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NUMERICAL ANALYSIS OF INFLUENCE OF COAL SEAMS WATER SATURATION AFTER WATER INJECTION ON THEIR OUTBURST HAZARD

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Abstract. The influence of water on the outburst hazard of coal seams by changing the phase permeability and coal properties was investigated. To do this, a numerical model of the gas-dynamic processes in the mine face in the outburst-prone zone near the tectonic fault was developed with taking into account the presence of water in the crack-pore space of coal. Calculations were performed for four cases: without water influence, with the influence of water presence on the change of phase permeability, with its influence on the change of the coefficient of elasticity and Poisson's ratio.

Calculation of geomechanical and filtration parameters under conditions of minimum natural moisture saturation s_w = 1% showed that under these boundary and initial conditions there is an outburst of coal and methane in the outburst-hazardous zone. The zone of inelastic deformations rapidly grows from the mine face along the coal seam; pressure gradients near the free surface take very high values; coal and gas outburst takes place and cavity forms. Then geomechanical processes and the process of methane filtration return to the quasi-stationary mode. As a result of calculations with variation of the moisture s_w values in crack-pore space of coal, it was obtained that gas-dynamic processes in the mine face start if s_w < 24%, for the boundary and initial conditions accepted in this work. When this limit is exceeded, geomechanical and filtration processes in the coal seam near the mine face do not start; geomechanical and filtration processes occur in quasi-stationary mode. The effect of moisture on the reduction of phase permeability for methane leads to the neutralization of the outburst-hazardous properties of coal. Additional consideration of the decrease in the coefficient of elasticity and increase in Poisson's ratio due to coal humidification reduces the safe limit of moisture saturation to s_w = 20%.

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.

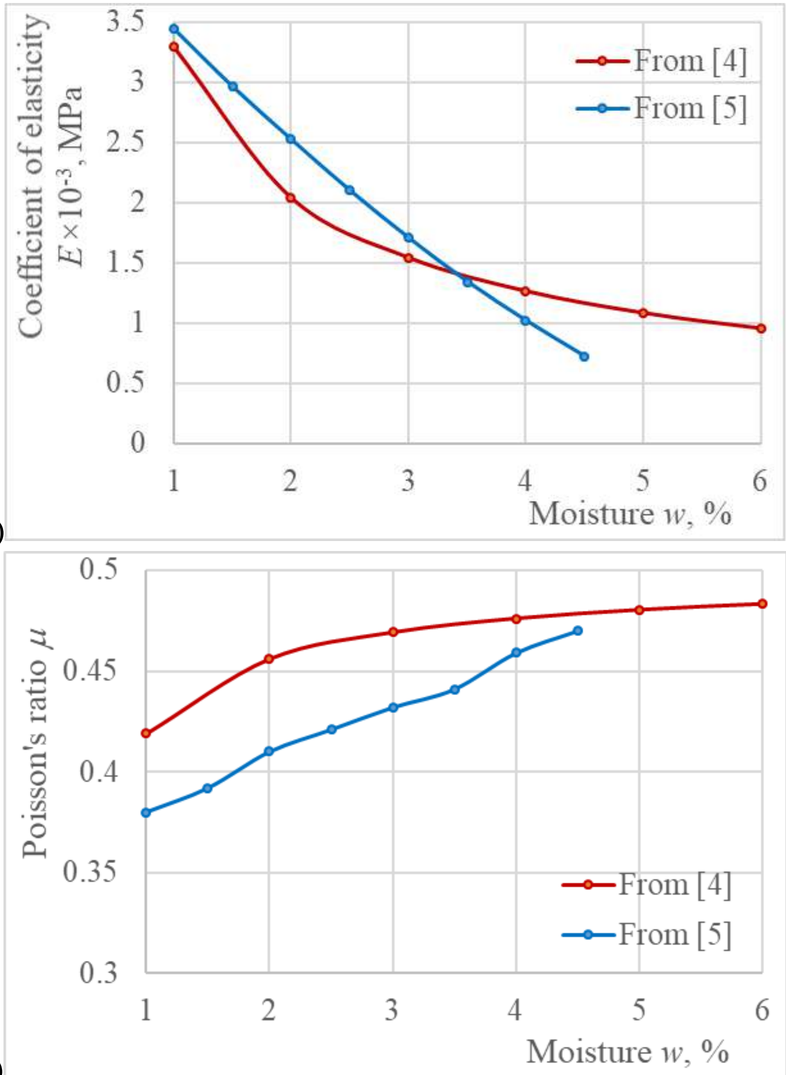
Keywords: mining safety, numerical simulation, outburst hazard, permeability to phase, water saturation.

Introduction. It is well known that the presence of water in the crack-pore space of coal significantly affects the development of gas-dynamic processes that are initiated during mining operations [1]. How does water affect the processes of coal seam deformation, methane filtration and desorption that occur during gas-dynamic phenomena?

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 [2, 3]. The effect of fluids on the strength and deformation properties, on development of cracks formation process was studied in the works [3, 5]. The dependences of the effect of humidification of coal samples on their coefficient of elasticity E and Poisson's ratio μ were established in [4, 5]. Graphs based on these data are shown in Fig. 1. With an increase in coal moisture 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. 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, which is formed from the natural, tectonic permeability k_{tect} and technological permeability k_{tech} due to mining excavation and depends on the ratio of the components of the principal stress tensor [6]:

$$K = k_{tect} + k_{tech}(\sigma_{ij}). \quad (1)$$



a) b)

a) coefficient of elasticity; b) Poisson's ratio.

Figure 1 – Effect of moisture on the coal properties, according to [4, 5]

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:

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

Moisture saturation or water concentration in the crack-pore space s_w is related to the humidity by the following equation:

$$s_w = 100w/m,$$

where m is coal porosity, %.

