Low-pressure hydraulic impact on the coal massif and the purpose of its application

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Abstract. The purpose of the application of low-pressure hydraulic impact on the coal massif is discussed. A brief description of the coal structure is given – from molecules to large structures separated by endogenous and exogenous cracks. The fractured porous structure of the coal seam is described. Information on micropores, transitional and macropores, systems of exogenous cracks is given. The results of the performed studies indicate the possibility of blocking gas in coal pores with pumped water and preventing high pressure of free gas near the plane of seam exposure, which opens up the prospect of hydraulic action on the massif to prevent gas accumulation in the workings and sudden outbursts of coal and gas. It was established that the most effective mode of injecting water into the seam to achieve this goal is low-pressure water infusion, and its parameters were defined by experimental studies. The results of theoretical and experimental studies showed that with low-pressure water infusion, coal becomes less durable and elastic and more plastic. The coal massif adjacent to the mine or contoured by several mine workings loses the ability to brittle fracture, and the arising loads are largely realized in the form of plastic deformations that do not lead to rock bumps.

1. Introduction
Hydraulic action on the coal massif, as shown by the data of multiannual research, can be widely used to prevent manifestations of danger, which is mainly due to natural factors. Such manifestations include sudden coal bursting and gas release, rock bumps, pollution of mine workings, ignitions and explosions of methane and coal dust, endogenous fires.

This article discusses the mechanism of the influence of low-pressure injection of water into coal seams on the outburst hazard of a coal massif, gas release into mine workings, and the manifestation of rock bursts.

2. The effect of low-pressure water infusion on the gas recovery of coal
It is well known that coal belongs to the heterocopolycondensate of organic compounds [1]. Molecules and macromolecules of coal, consisting of carbon graphite-like networks with side groups, form crystallites. The crystallites, interconnected, are grouped into micelles and micelle aggregates. The boundaries of the largest structures are endogenous and exogenous cracks, between which there is a
developed system of smaller channels and pores. The porosity of coal is 3–13%, or from 0.01 to 0.1 cm$^3$ per 1 g of substance. There are voids (cracks) and pores in coal comparable in molecules sizes with methane and water, up to pores of millimeter sizes [2].

When studying the differential porosity of coal, it was found that approximately 55% of the total porosity belongs to micropores, 28% to transition pores and 17% to macropores [3]. Gas filtration occurs mainly through macropores [1]. The largest of them are endogenous and exogenous cracks [4,5].

There are three systems of exogenous cracks: layered, longitudinal and transverse. The most developed is the first system of cracks. In the research by the VostNII Scientific Research Center it was found that gas and water permeability in the direction of layering is much higher than normal to layering (6).

The issues of the influence of humidity on methane sorption by fossil coals were studied by well-known scientists G.D. Lidin [7], I.L. Ettinger [8], V.V. Khodot [3]. They found that with the increase in the moisture content of coal, its methane sorption capacity significantly decreases. At the same time, water is very firmly held by coal. The research results showed that in the process of methane desorption, coals lose from 60 to 65 percent of water from a 100% saturation level. The remaining water is not displaced from coal even at high methane pressures.

According to [9], three types of water bonds in solid materials are distinguished:
1) chemical: molecular and ionic water;
2) physical and chemical: adsorbed and osmotic water;
3) physical and mechanical: microcapillary water.

Water in coal is contained in a free state – vaporous and liquid (gravitational water).

Chemically and physico-chemically bound water, which makes up a significant part of the water in coal, is most firmly held by coal. This primarily relates to sorbed water. In the process of sorption of water molecules act orientational, induction, and dispersion forces of interaction, while the local sections of coal molecules and macromolecules also have the feature of manifestation of all these types of forces. Therefore, we can assume that the coal-water system is characterized by a polymolecular type of sorption.

