at the time points: *a* - $t = 2$ s; *b* - $t = 6$ s; *c* - $t = 14$ s

If the distance between the fault and the mine face is L=10 m, methane pressure in the near-face part of the coal seam drops quickly (Fig. 5), pressure gradients take on high values, the rate of methane filtration increases significantly and the permeability of coal increases rapidly. Coal sloughs into the roadway and a small cavity is formed in the coal seam.

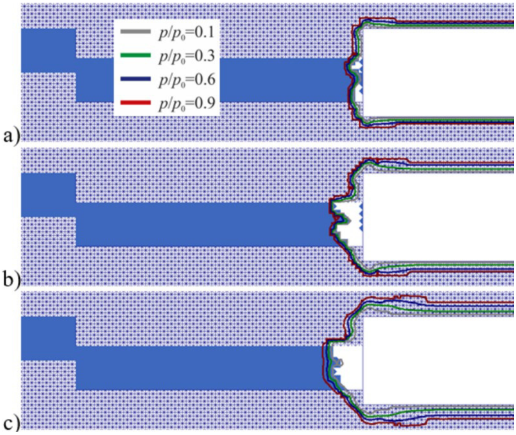


Fig. 5. Isobars of relative methane pressure ($L = 10$ m) at the time points: *a* - $t = 2$ s; *b* - $t = 4$ s; *c* - $t = 8$ s

However, this process ends quickly. Deformation of the coal seam and the process of methane filtration in the disturbed zone return to a quasi-stationary regime (Fig. 5*b*, 5*c*). During the first 4 seconds, a gas-dynamic phenomenon occurs, which, due to the small volume of burst coal, should be attributed not to an outburst, but to a coal sloughing.

Fig. 6 and 7 show the results of calculating the stress field, zones of inelastic deformation and relative gas pressure in the third case, when $L = 7.75$ m, in vertical and horizontal sections.

In the vicinity of a tectonic fault, in the zone of a disrupted coal seam, the area of increased diversity of the stress field components ($Q^* > 0.4$) rapidly increases into the coal seam. The zone of inelastic deformation (this zone is shown in red) is rapidly growing from the mine face (Fig.6, left side). Methane pressure in the coal seam near the mine face quickly falls, so the relative pressure isobars are tight to the exposed surface. The pressure gradients and the methane filtration rate take very high values, the permeability of coal is growing rapidly - coal is burst and a cavity is formed in the coal seam, the length of which reaches 6.25 m under given initial and boundary conditions.

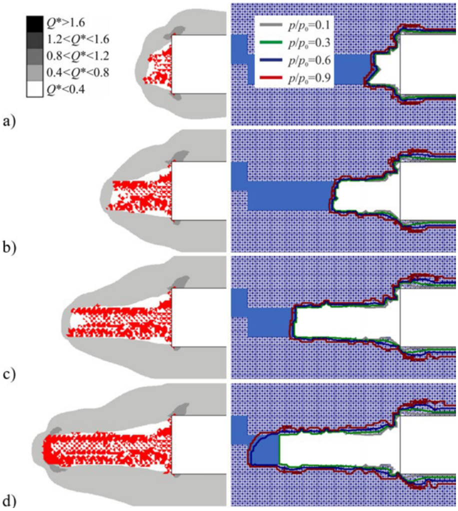


Fig. 6. Distributions of Q^* parameter values and inelastic deformation zones (left side), outburst cavities and isobars of relative methane pressure p/p_0 (right side) in the outburst-prone zone near the fault, vertical section: *a* - $t = 2$ s; *b*- $t = 4$ s; *c* - $t = 6$ s; *d* - $t = 10$ s

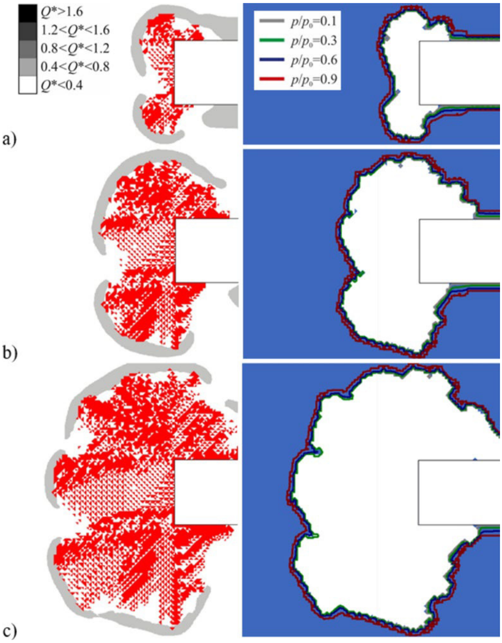


Fig. 7. Distributions of Q^* parameter values and zones of inelastic deformation (left side); outburst cavities and isobars of relative methane pressure (right side), horizontal section: *a* - $t = 2$ s; *b* - $t = 4$ s; c - $t = 10$ s

Then the growth of the cavity stops (Fig. 6*d*), the methane filtration rates fall, the pressure of methane in the coal seam continues to slowly decrease. The disruption process and the process of methane filtration return to the quasi-stationary regime. The duration of the dynamic process is 7 s. As it can be seen from Fig. 6, the outburst cavity is located within the coal seam and it is limited from above and below by the host rocks. The vertical section of the outburst cavity has a rectangular shape, with a curved end.

In the horizontal section, the shape of the outburst cavity also almost repeats the contour of the inelastic deformation zone (Fig. 7). It has the shape of an irregular ellipse, the major axis of which is perpendicular to the axis of the roadway.

At the "Hlyboka" mine of the Production Association "Donetskvuhillia", there was a sudden outburst in the gutter, horizon 719 m, coal seam h_8, during the removal of the rock mass (Fig. 8).

Outburst intensity was 60 tons of coal and 3000 m^3 of methane. The depth of the outburst cavity was 6 m, its width was 15 m [30].