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

$$k_g = (1 - 0{,}01 \cdot s_w) \cdot K. \tag{2}$$

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

Intensity of the process of gas (methane) sorption-desorption also depends on the water content in coal [7-11]. Under different conditions and at certain values of humidity, the mechanism of influence of water on the course of sorption-desorption processes changes.

Therefore, the purpose of this work is to establish the degree of influence of the above aspects on the coal-gas outburst risk and calculate the safe level of moisture saturation of coal by using numerical simulations.

Methods. In modelling, the hypothesis of continuity is accepted, the rock massif is considered homogeneous within each layer. The total force acting on each point of the solid is equal to the sum of the forces of geostatic pressure and fluid pressure. The change in time of stress-strain state of rocks near a mine working without taking into account inertia force is described by the follow system of equations:

$$c_g \frac{\partial}{\partial t} u_i = \sigma_{ij,j} + X_i(t) + P_i(t), \tag{3}$$

where c_g is the damping coefficient, kg/(m^3·s); t is time, s; u_i are the displacements, m; $\sigma_{ij,j}$ are the derivatives of the stress tensor components along x, y, Pa/m; $X_i(t)$ are the projections of the external forces acting on the volume unit of solid, N/m^3; $P_i(t)$ are the projections of forces due to gas pressure in the crack-pore space, N/m^3.

The problem is solved in the elastic-plastic formulation. A Coulomb-Mohr criterion is used to describe mathematically a process of rock transition into a disturbed state. A stress-strain state of rocks is analyzed with the help of following geomechanical parameters characterizing different-component nature of a stress field (Q^*) and geostatic pressure relief of the rocks (P^*):

$$Q^* = \frac{\sigma_1 - \sigma_3}{\gamma H}; \quad P^* = \frac{\sigma_3}{\gamma H},$$

where σ_1, σ_3 are the maximum component and the minimum component of the principal stresses tensor, Pa; γ is the average weigh of the overlying rocks, N/m^3; H is the mining depth, m.

The next equation is used to describe gas filtration:

$$\frac{\partial p}{\partial t} = \frac{k_g}{2\mu_g m}\left(\frac{\partial^2 p^2}{\partial x^2} + \frac{\partial^2 p^2}{\partial y^2}\right) + q(t), \tag{4}$$

where p is gas pressure, Pa; μ_g is gas viscosity, Pa·s; q is the gas release function, that simulates methane desorption.

As a result of mining operations, an initial stress field is redistributed causing certain changes in filtration permeability k_{tech} of coal and rock [12, 13]. It was previously shown that k_{tech} values at each point of the study area depend on the stress state of the rock at this point as follows [14, 15]:

$$k_{tech} = \begin{cases} 0 & \text{for } Q^* < 0.6;\ P^* > 0.25; \\ k_{\min} & \text{for } 0.6 < Q^* < 0.8; \\ e^{0.26Q^* - 4.65} & \text{for } 0.8 < Q^* < 1.2;\ P^* > 0.1; \\ k_{\max} & \text{for } Q^* > 1.2;\ P^* < 0.1, \end{cases} \quad (5)$$

where $k_{\min}$ is minimal value of permeability coefficient required for the filtration process start, m^2; $k_{\max}$ is permeability within the zone of breaking, m^2.

The presence of water in the crack-pore space of coal is set through the moisture saturation s_w. The value of s_w remains unchanged during one calculation, because the time of gas-dynamic processes is usually equal to a few seconds, and the parameters of the process of water filtration during this time does not change.

Outburst-hazardous properties of the coal seam in the disturbed zone near the tectonic fault (Fig. 2) were simulated as follows [18]: adhesion C decreases linearly, and the permeability k_{tect} linearly increases from the boundary of the disturbed zone to the plane of the tectonic fault displacer, the tensile strength σ_τ is approximately zero:

$$C = C_0 - \frac{(C_0 - C_{\min})(x_d + l_d - x)}{l_d};\ \ k_{tect} = \frac{k_{\max}(x_d + l_d - x)}{l_d};$$
$$\sigma_t \approx 0;\ \ for\ x \in [x_d; x_d + l_d], \quad (6)$$

where C_0 is the coal cohesion in the unbroken zone, Pa; C_{min} is the minimum cohesion value in the broken zone, Pa; x_d is x coordinate of the tectonic fault, m; l_d is the length of the broken zone, m; σ_τ is tensile strength, Pa.

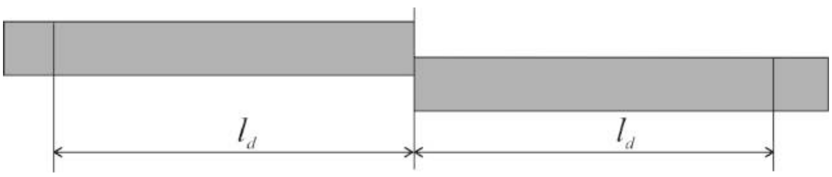


Figure 2 – Coal seam section with tectonic fault

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

$$k_g = \left(1 - 0{,}01 s_w\right) K + f(V_g). \qquad (7)$$

The system of equations (1)-(7) is solved by using the finite element method. The initial and boundary conditions for the task set are:

$$\sigma_{yy}\Big|_{t=0} = \gamma H; \quad \sigma_{xx}\Big|_{t=0} = \lambda\gamma H; \quad p\Big|_{t=0} = p_0;$$
$$u_x\Big|_{\Omega_1} = 0; \quad u_y\Big|_{\Omega_2} = 0; \quad p\Big|_{\Omega_3} = p_{at}; \quad p\Big|_{\Omega_4(t)} = p_0,$$