The water molecules in the adsorbed film in contact with the solid phase of coal are attracted to each other with very great force. According to [10], the attractive force between soil particles and water is about 10000 kgf/cm$^2$, and in accordance with the data given in [11] – several tens of thousands of kilograms per cm$^2$. Films of adsorbed water are not removed from the soil when centrifuged with an acceleration of 70 thousand times higher than the gravity acceleration. The subsequent layers of water are less firmly bound to the solid phase – this is loosely bound water, which gradually turns into free one.

3. The use of low-pressure water infusion for prevention of sudden coal outbursts, gas releases and its accumulation in the workings

When applying low-pressure water infusion for prevention of sudden coal outbursts, gas releases and its accumulation in the workings, the goal is set to block the gas by the pumped water in the coal pores. This allows high pressure of free gas near the plane of seam exposure to be prevented, without which the sudden outburst will become impossible. Low-pressure water infusion is the slow saturation of the seam with water without changing its filtration characteristics, which ensures the conservation of the gas contained in it. The pressure and discharge rate should not exceed the natural capacity of the massif to receive fluid. In this case the seam becomes non-hazardous due to sufficient water saturation.

At the same time, depending on the amount of water pumped into the coal massif, it is possible to achieve the necessary reduction in gas release into the working during coal drawing, in order to facilitate the ventilation of the working and prevent gas accumulation.

Experimental studies performed by the Scientific Center of VostNII established that the low-pressure mode of water injection into the seam is ensured at the injection pressure $P_i$ corresponding to the
condition \( P_g < P_i < 0.75 \gamma H \), where \( P_g \) is the gas pressure in the seam; \( \gamma \) – the specific coal gravity; \( H \) – the depth from the surface.

The results of experimental observations of the VostNII Research Center show [12] that the use of low-pressure water infusion can reduce gas release from wells drilled in the seam by 10-15 times, and from the broken-down coal – by 2-3 times.

The effectiveness criterion for the low-pressure water infusion is the increase in the moisture content of coal to 6% or to complete water saturation if its value is less than 6% [12]. Based on this criterion, natural moisture content of coal, water saturation rate, the optimal distance between the humidification wells and the corresponding water infusion time are calculated according to the methodological recommendations developed at the VostNII Scientific Center. The depth of well sealing is taken to be equal to half the distance between the injection wells, and in the disturbed massif it should be at least 10 m.

When applying water infusion to prevent rock bumps, the discharge pressure should be \( P_i \leq 0.75 \ k\phi H \), where \( k \) – is the stress concentration coefficient at the site of water infusion, and the humidity should be increased from its natural value to the maximum hygroscopic humidity or the full moisture capacity of coal.

To establish the effect of filling coal pores with liquid on the permeability of coal, the formula can be used expressing the relationship between the permeability coefficient \( k \) and the size of cracks

\[
k = ab^j,
\]

where \( a \) – the transition coefficient; \( l \) and \( b \) are, respectively, the specific length of the cracks and their average gap.

Based on analytical studies taking into account (1), the following was obtained:

\[
\frac{k_d}{k_w} = \left( \frac{100}{100 - \eta} \right)^2,
\]

where \( k_d \) and \( k_w \) – the permeability coefficients of dry and wetted coal, respectively;

\[
\eta = W^* \times (1 - \frac{n_d}{n_i})100 - \text{the degree of filling the filtering pore volume with liquid,}\%
\]

\( W^* \) is the working moisture of coal; \( n_d \) and \( n_w \) is the effective filtering volume of dry and wetted coal).