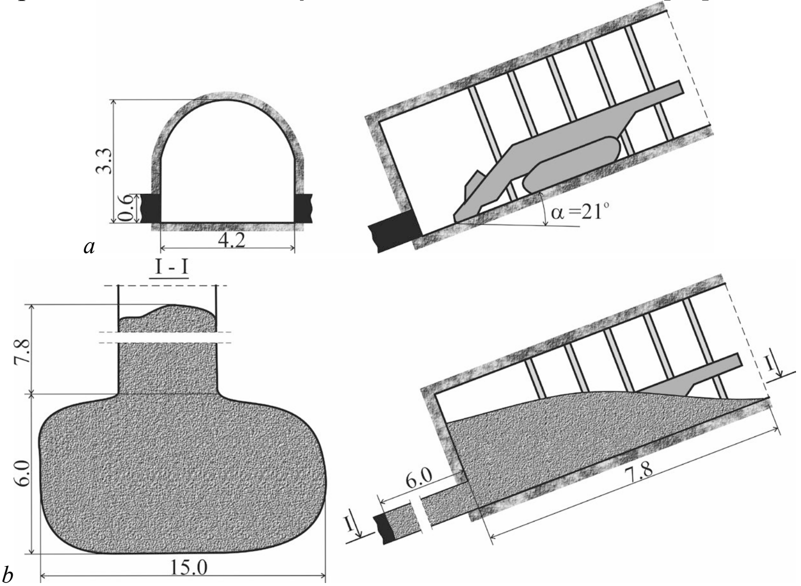
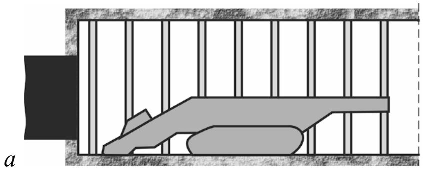


Fig. 8. The outburst cavity dimensions, the gutter in "Hlyboka" mine [30]: *a* - before the outburst; *b* - after the outburst

At the V.R. Menzhynskyi mine Production Association "Pervomaiskvuhillia", in the southern gutter, the horizon 845 m, coal seam l_4, during coal extraction with a jackhammer, a sudden outburst occurred near the tectonic fault (Fig. 9). Outburst intensity was 70 tons of coal and 5000 m^3 of methane [30].



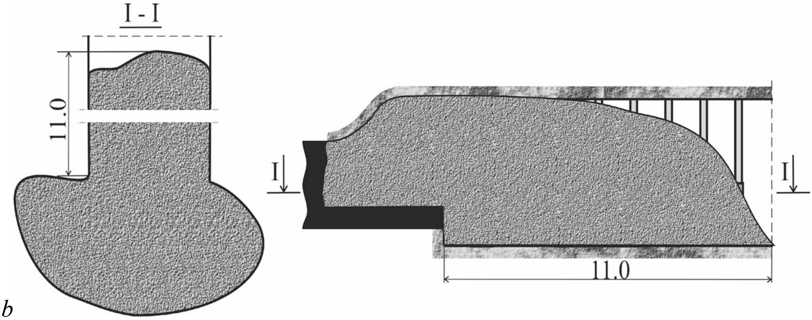


Fig. 9. The outburst cavity dimensions, the southern gutter in Menzhynskyi mine [30]: *a* - before the outburst; *b* - after the outburst

Thus, both calculated and actual data suggest that in the considered case the outburst cavity is located within the coal seam and it is limited from above and below by the host rocks.

The vertical section of the fracture cavity has a rectangular shape, possibly with a curved end, the horizontal section has the shape of an irregular ellipse, the major axis of which is perpendicular to the axis of the roadway [35, 36].

Comparing Fig. 6, 7 and 8, 9, we can see that, in general, the calculated shape of the outburst cavity in the near-face zone of the coal seam coincides with the actual data.

Let us consider the case when the properties of the rocks in the immediate roof of the seam, as well as the properties of coal, are weakened near a tectonic disturbance: cohesion C of argillite decreases linearly from the boundary of the disturbed zone to the tectonic disturbance, tensile strength σ_τ is reduced by half.

The distribution of Q^* parameter values and the relative methane pressure at different time points in the vertical section along the roadway are shown in Fig.10.

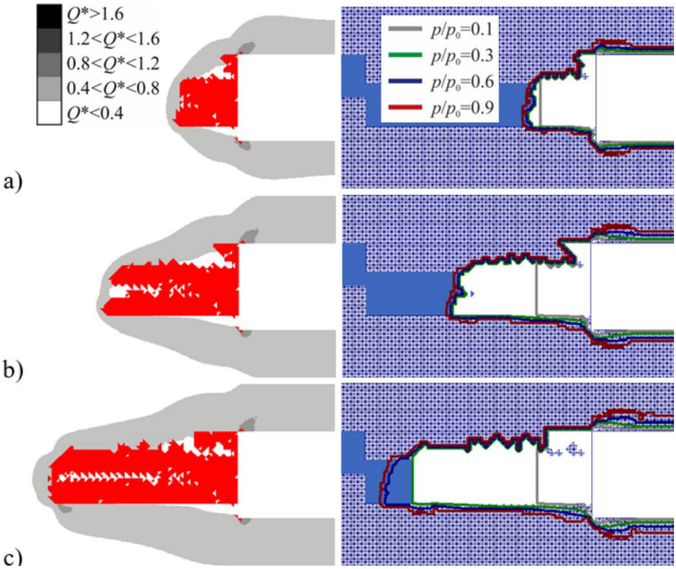


Fig. 10. Distributions of Q^* parameter values and inelastic deformation zones (left side), outburst cavities and isobars of relative methane pressure p/p_0 (right side) when properties of the host rocks are weakened near the tectonic fault: *a* - t =2 s; *b* - t =4 s; *c* - t =6 s

It can be seen that in this case part of the argillite above the coal seam is fractured. Near the face, the height of the cavity becomes equal to the height of the roadway. The simulation shows that if the properties of the host rock are weakened near a tectonic disturbance, then, during the outburst, it is fractured and thrown out along with coal from the growing cavity.

A similar situation was observed in the face of the transport drift of panel no. 33 near a tectonic disturbance (horizon 1012 m, coal seam M_8, Bazhanov mine, Production Association “Makeevugol”), where a sudden coal and gas outburst occurred during the stripping of the lower part of the seam by shaft-sinking set, Fig. 11. Outburst intensity was 80 tons of coal and 600 m^3 of methane. The depth of the outburst cavity was 5.8 m [30].

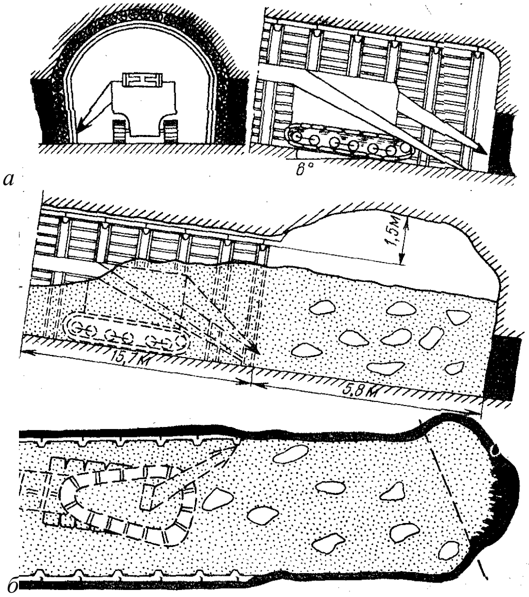


Fig. 11. The outburst cavity dimensions in the transport drift, Bazhanov mine [30]: *a* - before the outburst; *b* - after the outburst