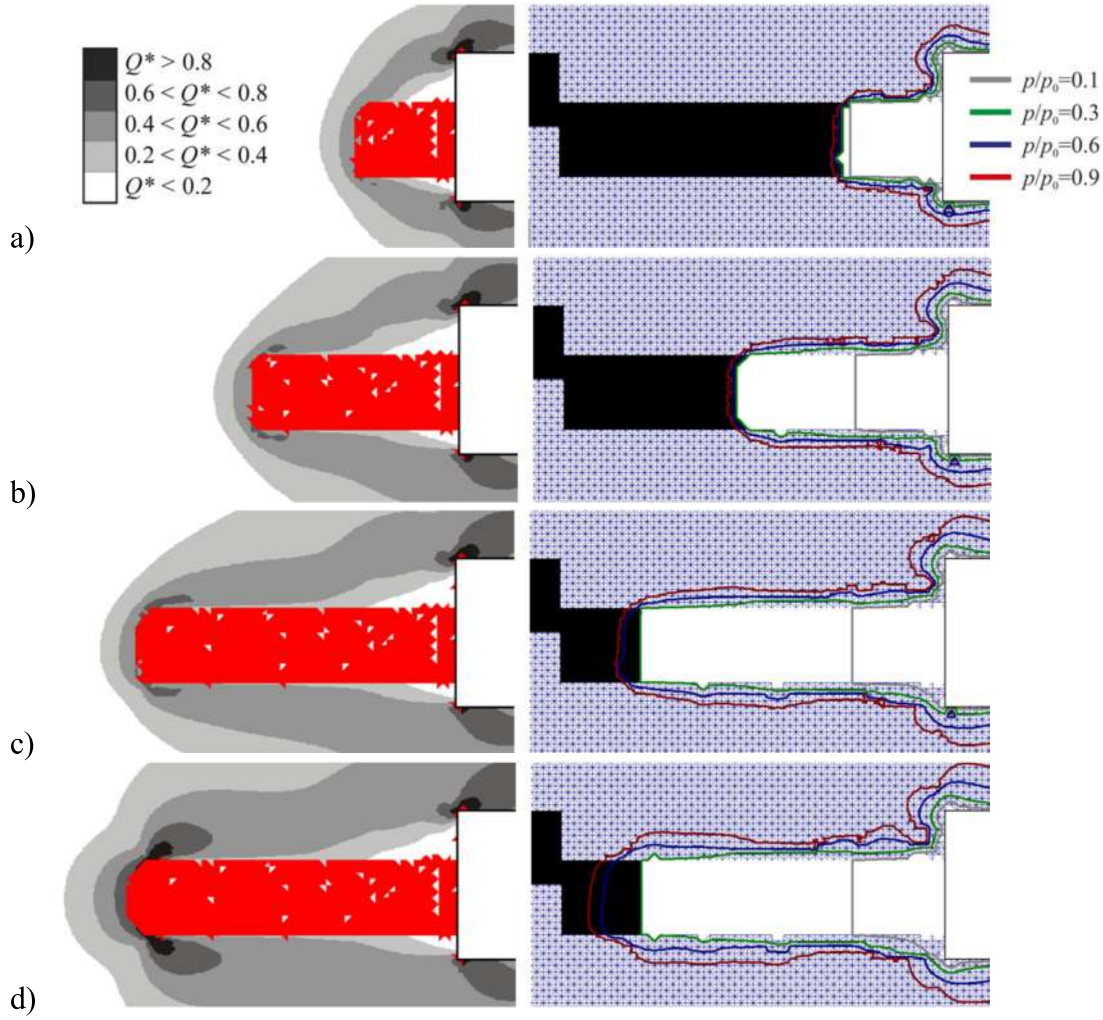
where Ω_1 are the vertical boundaries of the outer contour; Ω_2 are the horizontal boundaries of the outer contour; Ω_3 is the internal contour (mine working); $\Omega_4(t)$ is the time-varying boundary of the filtering area; p_0 is formation methane pressure, Pa; p_{at} is air pressure, Pa.

The condition for formation of outburst cavities in the case if gas-dynamic phenomena start is belonging of finite elements to area of inelastic deformations caused by tensile stress, and fulfillment of the criterion for gradients of methane pressure to exceed the critical value grad $p > P_c$. For further calculations, it was assumed that the mine face is at a distance of 7.75 m from the tectonic fault with a displacement amplitude of 1 m; host rock is argillite; H = 1000 m; m = 10%; l_d = 10 m; $p_0 = 8 \cdot 10^6$ Pa; $P_c = 2 \cdot 10^7$ Pa/m.

Results and discussion.

Calculation of geomechanical and filtration parameters of gas-dynamic processes under the condition s_w =1%. Under the condition of s_w = 1%, the influence of water on the change of physical and mechanical properties of coal, on the processes of its deformation, methane filtration and desorption is practically absent. Let's perform the calculation and see how geomechanical and gas-dynamic processes occur under the given conditions.

The results of calculating the values of Q^* parameter, which characterizes different-component nature of the stress field, zones of inelastic deformations (red colour) and isobars of relative methane pressure p/p_0 at different points in time are shown in Fig. 3. 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 increases deep into the coal seam. The zone of inelastic deformations rapidly grows from the mine face along the coal seam (Fig. 3a-3c). The pressure of methane in the coal seam near the mine face quickly falls, so the relative pressure isobars are tight to the exposed surface (Fig. 3a-3c). The pressure gradients and the filtration rate of methane take very high values, the permeability of coal grows rapidly. Coal and gas outburst takes place and cavity forms in the coal seam, the length of which reaches 6.125 m under the given initial and boundary conditions. Then the growth of the cavity stops (Fig. 3d), methane pressure in the coal seam continues to slowly decrease – the geomechanical processes and the process of methane filtration return to the quasi-stationary mode. The time course of the dynamic process is 5.6 s under these initial and boundary conditions.

