The influence of coal and enclosing rock fracturing on the management of the rock massif during the exploitation of thick coal seams by the longwall top coal caving technology

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Abstract. The methods for the disintegration of coal-bearing rock massif have been developed that allow eliminating the areal hanging of roofs in the longwall faces and their dynamic impacts on mechanized complexes, to ensure the safety of reused mine workings in the coal face operation area, and also to create a system of cracks in the coal seam upper side along the entire length of the face and increase the efficiency of preliminary degassing without creating a large number of intermediate mine workings. A technique for the numerical study of reservoir properties of rocks containing a system of cracks is proposed. An algorithm and software for creating two-dimensional stochastic systems of cracks with a given distribution of the coordinates of their centers, lengths, and orientations are developed. Based on the finite element method, the problem of fluid filtration in a fractured massif is numerically investigated. The influence of parameters of crack systems on the filtration properties of the medium is shown.

1. Introduction

The main causes of accidents at coal mines remain the same: explosions of methane and coal dust, sudden emissions of coal and gas, underground fires, rock bursts, collapses, a sharp and sudden collapse of roofing rocks. Often, these causes arise jointly. For each factor contributing to the emergency situation, or their combination in the Russian Federation, preventive measures have been developed and implemented at various levels. For example, there are regional (preliminary degassing, humidification of an outburst hazardous formation, advancing excavation of protective seams) and local (hydraulic loosening and hydraulic fracturing changing the stress-strain state of the outburst hazardous rock massif) activities.

At many coal mines, the “mine-seam” technological scheme is used, while one coal seam is worked out, and there is one longwall face. The occurrence of an accident in such a longwall is equivalent to closing the mine with great financial losses.

The accident development mechanism can be represented as follows. A large amount of methane accumulates in the upper part of the worked out area and constantly moves upwards along existing cracks inside the collapsed rock massif. However, under the conditions of a poorly caving roofs, gas accumulates in the goaf, and when the roof collapses suddenly, a “piston” methane is released into
existing mine workings, which is accompanied by a powerful shock wave, which can cause ignition and explosion of gas and coal dust.

The control of the mechanical characteristics of the overlying rock massif, including the poorly caving roof, is achieved by the following methods [1–3]:

- excavation of the rock massif as a way of influencing the poorly caving roof above the underlying seam;
- a method of advanced torpedoing;
- forced collapse by the blasting of elongated borehole charges in the goaf for non-gas mines;
- hydroprocessing and hydro-micro torpedoing;
- explosive hydroprocessing.

The issues of a coal seam safe preparation, especially a powerful one (over 6 m height), have always been in the focus of the attention of the world scientific community. In recent years, there has been a surge in research aimed at studying the preparation of coal seam with preliminary degassing and disintegration for its subsequent excavation. Different physical concepts made it possible to explain from different views the processes of disintegration of the rock mass and coal during directed and interval hydraulic fracturing. A component of laboratory tests is noticeable in the models of rock destruction, although real processes in circumstances of underground mining (non-uniform stresses distribution, the stability of coal boreholes, etc.) play a crucial role in the efficiency of hydraulic fracturing methods [4, 5].

In [6, 7], issues of rapid stimulation of crack development due to the combustion of proppant and the formation of gaseous by-products of peak combustion are presented. The numerical method showed that low loading speeds lead to sparse but longer cracks, while high loading speeds lead to the formation of numerous but shorter cracks around the well. At the same time, the hydraulic fracturing of coal seam occurs at lower pressures and loading rates.

Each of the preventive measures has advantages and disadvantages and is effective in certain conditions. There are subjective reasons, mainly economic, that reduce their usage. This situation forces us to look for new solutions to emerging problems. For example, coal mining enterprises in the United States, Australia, and other countries use automated monitoring with real-time information to prevent potential adverse of rock pressure in a dynamic form. But this highly costly technical measure has only proactive meaning. Therefore, at the Institute of Coal of the Federal Research Center for Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences, research and improvement of technologies for managing the state of the coal-bearing massif due to its disintegration continue.

2. The technique of coal seam interval fracturing

The disintegration of a coal seam by the method of interval fracturing during the exploitation of thick gentle sloping and inclined coal seams allows to create a system of cracks in the seam along the entire length of the longwall face and increase the efficiency of preliminary degassing without the creation of a large number of intermediate workings (figure 1).

The technology for the development of thick gentle sloping and inclined seams is carried out by one layer with the discharge of coal to the armored face conveyor, using the support sections, having the discharge windows [8–11].

The first experimental work on interval hydraulic fracturing in Kuzbass was performed at the Yubileinaya mine [12]. According to monitoring data, the average methane consumption from one preliminary degassing well without hydraulic fracturing was 0.073 m$^3$/min, but the methane-air mixture flow from the wellhead of the experimental hydraulic fracturing well was 0.315 m$^3$/min.