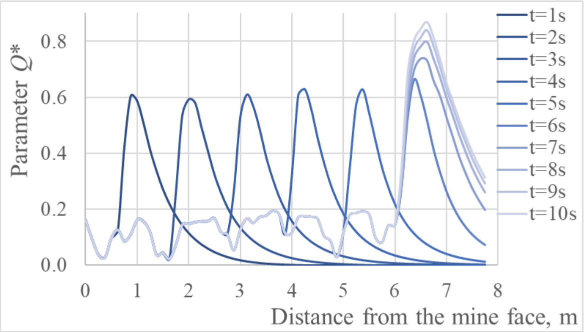
When analyzing the available statistical data on outbursts that occurred in the coal mines of Donbass [30], we find that:

- in the vertical section outburst cavities are located within the coal seam in 75% of cases, cavities capture host rocks in 25% of cases;
- in the horizontal section, outburst cavities have the shape of an irregular oval in 58% of cases, they are determined by the position relative to the tectonic fault and are limited to the fault plane in 32% of cases.

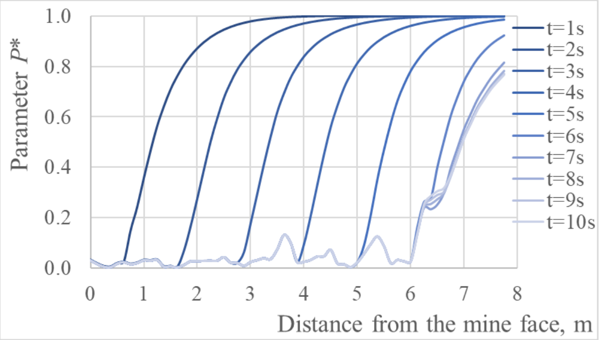
5 Changes in geomechanical and filtration parameters in the near-face zone

Graphs of changes in geomechanical and filtration parameters [37, 38] in the mine face, along the line that is perpendicular to the plane of the mine face and passes through the center of the coal seam, are shown in Fig. 12-14.

At the time interval $t<6$ s, the peak of Q^* parameter values, which is usually on the exposed surface, moves away from the mine face together with the newly formed surface of the outburst cavity at a speed of approximately 1 m/s for our initial and boundary conditions, Fig. 12*a*. Unloading of the coal seam from rock pressure (parameter P^*) also moves rapidly at the same speed (Fig. 12*b*).



a



b

Fig. 12. Changing of geomechanical parameters over time: *a* - Q^* parameter values; *b* - P^* parameter values

The shift of the maximum Q^* parameter values and the minimum P^* parameter values deep into the coal seam stops when t>6 s, at a distance of 6.25 m from the mine face.

Absolute permeability (Fig. 13*a*) in the area a few centimeters to the surface increases 6 times. Gas permeability, calculated by formulas (4)-(6), increases by the value of $f(V_g)$ in the boundary, near-surface zone, Fig. 13*b*, because the gas filtration rates are very high here, Fig. 14*b*.

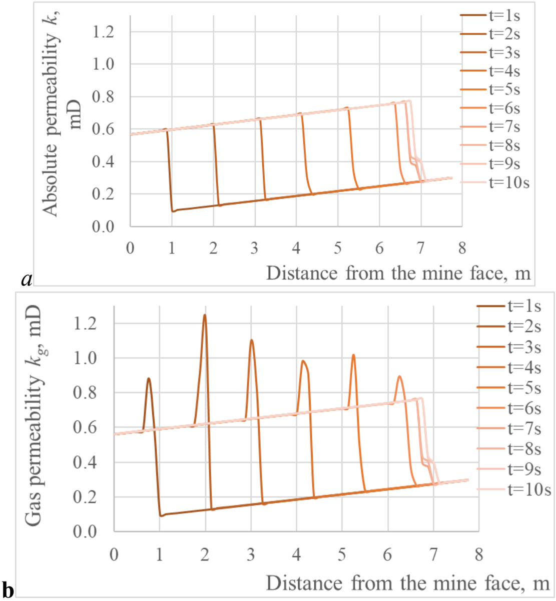
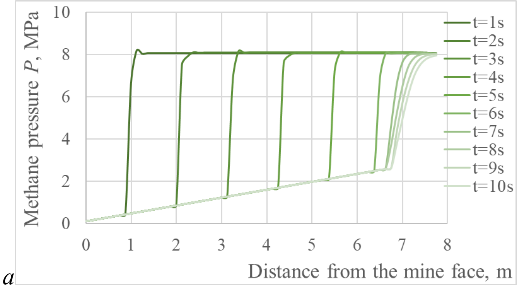


Fig. 13. Changing of values of permeability coefficients over time: *a* - absolute permeability; *b* - gas permeability

At the seventh second of coal and methane outburst, all processes slow down: the peak of parameter Q^* values increases, but now it does not move deep into the coal seam and reaches the mark of 6.5 m; coal permeability increases gradually; methane pressure gradually decreases in the near-surface zone and its filtration rate decrease, Fig. 14.



b

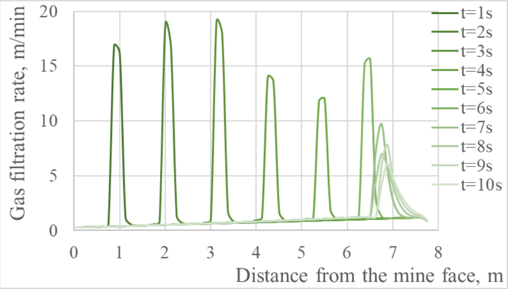


Fig. 14. Changing of geomechanical and filtration parameters over time, s_w = 1% *a* - gas pressure; *b* - gas filtration rate

6 The influence of moisture saturation on the occurrence and flow of outbursts

According to the Rules for mining operations on outburst-prone coal seams [39] coal seams wetting is used for preventing gas-dynamic processes. This method involves water injecting through long boreholes drilled within the coal seam from gateway in front of a longwall. It is well known that the presence of water in the crack-pore space of coal significantly affects the flow of gas-dynamic processes that are initiated during mining operations [40, 41].

First, moisture saturation leads to a decrease in the rock strength and bearing capacity, changes the nature of their behaviour after reaching the limiting state [42, 43]. The effect of fluids on the strength and deformation properties, on development of cracks formation process was studied in the works [43, 44]. The dependences of the effect of moistening of coal samples on their coefficient of elasticity *E* and Poisson's ratio *μ* were established in [44, 45]. Graphs based on these data are shown in Fig. 15.