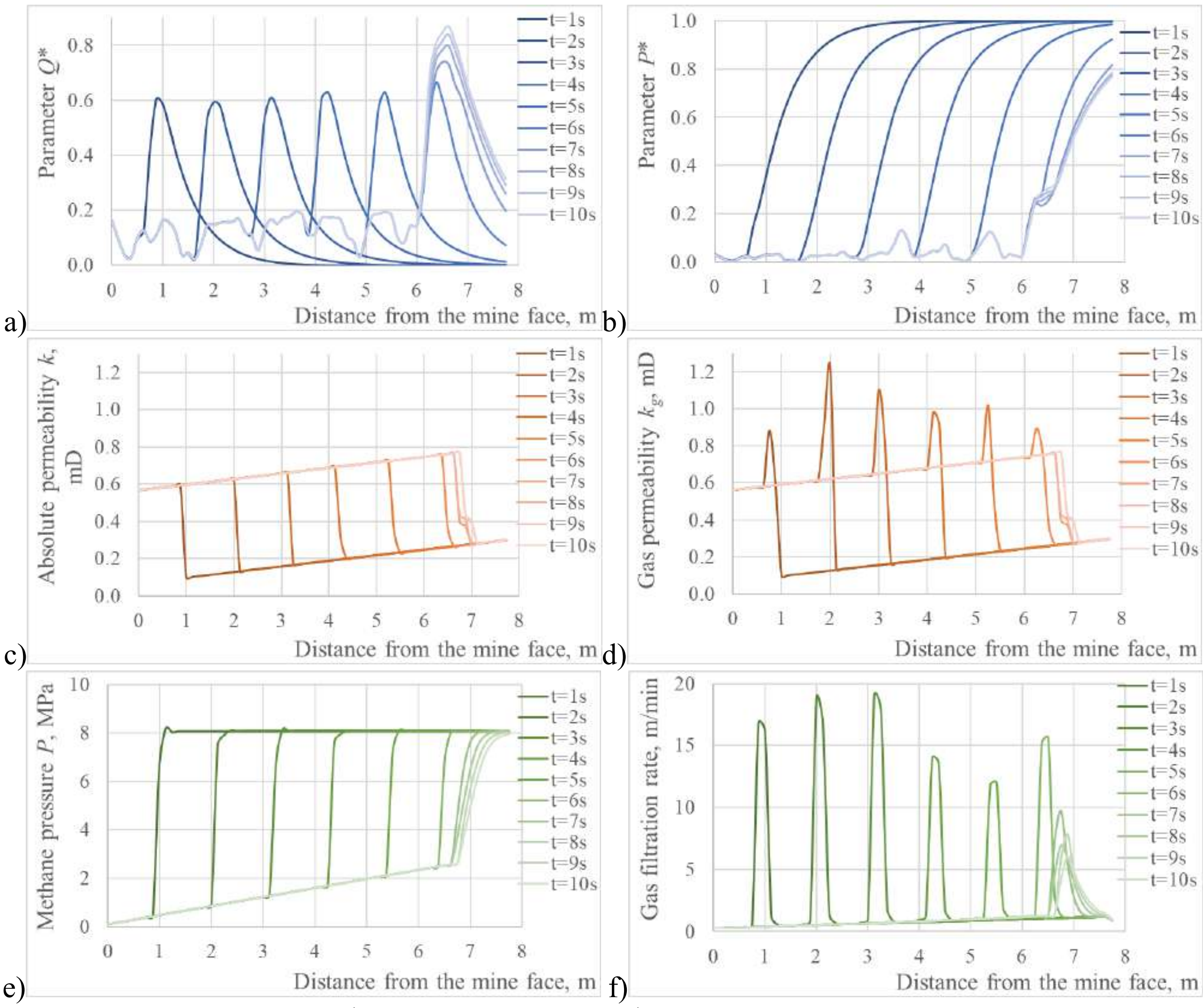


a) t = 2 s; b) t = 4 s; c) t = 6 s; d) t = 7 s.

Figure 3 – Distribution of parameter Q^* values and inelastic deformation zone (left side), fracture cavity and methane relative pressure p/p_0 (right side) in the outburst-prone zone near the tectonic fault, s_w = 1%

Graphs of changes in geomechanical and filtration parameters 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. 4.

At the time interval t < 6 s, the peak of parameter Q^* 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. 4a. Unloading of the coal seam from rock pressure (parameter P^*) also moves rapidly at the same speed (Fig. 4b). Absolute permeability (Fig. 4c) in the area a few centimeters to the surface increases 6 times. Gas permeability, calculated by formulas (1), (2) and (5), increases by the value of $f(V_g)$ in the boundary, near-surface zone, Fig. 4d, because the gas filtration rates are very high here, Fig. 4f.