In the presence of a poorly caving roof, it is necessary to disintegrate it using the directed hydraulic fracturing method in wells drilled from intermediate preparatory workings (figure 2). Vertical directional fracturing wells provide rock separation of poorly caving roofs, while inclined wells provide cantilever cutting off and elimination of hanging roofs in the worked out area.
Figure 1. Scheme of preparation of the coal seam upper side for excavation by interval hydraulic fracturing: 1 – excavation gallery; 2 – intermediate gallery; 3 – hydraulic fractures; 4 – degassing wells; 5 – goaf; 6 – longwall face.

Figure 2. The scheme of preparation of coal seam upper side for the discharge and the roof softening by interval and directed hydraulic fractures: 1 – excavation gallery; 2 – intermediate gallery; 3 – hydraulic fractures; 4 – degassing wells; 5 – goaf; 6 – longwall face; 7 – inclined wells of directional hydraulic fracturing; 8 – vertical wells of directional hydraulic fracturing.

The work carried out at the Chertinskaya-Koksovaya mine in the excavated section of longwall no. 555 for redistributing the rock pressure by the directional hydraulic fracturing method allowed: to reduce the size of the roof rocks hanging; to provide support for the main roof with collapsed rocks; to redistribute stress concentration from the conveyor tunnel circuit into the interior of the coal seam; to reduce the influence of abutment pressure from the existing longwall face [13].

Theory and practice indicate that the physical and technical properties and state of rocks are primarily determined by the degree of their disturbance. In relation to the tasks of mining, the main indicator of disturbance is the fracturing of rocks [14]. The fracturing of rocks has a significant impact on their stability and the fracture process during the exploitation. In addition, the fracture density of rocks and coal determines the size distribution of the resulting blocks during natural and forced fracture caused by different processes [15].

Studies [16] established that the direction of cracks falling, relative to the direction of movement of the longwall face in the technology with the coal release, affects the amount of coal loss in the working space. Here modeling was carried out on models of equivalent material in the form of wooden blocks and sand-gypsum mixture. When moving the longwall face in the direction of the dip lines of cleavage cracks the length of the hanging console is 1.2–1.3 shorter compared to the...
movement of the face toward the line of falling cracks. Accordingly, the coefficient of extraction of the upper part of coal seam is higher in the first case.

3. Numerical model of rocks with systems of cracks

The physical mechanism of rock deformation is associated with the displacement differences at various scale levels, especially with the evolution of microcracks, pores, inter-block slippage, etc. The rock massif always contains a large number of cracks, the characteristics of which are difficult to describe in detail. Cracks in rocks form complex spatial networks, and their structure determines the deformation, strength, and filtration properties of rock massif. At the same time, their distribution may correspond to some macroscopic averaged laws. In such a situation, it is necessary to involve statistical research methods based on the study of finite samples from many cracks [17, 18].

A model built on a statistical foundation can be the basis for studying the results of real physical phenomena. Naturally, a universal model does not exist. Therefore, each of them is suitable only for describing a certain range of tasks [19–21].

To numerically model plane stochastic crack systems, an algorithm was developed and software was created in the Python 3.7 programming language. Here, cracks are represented as line segments of a certain thickness that characterize the size of their opening. Each system is characterized by the number of cracks \( N \), the distribution of coordinates of their centers \((x_i, y_i)\), lengths \( h_i \) and orientations \( \alpha_i \) (angles of inclination to the Ox axis). Thus, the result of the algorithm is a grayscale image, where the white color corresponds to the rock massif, and the grayscale corresponds to the cracks. Figure 3 shows examples of such systems.

![Figure 3. Examples of crack systems used in numerical simulations.](image)

According to Darcy’s law, the rate of fluid filtration in a porous medium \( u(x, y) \) in the absence of gravity is directly proportional to the pressure gradient in the fluid and is directed towards the pressure decreasing:

\[
\mathbf{u}(x, y) = -\frac{K}{\mu} \nabla P(x, y),
\]

where \( K \) is the coefficient of permeability of the medium, \( \mu \) is the dynamic viscosity of the fluid. Currently, there are a number of experimental studies devoted to the determination of reservoir properties of rocks. In the presented study, we take \( K = 10^{-9} \) m², and \( \mu = 8.9 \cdot 10^{-4} \) Pa·s, which may correspond to the process of filtering water in a coal-bearing massif.

To assess the filtration properties of the medium presented, we assume that the values of the filtration coefficient in equation (1) are different depending on whether the point of the region lies on the crack or belongs to a continuous medium. If the crack belongs, we will set the filtration coefficient \( K^* = 10^{-6} \) m². Thus, we have a multi-module medium with different values of the filtration coefficient, depending on the coordinates.