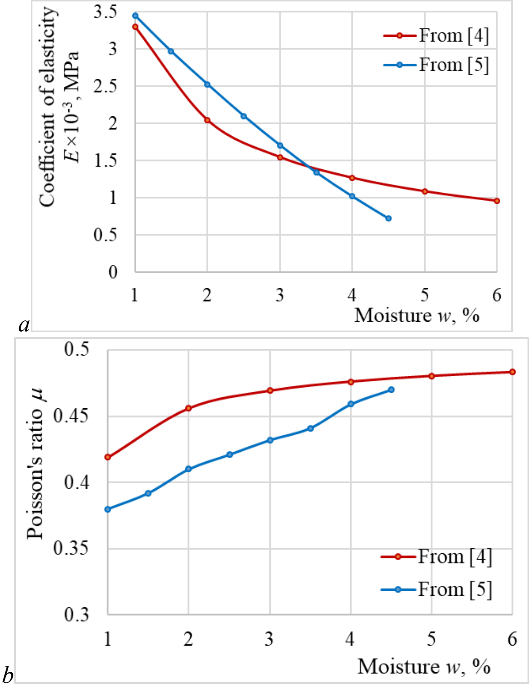


Fig. 15. Effect of moisture on the coal properties, according to [44, 45]: *a* - coefficient of elasticity; *b* - Poisson's ratio

With an increase in coal moisture ($w = 0.01s_w m$) from 3 to 6%, the coefficients of elasticity and shear decreased by 80-85%, the Poisson's ratio increased by 20%. This indicates an increase in the plastic properties of coal, reducing its ability to accumulate energy of elastic deformation and to brittle destruction.

Second, water affects the phase permeability, the amount of free gas in the crack-pore space and the methane filtration process, formula (5). Intensity of the process of gas (methane) sorption-desorption also depends on the water content in coal. Under different conditions and at certain values of moisture, the mechanism of influence of water on the flow of sorption-desorption processes changes.

Effect of reducing phase permeability on initiation of outbursts. All previous calculations were performed under the condition that moisture saturation was $s_w = 1\%$, and then s_w values in the crack-pore space of the coal seam varied in the interval [1%; 100 %].

Graphs of geomechanical and filtration parameters changing in the mine face, along the line passing through the center of the coal seam, for $s_w = 30\%$ are shown in Fig. 16-18.

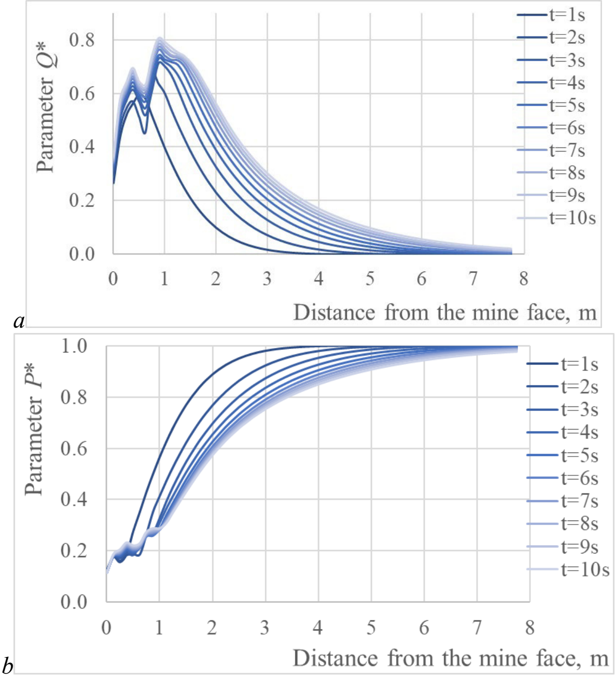


Fig. 16. Changing of geomechanical parameters over time, $s_w = 30\%$: *a*- Q^* parameter values; *b*- P^* parameter values

In the studied moments of time the peak of Q^* parameter values is at a distance of about 1 m from the mine face, Fig. 16*a*. Fluctuations in the Q^* and P^* parameters values near the surface of the mine face are due to influence of the zone of inelastic deformations. Unloading of the coal seam from rock pressure (Fig. 16*b*) and the drop in methane pressure (Fig. 18*a*) are slow.

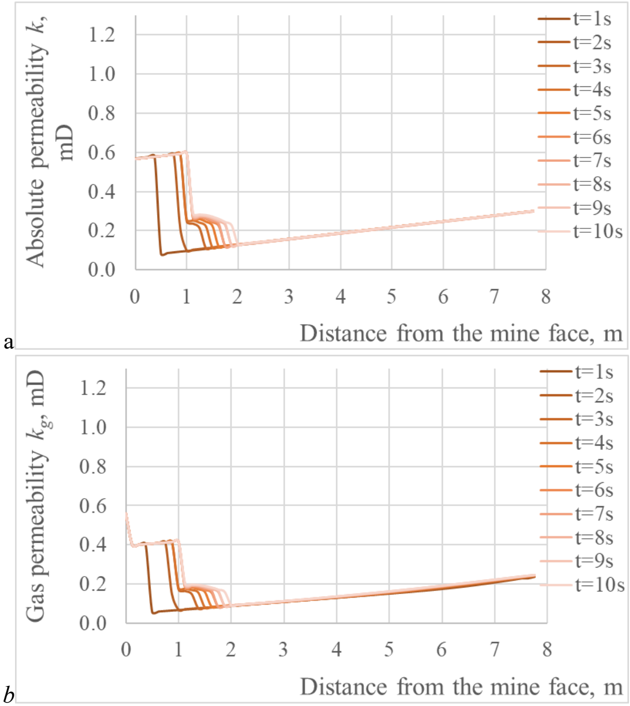


Fig. 17. Changing of values of permeability coefficients over time, s_w = 30% *a*-absolute permeability; *b*-gas permeability.

Absolute permeability and gas permeability spread deep into the coal seam faster with the growth of the zone of inelastic deformations, and outside it this process also slows down, Fig. 17*a* and 17*b*. Gas permeability in this case is devoid of the nonlinear component $f(V_g)$, because the gas filtration rates do not exceed critical values, Fig. 17*b*. By comparing the graphs in Fig. 17*a* and 17*b*, one can see that gas permeability differs from the absolute permeability by 30% - this is the portion of the crack-pore space of coal occupied by water.

As a result of calculations it was obtained that gas-dynamic processes start in the mine face if $s_w < 24\%$. When this limit is exceeded, geomechanical and filtration processes in the coal seam near the mine face do not start.