Calculations performed according to formula (2) show that as a result of filling pores with liquid, the coefficient of permeability of coal can greatly decrease. So, at \( \eta \) equal to 20, 50, 80, and 97%, the permeability coefficient decreases by 1.6, 4.0; 25; 1100 times, respectively (table 1).

| \( \eta \), % | \( n_d/n_w \) | \( k_d/k_w \) | \( \eta \), % | \( n_d/n_w \) | \( k_d/k_w \) |
|------------|-------------|-------------|------------|-------------|-------------|
| 0          | 1.0         | 1.0         | 60         | 2.5         | 6.3         |
| 10         | 1.1         | 1.2         | 70         | 3.3         | 11.1        |
| 20         | 1.2         | 1.6         | 80         | 5.0         | 25.0        |
| 30         | 1.4         | 2.0         | 90         | 10.0        | 100.0       |
| 40         | 1.7         | 2.8         | 95         | 20.0        | 400.0       |
| 50         | 2.0         | 4.0         | 97         | 33.3        | 1100.0      |

The greatest effect of slowing of gas release is possible when filling the pores to its full cross section with liquid. The latter is retained in a pore with radius \( r \) due to capillary pressure \( P_c \), which is opposed by the gas pressure \( P_g \).
If \( P_r = \frac{2 \alpha \cos \theta}{r} > P_g \), then the gas cannot push the liquid out of the pore (\( \sigma \) – the surface tension of the liquid, \( \theta \) – the contact angle of wetting the coal with fluid). In the pores the maximum radius of which

\[
r_{\text{max}} = \frac{2 \alpha \cos \theta}{P_r},
\]

the gas can only move as a result of diffusion through the liquid, i.e., it will practically not leave them. If for water \( \sigma = 75 \times 10^7 \) \( \text{H/cm} \) and \( \theta = 76^\circ \), then the data calculated by formula (3) show that at a gas pressure of 300, 500 and 700 \( \text{N/cm}^2 \), gas cannot escape from pores, the radius of which is equal to or less 12, 7 and 5 \( \mu \text{m} \), respectively. Assuming that water penetrates into micropores (\( r \leq 5 \mu \text{m} \)), it should impede the movement of methane in them at a gas pressure of 700–800 \( \text{N/cm}^2 \) or more.

A significantly higher gas pressure can be counteracted by a prophylactic liquid that has passed into a gel state, since it has an increased affinity for coal and has a high viscosity.

The decrease in permeability of coal as a result of treatment with water or another liquid was confirmed by numerous laboratory and mine experiments.

At the VostNII Scientific Center, the permeability of coal was studied in laboratory conditions on a special installation. Depending on the magnitude of the load on the samples, the permeability coefficient of unwetted coal was 100×10³–1300×10³ \( \text{md} \), and of wetted coal – 0.31×10³ – 1.94×10³ \( \text{md} \), i.e., as a result of water infusion it decreased by 320-1200 times (table 2).

The permeability of coal in mine conditions was determined by the rate of increase of gas pressure in the control wells. It was found that, as a result of water infusion the permeability of coal massif is significantly reduced. So, for the Lutuginsky seam (Kuzbass) with the degree of filling the filtering pore \( \eta = 25–62\% \), the ratio \( k_d/k_w = 1.8–7.0 \) (table 3) and Bezymyanny seam (Kuzbass) at \( \eta = 16–61\% \), \( k_d/k_w = 1.4–6.7 \).

When treating coal with preventive liquids turning into the polymerized state, the experiments showed that there is an even greater decrease in the coefficient of permeability. In this case, it is 10 or more times lower than for coal wetted with water (figure 1). Naturally, this effect significantly affects the reduction of methane releases from coal (figure 2).

### Table 2. Values of permeability coefficient of dry and wet coal at various mechanical loads on the samples.

| Mechanical load on samples, kg/cm² | Coal permeability coefficient \( k \times 10^3 \), \( \text{md} \) |
|------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|                        | minimal          | maximal          | average          | minimal          | maximal          | average          |
| 1                      | 2                | 3                | 4                | 5                | 6                | 7                |
| 40                     | 980              | 1360             | 1130             | 0.78             | 1.18             | 0.94             |
| 50                     | 763              | 1110             | 880              | 0.63             | 0.81             | 0.71             |
| 60                     | 389              | 660              | 480              | 0.50             | 0.56             | 0.53             |
| 70                     | 198              | 350              | 240              | 0.35             | 0.46             | 0.40             |
| 80                     | 141              | 230              | 170              | 0.30             | 0.44             | 0.35             |
| 90                     | 119              | 131              | 125              | 0.24             | 0.53             | 0.34             |
| 100                    | 102              | 125              | 110              | 0.24             | 0.48             | 0.32             |
| 110                    | 93               | 122              | 100              | 0.24             | 0.46             | 0.31             |