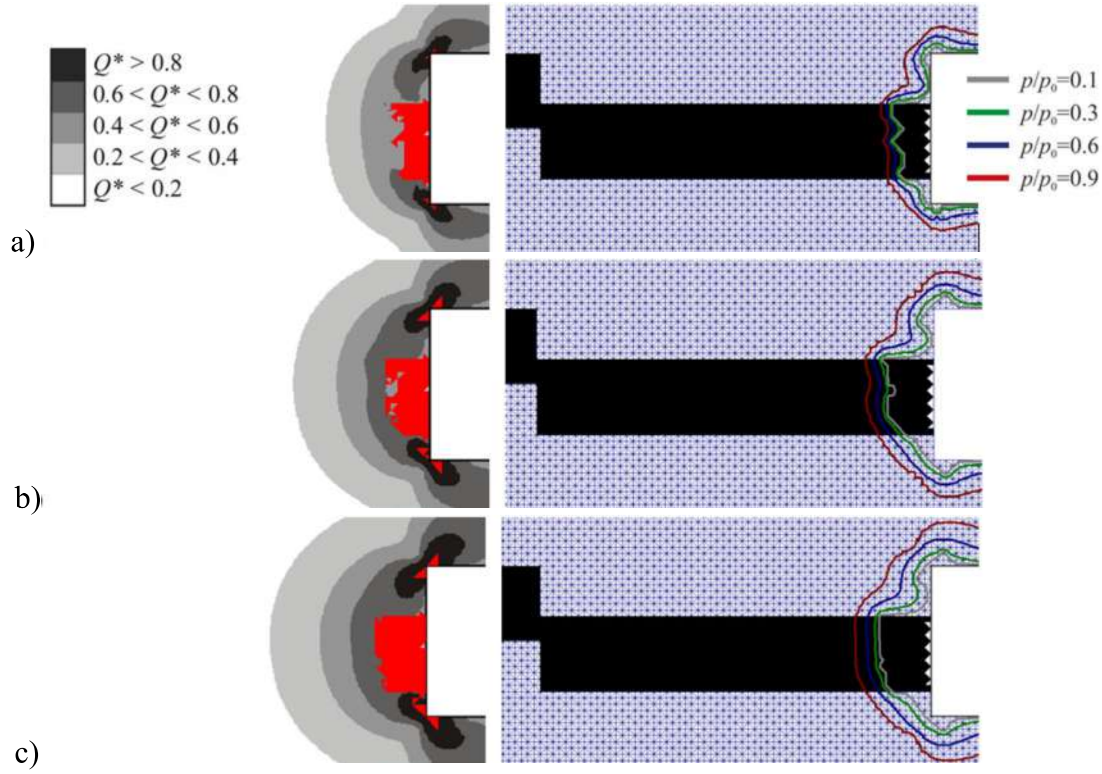
a) parameter Q^* values; b) parameter P^* values; c) absolute permeability;
d) gas permeability; e) gas pressure; f) gas filtration rate.

Figure 4 – Changing of geomechanical and filtration parameters over time, s_W = 1%

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 gradients and its filtration rate decrease, fig. 4.

Effect of reducing phase permeability on initiation of gas-dynamic processes in the outburst-prone zone of the coal seam. Calculations were performed for different moisture s_W values in the crack-pore space of the coal seam. As a result of calculations it was obtained that gas-dynamic processes in the mine face start if $s_W < 24\%$. When this limit is exceeded, geomechanical and filtration processes in the coal seam near the mine face do not start. 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 course of the studied processes occurs in a quasi-stationary mode.

Distributions of parameter Q^* values, zones of inelastic deformations and isobars of the relative methane pressure at different points in time, if s_w = 30% are shown in Fig. 5



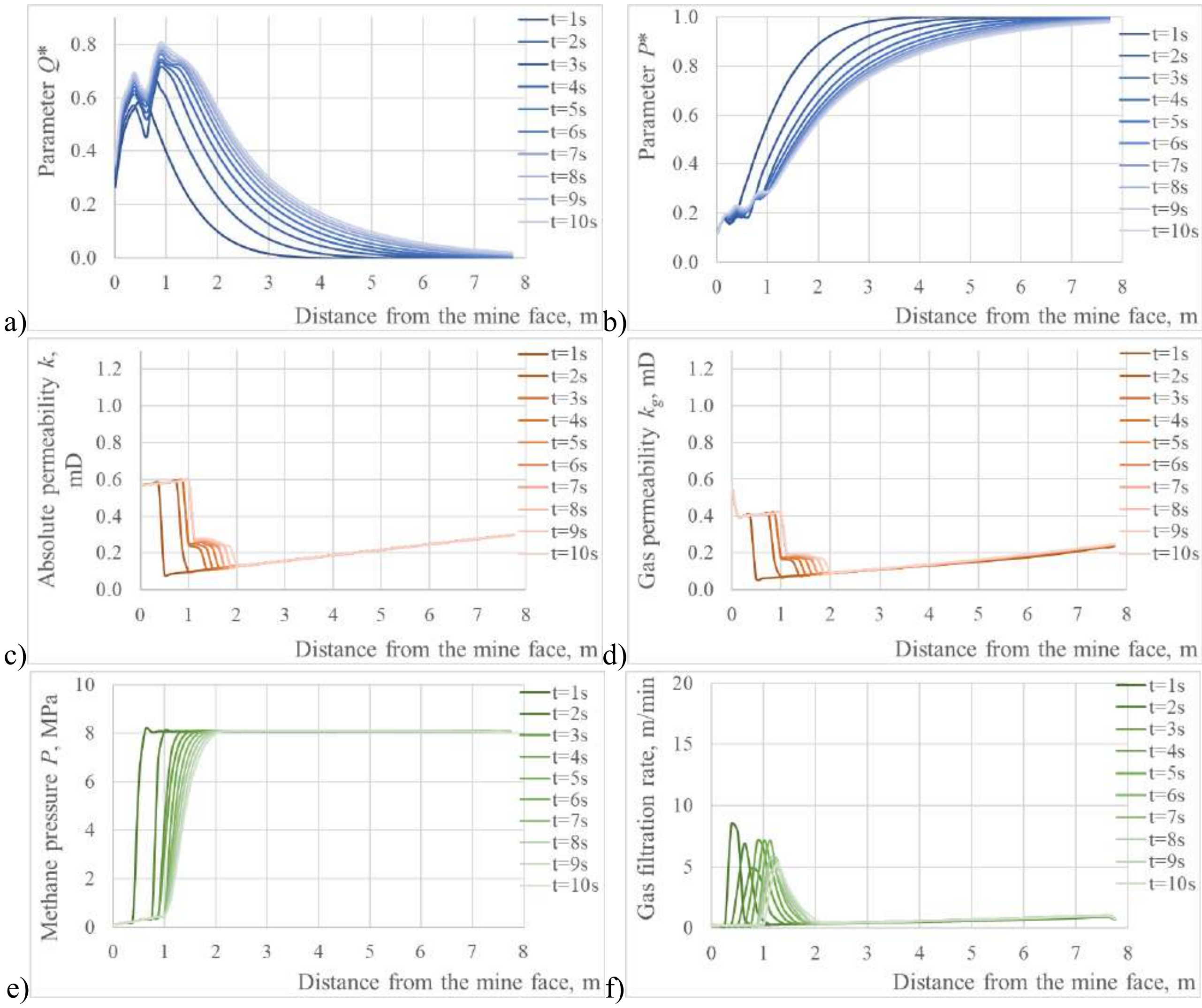
a) t = 2 s; b) t = 4 s; c) t = 6 s.