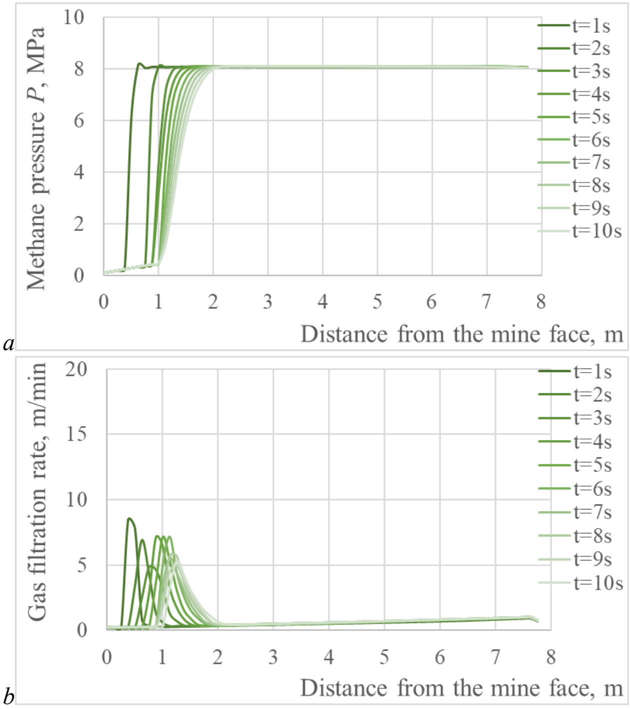


Fig. 18. Changing filtration parameters over time, s_w = 30%: *a*-gas pressure; *b*- gas filtration rate

That is, for the above boundary and initial conditions, the effect of moisture on the reduction of phase permeability for methane leads to the neutralization of the outburst-hazardous properties of coal under the condition of $s_w \geq 24\%$. Under this condition, the flow of the studied processes occurs in a quasi-stationary mode.

Effect of change of coal properties during moistening on initiation of gas-dynamic processes. Based on experimental data in [44, 45], it is shown that moisture saturation affects the coefficient of elasticity of coal E and the Poisson's ratio μ. We calculated how the studied processes occur with taking into account the change in these coal properties with increasing moisture content s_w. For the calculations, E and Q^* values were taken according to [44, 45], Fig. 15. As a result of numerical calculations with variation of s_w, it was found that: Q^* values (parameter that characterizes different-component nature of the stress field) markedly decrease in the coal seam in front of the zone of inelastic deformations; the area of the zone of inelastic deformations in the mine face is also reduced; the growth rate of the zone of inelastic deformations (coal seam destruction) and the outburst cavity slows down [46].

If s_w=20%, E=2287 MPa and μ=0.433, any gas-dynamic phenomena do not occur in the mine face. The peak of parameter Q^* values is less than 1 m from the mine face. Unloading of the coal seam from rock pressure and falling methane pressure are slow. Gas permeability spreads deep into the coal seam with the growth of zone of inelastic deformations; it is devoid of nonlinear component, because the gas filtration rates do not exceed critical values. In this case, safe limit of moisture saturation decreases to s_w = 20%, for the boundary and initial conditions accepted in this work.

Thus, the regularities of the influence of moisture on the outburst hazard of coal seams were established. The numerical model was developed that allows to identify a safe limit of moisture saturation, at which the nature of geomechanical and filtration processes in the coal seam changes from dynamic to quasi-stationary in specific geological conditions.

7 The influence of vertical unloading of the near-face zone of the coal seam on the occurrence of outbursts

Unloading chinks in host rocks are used to prevent coal and gas outbursts, extrusions of coal, and rock bursts during roadways driving by shaft-sinking set on thin coal seams [39]. The unloading chink is created by pre-excavating the rock in the roof or floor of the coal seam to a depth of at least 2 m. Between the unloading chink and the coal seam, a protective rock layer with a thickness of at least 0.5 m is left. The unreduced leading of the unloading chink in the direction of roadway driving should be at least 1 m. The minimum height of the chink is 0.4 m, its maximum height is not limited [39].

For the simulation, we considered the case when the mine face is located at a distance of 8.75 m from the tectonic fault, the mining depth is 1200 m. Other conditions remained the same as in the previous calculations.

Fig. 19 shows the simulation results. From the figures it is clear that there is a sharp decrease in methane pressure in the near-face zone of the coal seam. High values of pressure gradients and filtration rates, as well as tensile stresses on the free surface lead to the separation of plates of tectonically disturbed coal. The spalling of coal causes instantaneous exposure of a new face surface. The minimum component of the stress tensor on this surface is zero, and in the immediate vicinity of it significant compressive stresses of the bearing pressure still remain. Then the next surface layer is exposed and the whole process is repeated again.

Under these boundary and initial conditions, the duration of the gas-dynamic process is 11 s. In the first seconds, the outburst is initiated; in the interval of 2-10 s the outburst process continues, at 10-11 s this process stops. During this time, the methane pressure in the coal seam near the mine face quickly drops, the permeability of coal increases rapidly; coal is ejected and a cavity is formed in the coal seam (Fig. 19*a*-19*e*) the length of which reaches 7.75 m. Then the growth of the cavity stops (Fig. 19*f*) the methane pressure in the coal seam continues to slowly decrease; geomechanical and filtration processes return to a quasi-stationary regime.

Next, we simulate the flow of deformation and filtration processes if, under the same initial conditions, the roadway is driven with an unloading chink 2 m deep in the host rocks, Fig. 20.

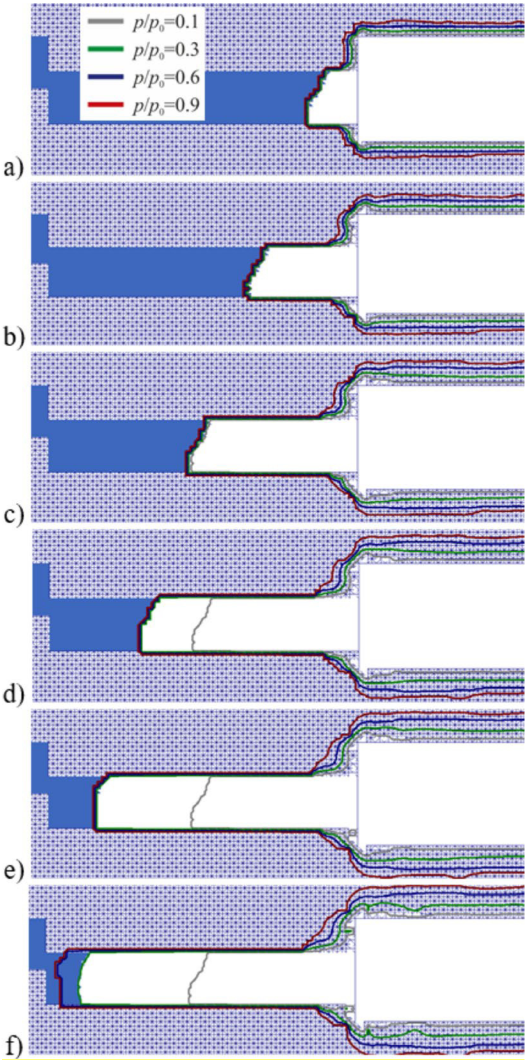


Fig. 19. Isobars of relative methane pressure at the time points: *a*- $t = 2$ s; *b*- $t = 4$ s; *c*- $t = 6$ s; *d*- $t = 8$ s; *e*- $t = 10$ s; *f*- $t = 12$ s