The task is to determine the scalar pressure field \( P = P(x, y) \) and the vector field of the fluid flow rate \( \mathbf{u} = (u(x, y), u(x, y)) \) in the entire region for a given pressure drop on the left (inlet) and right (outlet) boundaries: \( P_{\text{int}} = 10 \) kPa, \( P_{\text{out}} = 0 \), respectively, and also the non-leakage condition \( \mathbf{u} \cdot \mathbf{n} = 0 \) specified on the upper and lower boundaries, where \( \mathbf{n} \) is the unit normal vector to the boundary.
In this task, the solution is constructed numerically by the finite element method. For the numerical solution of differential equations such as the Darcy’s law by the finite element method taking into account a multi-coefficient environment, there are some free open-source software systems such as FreeFEM or OpenFOAM, and also the possibility of such calculations is implemented in the COMSOL Multiphysics® [22].

4. Results of calculations and discussion

Figure 4 shows patterns of distribution of the magnitude of the fluid velocity vector $|\mathbf{u}|$ in the presence of systems of vertical cracks (figure 4a); crack systems with a uniform distribution of inclination angles $\alpha_i$ from $0^\circ$ to $180^\circ$ (figure 4b); crack system with a uniform distribution of angles $\alpha_i$ from $0^\circ$ to $180^\circ$ and uniform distribution of crack lengths from 0.05 to 0.1 m (figure 4c). It is clearly seen that the flow rate and nature of the fluid flow are directly related to the features of the geometry of the crack system.

![Figure 4](image)

**Figure 4.** Distribution of the magnitude of the fluid flow rate vector $|\mathbf{u}|$ for various crack systems.

The pressure distribution in the fluid for the above crack systems is shown in figure 5. It is also clearly seen here that the presence of crack systems has a great influence on the nature of the pressure change.

![Figure 5](image)

**Figure 5.** Pressure distribution in the fluid.

Let us consider the influence of the systems of cracks on the distribution of fluid flow rate at the right (outlet) boundary of the reservoir. Figure 6a shows, as an example, the plot of the horizontal component of the flow rate vector $u_x$ at the right boundary (outlet) in the presence of cracks in the medium with a uniform distribution of inclination angles $\alpha_i$ from $0^\circ$ to $180^\circ$ (see figure 3c). It can be seen that each crack crossing the boundary gives a rise in the fluid velocity. The average fluid flow rate distribution $U_{avg}$ at the right boundary (outlet) for different crack systems, depending on their quantity $N$, is shown in figure 6b. Here, the graph with number 1 corresponds to the system of vertical cracks (see figure 3a); graph 2 corresponds to diagonal cracks (see figure 3b); graph 3 corresponds to...
systems of cracks with a uniform distribution of angles $\alpha_i$ from $0^\circ$ to $180^\circ$ (see figure 3c); graph 4 matches horizontal cracks.

Figure 6. The profile of the horizontal component of the velocity vector $u_x$ at the outlet (a); changes in the average velocity $U_{\text{avg}}$ of the fluid at the outlet for different values of the number of cracks $N$ (b).

5. Conclusions
It has been established that fractures significantly increase rocks filtration properties: the fluid flow rate is closely related to the features of the geometry of the fracture system contained in the pore reservoir, namely, the intensity, orientation, and connectivity of the fractures.

The main criterion that determines the efficiency and safety of the technology for exploitation of thick coal seams with the coal discharge is the level of coal losses, the value of which depends on the probability of spontaneous combustion of coal in the worked-out area and the safety of work. The most preferable conditions for the use of equipment with roof supports having a device for coal discharge are coal seams with brittle fractured coals that easily peel off from the rocks of the immediate roof, having low humidity and gas content, without large-sized solid inclusions. Deviations from these conditions may limit the effective use of the technology with the top coal discharge to the face conveyor.

The disintegration of the coal-bearing massif allows eliminating the areal hanging of roof rocks in the longwall faces and its possibility of a sharp dynamic impact on underground equipment and also ensures the safety of reused mine workings in the excavation area.

The development of methods for the disintegration of poorly caving roofs by directional hydraulic fracturing in various technological schemes leads to their controlled collapse, and the disintegration of a coal seam by interval hydraulic fracturing leads to an intensification of the process of its degassing due to the artificial formation of new crack systems in the rock mass.

New technical solutions for methods of controlling the state of the rock massif or for the conversion of part of the massif to a free-flowing state make it possible to create new original technological schemes for coal-face works in coal mines.

Institute of Coal of Federal Research Center for Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences developed:

- device for cutting initial cracks that are stress concentrators in a coal-bearing rock massif to create a long artificial hydraulic fracturing crack (utility model patent no. 129148);
- device for hydraulic fracturing of rocks that contribute to the disintegration of the coal-bearing massif (utility model patent no. 123064);
- method of hydraulic fracturing of coal seams (utility model patent no. 2472941);
- method for effective management of poorly caving roofs in heavily equipped longwall mines (utility model patent no. 2659292).
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