Figure 5 – Distribution of parameter Q^* values and inelastic deformation zone (left side), fracture cavity and methane relative pressure p/p_0 (right side) in the outburst-prone zone near the tectonic fault, s_w = 30%

As you can see, in conditions similar to the previous case, near the tectonic fault, in the broken zone, the area of high parameter Q^* increases much more slowly with depth into the coal seam. Zone of inelastic deformations deepens into the coal seam by not more than 1 m, the methane pressure in the mine face falls slowly, the cavity in the coal seam is not formed, Fig. 5.

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. 6.

In the studied moments of time the peak of parameter Q^* values is at a distance of about 1 m from the mine face, Fig. 6a. Fluctuations in the parameters Q^* and P^* 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. 6b) and the drop in methane pressure (Fig. 6e) are slow. Absolute 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. 6c and 6d. 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. 6f. By comparing the graphs in Fig. 6c and 6d, 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.



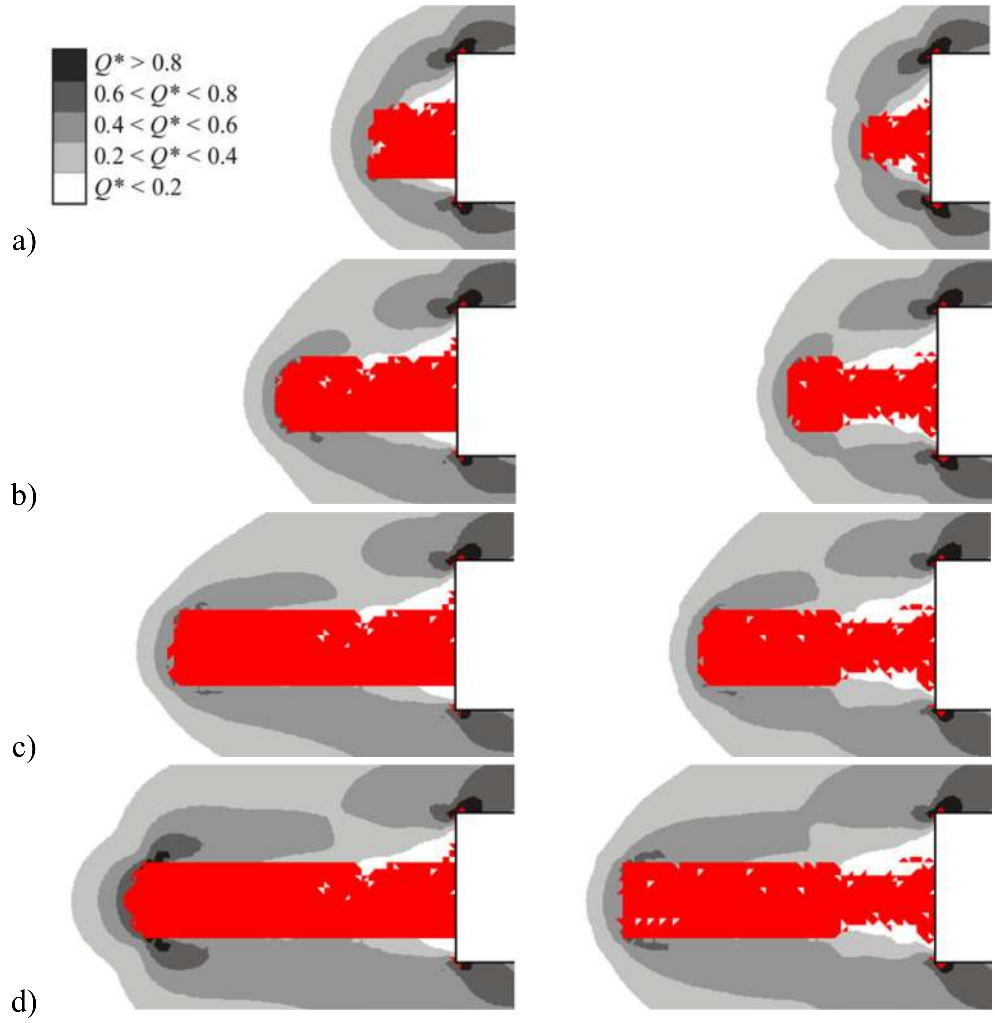
a) parameter Q^* values; b) parameter P^* values; c) absolute permeability;
d) gas permeability; e) gas pressure; f) gas filtration rate.

Figure 6 – Changing geomechanical and filtration parameters over time, s_w = 30%

Thus, the moisture effect on reduction of phase permeability for methane leads to neutralization of the hazardous properties of coal under the condition of $s_w \geq 24\%$. Under this condition, the course of studied processes occurs in a quasi-stationary mode.