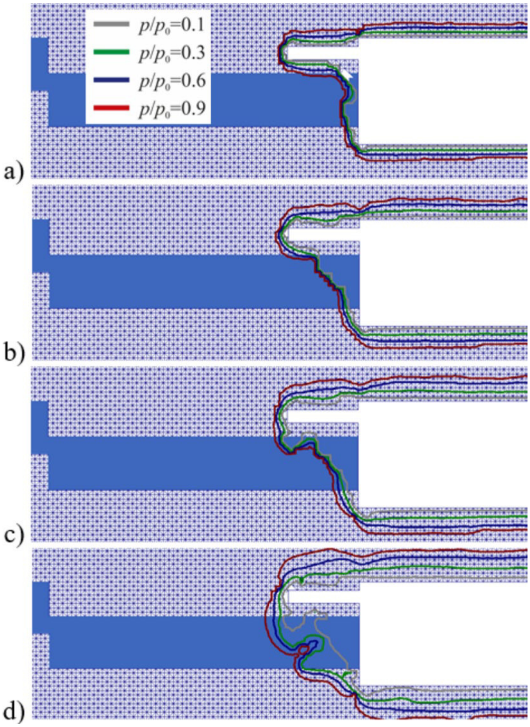


Fig. 20. Isobars of relative methane pressure in the roadway with the unloading chink at the time points: *a*- $t = 2$ s; *b*- $t = 4$ s; c- $t = 6$ s; *d*- $t = 12$ s

In this case, the coal and gas outburst does not occur, the outburst cavity is not formed. Isobars of relative methane pressure, limiting the degassed area, gradually move away from the mine face. Over the considered time period, the unloaded and degassed area extends to a depth of up to 2 m [47-49].

The unloading chink significantly changes the stress distribution in the near-face zone, Fig. 21.

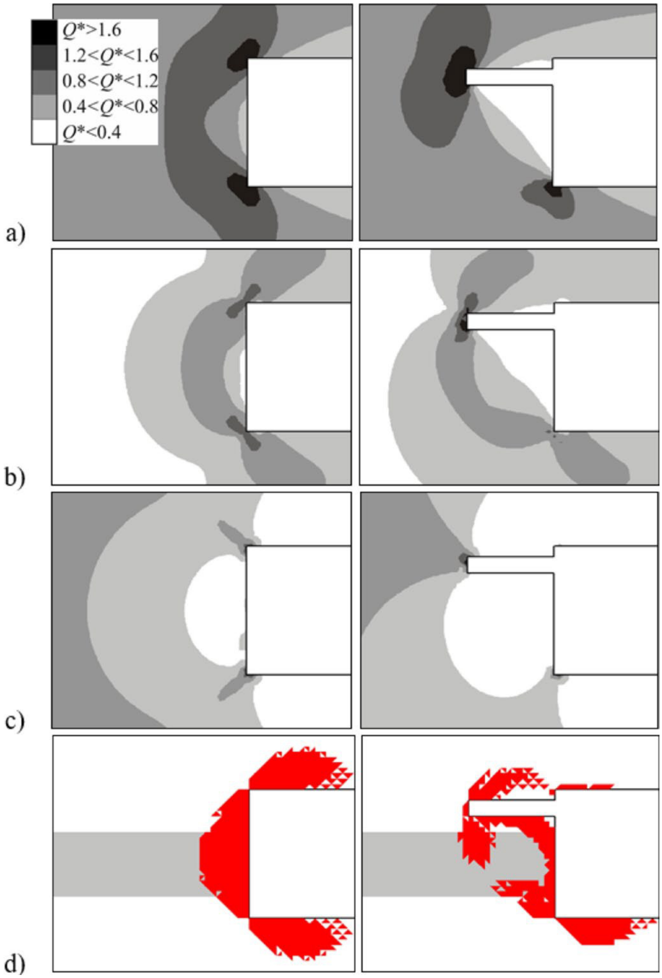


Fig. 21. Distributions of geomechanical parameters values in the roadway without the unloading chink (on the left side) and in the roadway with the unloading chink (on the right side): *a* -$\sigma_1/\gamma H$; *b*- Q^* parameter; *c*- P^* parameter; *d*- zones of inelastic deformations

The distribution of the reduced maximum component of the principal stress tensor, which is shown in Fig. 21*a* on the right side, reveals a large zone located under the unloading chink, where $\sigma_1/\gamma H<0.4$. The length of this zone is equal to the length of the unloading chink. In the roadway without the unloading chink (Fig. 21*a*, the left side), maximum stresses in the near-face zone were not lower than 0.4. On the contrary, the maximum abutment pressure was located within the two-meter near-face zone. In the presence of the unloading chink, the abutment pressure zone moves from the near-face region of the roadway to the near-face region of the unloading chink (Fig. 21*b*, the right side).

The spread of the zone of increased difference of the stress tensor components (Q^* parameter), in which the process of crack formation is actively occurring, deep into the coal seam slows down, and the peak of Q^* parameter values moves away from the mine face (Fig. 21*b*, the right side). The area of rocks unloaded from rock pressure, where $P^* < 0.4$, in the roadway with the unloading chink increases significantly compared to the one without the unloading chink (Fig.21*c*).

Breaking of the near-face part of the coal seam begins from the face of unloading chink downward and from the lower corner of the mine face upwards. Then these zones are closed, covering the coal seam at a distance of 2 m from the mine face, which is equal to the depth of the unloading chink (Fig. 21*d*).

The near-face stresses in the roadway with the unloading chink are radically different from the stresses in the roadway without the unloading chink. The peak Q^* and $\sigma_1/\gamma H$ parameters values are moved from the position of 0.75 m from the plane of mine face to the depth of unloading chink. At the same time, both the difference of the stress tensor components and the maximum stress remain at a low level and, in a long time interval, ensures deformation of the near-face zone in the elastic mode. Unloading of this zone from rock pressure occurs in two directions: in the direction of the mine face and in the direction of the unloading chink, therefore P^* parameter values for this case are the least [50].

Thus, when using an unloading chink, a zone completely unloaded from rock pressure is formed near the mine face, in which the occurrence of cracking and destruction processes is excluded.

The use of an unloading chink significantly slows down the process of fracturing, which prevents the onset of dynamic phenomena.

8 Conclusions

The mathematical model of the coupled processes of elastoplastic deformation of a coal seam, methane filtration and desorption, which occur in the outburst-prone zone of the coal seam, was developed to study the conditions for the occurrence and regularities of gas-dynamic phenomena flow.

The problem formulation takes into account the changes in the properties of coal near tectonic disturbances, the influence of coal moisture on phase permeability, an increase in permeability at high gas filtration rates.

Simulation of the joint flow of geomechanical and filtration processes in the outburst-prone zone, on its border and beyond it was made. It was demonstrated that when a mine face is in an undisrupted area of the coal seam, methane pressure decreases slowly, an outburst cavity does not form, all processes are quasi-stationary in nature.

At the border of the outburst zone, coal sloughs from the seam into the roadway and a small cavity is formed in the coal seam.

In the vicinity of a tectonic fault, in the zone of a disrupted coal seam, the zone of inelastic deformation grows rapidly from the mine face deep into the coal seam.

Methane pressure near the mine face quickly falls and a cavity is formed in the coal seam. Mine data confirms the correctness of the numerical calculation of the shape of the outburst cavity.

The regularities of changes in geomechanical and filtration parameters in the near-face zone of the coal seam were established. During coal and gas outburst, the peak of Q^* parameter moves away from the mine face together with the newly formed surface of the outburst cavity. Absolute permeability in the area a few centimeters to the surface increases 6 times.

When all processes slow down, the peak of Q^* parameter values increases, but now it does not move deep into the coal seam; coal permeability increases gradually; methane pressure gradually decreases in the near-surface zone and its filtration rate decrease.

The regularities of the influence of moisture on the outburst hazard of coal seams were established. The developed numerical model allows to identify a safe limit of moisture saturation, at which the nature of geomechanical and filtration processes in the coal seam changes from dynamic to quasi-stationary in specific geological conditions.

The influence of the unloading chink on gas-dynamic processes was studied. It was shown that when using an unloading chink, a zone completely unloaded from rock pressure is formed near the mine face, in which the occurrence of cracking and destruction processes is excluded. The use of the unloading chink significantly slows down the process of fracturing, which prevents the onset of dynamic phenomena.

References

1. **Shevelev, G.A.** (1989). Dynamics of coal, rock and gas outbursts. Naukova dumka.
2. **Liang, W.** et al. (2013). Safety technologies for the excavation of coal and gas outburst-prone coal seams in deep shafts, International Journal of Rock Mechanics & Mining Sciences, 57, 24–33. https://doi.org/10.1016/j.ijrmms.2012.08.006
3. **Ruilin, Z., & Lowndes, I.S**. (2010). The application of a coupled artificial neural network and fault tree analysis model to predict coal and gas outbursts. International Journal of Coal Geology, 84, 141–152. https://doi.org/10.1016/j.coal.2010.09.004
4. **Shu, L., Wang, K., Liu, Z., Zhao, W., Zhu, N., & Lei, Y**. (2022). A novel physical model of coal and gas outbursts mechanism: Insights into the process and initiation criterion of outbursts. Fuel, 323, Article 124305. https://doi.org/10.1016/j.fuel.2022.124305
5. **Li, H.** (2001). Major and minor structural features of a bedding shear zone along a coal seam and related gas outburst, Pingdingshan coalfield, northern China. International Journal of Coal Geology, 47(2), 101–113. https://doi.org/10.1016/S0166-5162(01)00031-3
6. **Hardgraves, A.J.** (1983). Instantaneous outbursts of coal and gas: a review. Proceedings of the Australian Institute of Mining and Metallurgy, 285(3), 1–37.
7. **Williams, R.J., & Weissmann, J.J.** (1995). Gas emission and outburst assessment in mixed CO_2 and CH_4 environments. Proc. ACIRL Underground Mining Sem. Australian Coal Industry Res. Lab., 12.
8. **Aguado, M.B.D., & Nicieza, C**.G. (2007). Control and prevention of gas outbursts in coal mines, Riosa–Olloniego coalfield, Spain. International Journal of Coal Geology, 69(4), 253–266. https://doi.org/10.1016/j.coal.2006.05.004
9. **Zabigaylo, V.E., & Nikolin, V.I.** (1990). The influence of rock catagenesis and coal metamorphism on their outburst hazard. Naukova dumka.
10. **Krukovska, V.V.** (2012) Features of the process of the coal and gas outburst in the roadway face at various ways of development. Geo-Technical Mechanics, 102, 88–93.
11. **Zabigaylo, V.E.,** et al. (1980). Geological conditions of outburst hazard in Donbass coal seams. Naukova dumka.

12. **Xua, T., Tanga, C.A., Yangc, T.H., Zhuc, W.C., & Liu, J.** (2006). Numerical investigation of coal and gas outbursts in underground collieries. International Journal of Rock Mechanics & Mining Sciences, 43(6), 905–919. https://doi.org/10.1016/j.ijrmms.2006.01.001

13. **Cao, Y., He, D., & Glick, D.C.** (2001). Coal and gas outbursts in footwalls of reverse faults. International Journal of Coal Geology, 48, 47–63. https://doi.org/10.1016/S0166-5162(01)00037-4

14. **Krukovskaya, V.V.** (2014). Influence of penetration depth in outburst danger zone on the gas-dynamic processes near tectonic displacement. Geo-Technical Mechanics, 119, 100–111.

15. **Tu, Q., Cheng, Y., Liu, Q., Guo, P., Wang, L., Li, W., & Jiang, J.** (2018). Investigation of the formation mechanism of coal spallation through the cross-coupling relations of multiple physical processes. International Journal of Rock Mechanics and Mining Sciences, 105, 133–144. https://doi.org/10.1016/j.ijrmms.2018.03.022

16. **Qin, H., Wei, J., & Li, S.** (2019). Analysis of the coal seam spalling–failure mechanism based on the seepage instability theory. PLOS ONE, 1–18. https://doi.org/10.1371/journal.pone.0219735

17. **Zhu, W**. et al. (2007). Analysis of coupled gas flow and deformation process with desorption and Klinkenberg effects in coal seams. International Journal of Rock Mechanics & Mining Sciences. https://doi.org/10.1016/j.ijrmms.2006.11.008

18. **Yankun, M., Xueqiu, H., & Zhaohua, L**. (2020). A unified model with solid-fluid transition for coal and gas outburst and FEMLIP modeling. Tunnelling and Underground Space Technology, 99, Article 103349. https://doi.org/10.1016/j.tust.2020.103349

19**. Krukovskyi, O.P.** (2011). Modelling changes of stress-strain state of solid edge during the distance of working face of mine workings. Problemy obchysliuvalnoi mekhaniky i mitsnosti konstruktsii, 17, 175–181.

20. **Basniev, K.S., Dmitriev, N.M., Kanevskaya, R.D., & Maksimov, V.M.** (2006). Underground fluid mechanics. Institute for Computer Research.