Effect of change of coal properties at humidification on initiation of gas-dynamic processes in the outburst-prone zone of the coal seam. Based on experimental data in [6, 7], it is shown that moisture saturation affects the coefficient of elasticity of coal E and the Poisson's ratio μ. Let's calculate how the studied processes will occur with taking into account the change in the coefficient of elasticity of coal with increasing moisture content s_w. For calculations, E values was taken according to [6, 7], Fig. 1a. As a result of numerical calculations with variation of s_w, it was found that taking into account the decrease in the coefficient of elasticity E decreases the safe limit of moisture saturation to s_w = 22%, at which the nature of geomechanical and filtration processes in the coal seam changes from dynamic to quasi-stationary.

The results of calculations are shown in Fig. 7 in comparison with the results, which did not take into account the moisture effect on the change in the coefficient of elasticity of coal.



a) t = 2 s; b) t = 4 s; c) t = 6 s; d) t = 8 s.

Figure 7 – Distribution of parameter Q^* values and inelastic deformation zone in the outburst-prone zone near the tectonic fault, s_w = 20%, coefficient of elasticity E does not depend on s_w (left side, E = 2287 MPa) and it depends on s_w (right side, E = 3375 MPa)

Taking into account reducing of E value by 32% with increase of s_w to 20% leads to a weakening of the deformable characteristics of the coal seam, which is clearly seen in Fig. 7:

- 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.

Thus, the decrease in the value of coefficients of elasticity E when humidifying coal leads to a weakening of the deformable characteristics of the coal seam, as well as to slow down the rate of dynamic processes during the gas-dynamic phenomenon.

Let's calculate how the studied processes will occur with additional consideration of the change in the Poisson's ratio in coal with increasing moisture content s_w. For the calculations, average μ values is taken according to [6, 7], Fig. 1b. The results of calculations when $s_w = 20\%$ are shown in Fig. 8 in comparison with the results, which take into account the moisture effect only on the change in coefficients of elasticity.

Graphs of geomechanical and filtration parameters in the mine face, along a line which is perpendicular to the mine face plane and passes through the center of the coal seam, show that when $s_w = 20\%$, E = 2287 MPa, and μ = const, a gas-dynamic phenomenon takes place in the mine face.

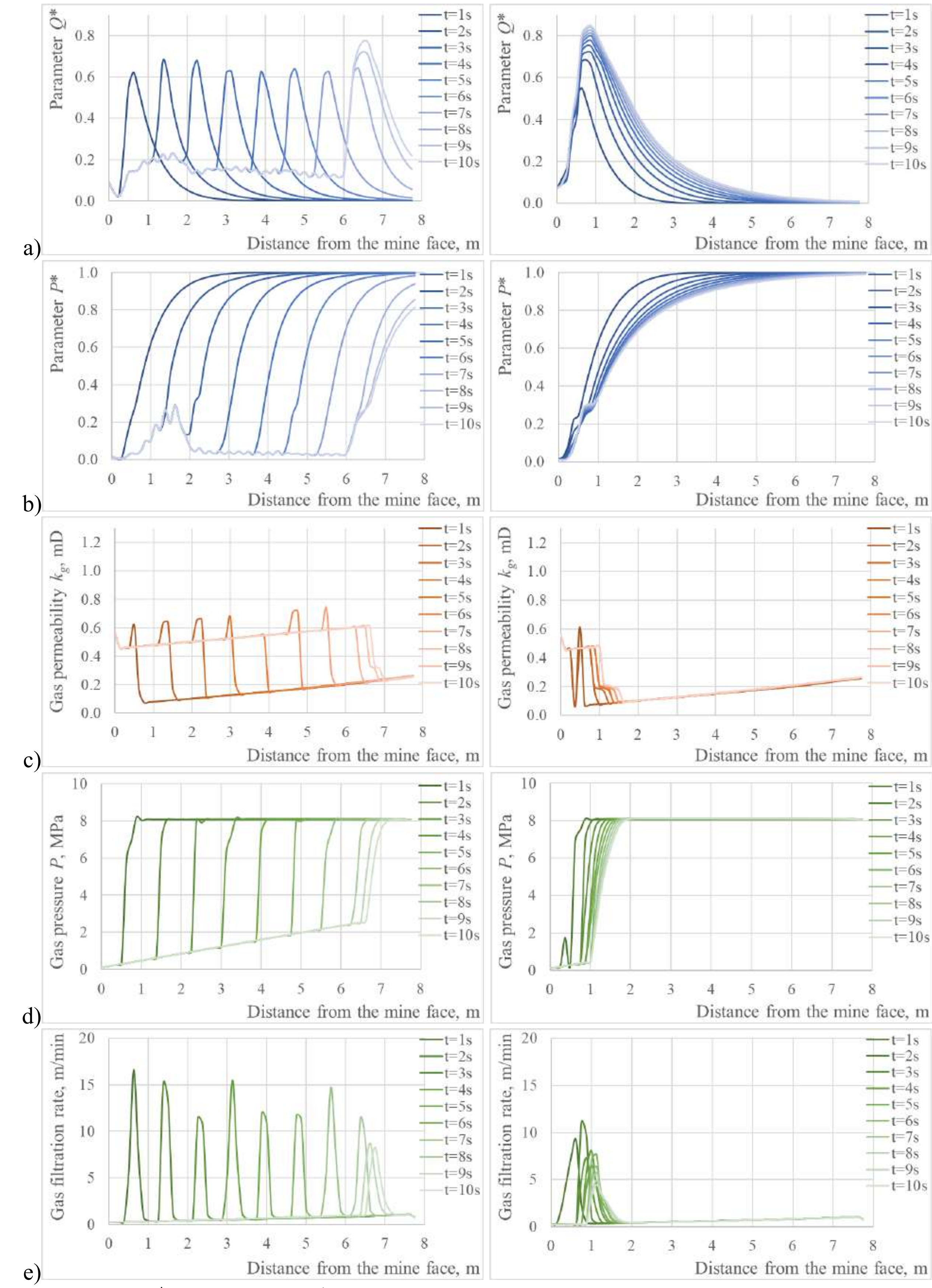
In the period of time t < 6.5 s, the peak of parameter Q^* values moves away from the mine face together with the newly formed surface of the outburst cavity, Fig. 8a left side. Unloading of coal seam from rock pressure (parameter P^*), fig. 8b left side, is also rapidly moving deep into the seam. Gas permeability in the boundary, near-surface zone of the disruption front increases by $f(V_g)$ value, because the gas filtration rates take high values here, Fig. 8c left side. The gas pressure gradients in the coal seam near the exposed surface increase significantly because methane pressure over a small distance drops from the formation pressure p_0 to the atmospheric pressure p_{am}, Fig. 8d left side. Till the seventh second of coal and methane outburst, all the processes are slowing down.