21. **Krukovskyi, O., & Krukovska, V.** (2019). Numerical simulation of the stress state of the layered gas-bearing rocks in the bottom of mine working. E3S Web of Conferences. International Conference Essays of Mining Science and Practice, 109, Article 00043. https://doi.org/10.1051/e3sconf/201910900043

22. **Krukovska, V.V.** (2015). Simulation of coupled processes that occur in coal-rock massif during mining operations. Geo-Technical Mechanics, 121, 48–99.

23. **Krukovska, V.V.** (2022). Numerical analysis of influence of coal seams water saturation after water injection on their outburst hazard. Geo-Technical Mechanics, 161, 14–27. https://doi.org/10.15407/geotm2022.161.014

24. **Krukovska, V.V.** (2021). Numerical analysis of influence of coal bed moisture on outburst hazard. Science and society, patterns and trends of development: Abstracts of XVI International Scientific and Practical Conference, 233–236. https://doi.org/10.46299/ISG.2021.I.XVI

25. **Zienkiewicz, O.C., & Taylor, R.L.** (2000). The finite element method. Butterworth-Heinemann.

26. **Krukovskaya, V.V.** (2006). Preparation method of calculation of methane filtration parameters with the account a mode of stressedly-deformed state of coal-rock mass. M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine.

27. **Krukovskaya, V.V**. (2013). The development of the coupled processes theory in the application to geomechanics of coal-rock massif. M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine.

28. **Zabigaylo, V.E., Lukinov, V.V., Pimonenko, L.I., & Sahnevich, N.V.** (1994). Tectonics and mining and geological conditions for the development of coal deposits in Donbass. Naukova dumka.

29. **Shepherd, J., Rixon, L.K., & Griffiths, L. (**1981). Outbursts and Geological Structures in Coal Mines: A Review. International Journal of Rock Mechanics and Mining Sciences, 18, 267–283.

30. Catalogue of sudden coal and gas outbursts in mines. (1989). Research Institute of Mining Geomechanics and Mine Surveying, Ukrainian Branch.

31. **Antsiferov, A.V., & Golubev, A.A**. (2006). A new approach to the problem of sudden outbursts. Coal of Ukraine, 5, 34–37.

32. **Baranov, V.A.** (2021). Comprehensive forecast of rock outburst hazard. Publisher Belaya E.A.

33**. Meng, ZP, Peng, SP, & Li, H.** (2001). Influence of normal faults on the physical and mechanical properties of coal and the distribution of underground pressure. Journal of China Coal Society, 26(6), 561–566.

34. **Krukovska, V.V., & Krukovskyi, O.P.,** (2008). Computer modelling of outburst of coal and methane process near to various tectonic displacements. Geo-Technical Mechanics, 80, 238–250.

35. **Krukovskyi, O.P., Krukovska, V.V., & Zhang W.** (2020). Outburst cavity formation in the working face driven along the outburst-prone coal seam. II International Conference Essays of Mining Science and Practice 2020. E3S Web of Conferences, 168, 00052. https://doi.org/10.1051/e3sconf/202016800052

36. **Krukovskaya, V.V.** (2015). About form of outburst cavity in mine working at roadheading by outburst coal seam. Geo-Technical Mechanics, 125, 216–228.

37. **Krukovskiy, A.P., & Krukovskaya, V.V.** (2015). Changing of geomechanical parameters of gas-saturated coal-rock massif under gas-dynamic phenomena. Geo-Technical Mechanics, 122, 57–66.

38**. Krukovska, V.V.** (2008). Change of coal permeability and parameters of the methane flow at the outburst front. Geo-Technical Mechanics, 78, 34–42.

39. SOU 10.1.00174088.011-2005. Rules for conducting mining operations on strata prone to gas-dynamic phenomena. (2005). Ministry of Coal Industry of Ukraine.

40. **Bulat, A.F., Skipochka, S.I., Palamarchuk, T.A., & Antsyfierov, V.A.** (2010). Methane generation in coal seams. Lira LTD.

41. **Bulat, A.F., Krukovska, V.V., Krukovskyi, O.P., & Zberovskyi, V.V.** (2012). Numerical simulation of hydroimpulsive impact on outburst coal seam. Geo-Technical Mechanics, 105, 14–25.

42. **Gu, H**. et al. (2019). The effects of water content and external incident energy on coal dynamic behavior, International Journal of Rock Mechanics and Mining Sciences, 123, Article 104088. https://doi.org/10.1016/j.ijrmms.2019.104088

43. **Makieiev, S.Iu., Pylypenko, Yu.N., Ryzhov, H.A., Andrieiev, S.Iu., & Bobro, M.T.** (2012). Study of the influence of fluids on the deformation properties of coal and rocks under different load conditions, Suchasni resursoenerhozberihaiuchi tekhnolohii hirnychoho vyrobnytstva, 2(10), 73–82.

44. **Petuhov, I.M., Litvin, V.A., Kucherskiy, L.V.** et al. (1969). Rock bursts and their control in the mines of the Kizel basin. Perm book publishing house.

45. **Artamonov, V.N., & Nikolaev, E.B**. (2020), Forecasting changes in dust formation by hydraulic impact during drilling and blasting in coal mines, Proceedings of the IV scientific-practical conference Donbas 2020: science and technology for production, 89–96.

46. **Krukovska, V.V., Krukovskyi, O.P., Kocherga, V.M., & Kostrytsia, A.O**. (2022). Solving coupled problems of geomechanics and gas filtration for mining safety ensuring. Geo-Technical Mechanics, 160. 106–122. https://doi.org/10.15407/geotm2022.160.106

47. **Krukovska, V.V., & Krukovskyi, O.P.** (2011). Primenenie razgruzochnyih polostey pri provedenii podgotovitelnyih vyirabotok po vyibrosoopasnyim plastam [The use of unloading cavities when preparatory roadways are driven on outburst-hazardous seams]. Materials of the international conference Forum hirnykiv-2011, 121–127.

48. **Krukovskyi, O.P., & Krukovska, V.V.** (2011). Modeling acting unloading caves by roadheading on coal seams, which dangerous by gas and coal emission. News of Tula State University. Geosciences, 1, 129–136.

49. **Krukovska, V.V., & Krukovskyi, O.P.** (2010). Computer simulation of the action of unloading cavities to prevent gas-dynamic phenomena in the face of preparation roadway. Materials of the XX International Scientific School "Deformation and fracture of materials with defects and dynamic phenomena in rocks and workings", 172–174.

50. **Krukovska, V.V., & Krukovskyi, O.P.** (2023). Formation of the near-face stress field under the influence of natural and technological factors. Geo-Technical Mechanics, 165, 97–116. https://doi.org/10.15407/geotm2023.165.097