If $s_w = 20\%$, E = 2287 MPa, and the Poisson's ratio varies according to the graph of Figs. 1b and is equal to $\mu = 0.433$, 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.

As a result of this series of numerical calculations with variation of moisture saturation s_w in the range from 15% to 22%, it was found that additional consideration of the increase in Poisson's ratio due to coal humidification reduces the safe limit of moisture saturation to $s_w = 20\%$.

Conclusions. According to the analysis of practical and theoretical researches, it was established that the presence of water in the crack-pore space of coal influences the phase permeability and methane filtration process; coal properties and intensity of gas desorption.

The calculation of geomechanical and filtration parameters of gas-dynamic processes in the mine face in the outburst-prone zone at $s_w = 1\%$ showed that under these boundary and initial conditions the following gas-dynamic processes occur.



a) Q^* parameter; b) P^* parameter; c) k_g; d) gas pressure; e) gas filtration rate.

Figure 8 – Change in parameters over time, s_w = 20%, E = 2287 MPa, Poisson's ratio does not depend on s_w (left side, μ = 0.433) and it depends on s_w (right side, μ = 0.4)

The area of increased diversity of the stress field components (parameter Q^* values) rapidly increases deep into the coal seam. The zone of inelastic deformations rapidly grows from the mine face along the coal seam. Methane pressure in the coal seam near the mine working quickly falls, the coal and gas outburst takes place and a cavity forms in the coal seam, the length of which reaches 6.125 m under given initial and boundary conditions. Then the growth of the cavity stops, methane pressure in the coal seam continues to slowly decrease. Geomechanical processes and the process of methane filtration return to the quasi-stationary mode.

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

It was found that the safe limit of moisture saturation, at which the nature of geomechanical and filtration processes in the coal seam changes from dynamic to quasi-stationary, decreases to $s_w = 22\%$ when taking into account the decrease in the coefficient of elasticity E. Additional consideration of the increase in Poisson's ratio due to coal humidification reduces the safe limit of moisture saturation to $s_w = 20\%$.

Thus, the regularities of the influence of moisture on the outburst hazard of coal seams were established. It 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.

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ЧИСЕЛЬНЕ ДОСЛІДЖЕННЯ ВПЛИВУ ВОЛОГОНАСИЧЕННЯ ВУГІЛЬНИХ ПЛАСТІВ ПІСЛЯ ГІДРООБРОБКИ НА ЇХ ВИКИДОНЕБЕЗПЕЧНІСТЬ

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Анотація. В даній роботі досліджено вплив води на викидонебезпечність вугільних пластів через зміну фазової проникності і властивостей вугілля. Для цього розроблено чисельну модель перебігу газодинамічних процесів у вибої гірничої виробки в викидонебезпечній зоні поблизу тектонічного порушення з урахуванням наявності води в тріщинно-поровому просторі вугілля. Розрахунки виконано для чотирьох випадків: без урахування впливу води, з впливом її наявності на зміну фазової проникності, з впливом на зміну модулю пружності і коефіцієнту Пуассона.

Розрахунок геомеханічних і фільтраційних параметрів за умови мінімального природного вологонасичення s_w = 1%, показав, що при заданих граничних і початкових умовах розпочинається газодинамічний процес. Зона непружних деформацій швидко зростає від вибою виробки по вугільному пласту, градієнти тиску метану поблизу вільної поверхні приймають дуже високі значення – відбувається викид вугілля та газу і утворення порожнини в вугільному пласті. Потім геомеханічні процеси і процес фільтрації метану повертаються до квазістаціонарного режиму. В результаті виконання серії чисельних розрахунків із варіюванням значень кількості вологи в тріщинно-поровому просторі вугільного пласта отримано, що для прийнятих граничних і початкових умов газодинамічні процеси в вибої виробки розпочинаються, коли s_w < 24%. При перевищенні цієї межі газодинамічні процеси в привибійній зоні вугільного пласта не розв'язуються, перебіг геомеханічних і фільтраційних процесів відбувається в квазістаціонарному режимі. Вплив вологи на зниження фазової проникності для метану призводить до нейтралізації викидонебезпечних властивостей вугілля. Додаткове урахування зниження значення модуля пружності і зростання коефіцієнту Пуассона при збільшенні вмісту води в поровому просторі вугілля зменшує безпечну межу вологонасичення до s_w = 20%.

Таким чином, встановлено закономірності впливу вологи на викидонебезпечність вугільних пластів. Розроблено чисельну модель, що дозволяє в конкретних умовах виявити безпечну межу вологонасичення, за якої характер перебігу геомеханічних і фільтраційних процесів у вугільному пласті змінюється з динамічного на квазістаціонарний.

Ключові слова: безпека гірничих робіт, чисельне моделювання, викидонебезпека, фазова проникність, вологонасиченість.

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