Comparative measurements of gas release in the development workings, carried out on untreated and treated areas, were carried out in ten seams of Kuzbass developed by very gassy mines. In all 26 workings...
where the comparison was made, preventive treatment of the seam allowed to reduce gas release by a relative amount from 21 to 90%, and on average by more than 50%.

The degree of reduction of gas release in the development workings depends on the amount of fluid supplied to the seam (figure 3). It is determined that

\[ V_w = V_d e^{-\alpha \Delta W}, \]

where \( V_w \) – is the rate of gas release into working with an increase in the fluid content in the seam by \( \Delta W \), m\(^3\)/day; \( V_d \) – the same in the untreated seam \( (W = 1.5–2.0\%); \Delta W = 0 \), m\(^3\)/day; \( \alpha \) is the coefficient (for the research conditions \( \alpha = 0.7 \)).

From \( \Delta W = 1\% \) the rate of gas release into the development working is reduced by 1.3 times, and at \( \Delta W = 2\% \) – by approximately 1.6 times, or by 38%. Gas is most intensely released during coal coal drawing, and especially during blasting operations. But in this case, there is a lower gas release from the wetted massif in comparison with the non-wetted one. For example, at Bezymyanny seam (Kuzbass) at the time of blasting works in the drift, the gas release in the untreated and treated zones was 2.25 and 1 m\(^3\)/min, respectively. It follows from the above that, using low-pressure water infusion, it is possible to significantly reduce gas release from the gas-bearing massif into the mine workings, facilitating the ventilation conditions, especially in areas with abnormally high gas content.

### 4. The use of low-pressure water infusion for reduction stress in the massif and prevention of rock bumps

The methods of water infusion can be effectively applied to reduce the rock-bump hazard of the coal massif.

Rock bumps in mines occur as a result of rapid brittle fracture of a coal seam under the influence of rock pressure. The main natural properties that determine the rock-bump hazard of seams are the increased strength and elastic properties of coal, as well as its brittleness.
With the increase in the moisture content in coal, it becomes less durable and elastic and more plastic, which makes it rock-bump safe. These features lead to the reduction in the rock-bump hazard of coal seams. In the process of mine experimental research carried out at the Scientific Center of VostNII, it was found that during the water injection into the undisturbed coal massif, the stresses in it increase, and the increase in stress is proportional to the injection pressure and decreases exponentially with the increase in the distance from the wetting well.

1 – V parallel drift of seam II Vnutrenny; 2 – the same, IV parallel drift; 3 – the main drift of the seam Prokopyevsky II; 4 – the main drift of the seam Bezymyanny (Kuzbass)

**Figure 2.** Change in time \( t \) of gas release \( q \) from unwetted and wetted coal by water with the use of various additives in the seam Kemerovsky (Kuzbass).

**Figure 3.** Change in the relative methane release \( V_w/V_d \) in the development workings depending on the fluid increase \( \Delta W \) in the coal.
After the water infusion stops, the stresses in the massif in a short period of time take values close to the original ones. This is due to stress relaxation, as well as the continued movement of water under the influence of pressure drops and capillary forces.

The theoretical studies on the influence of preventive treatment of coal seams on the redistribution of stresses in the vicinity of workings were carried out based on the decisions of G.I. Barenblatt, S.A. Khristianovich and S.B. Kuznetsov. These authors obtained the following law of stress distribution in the plastic \( \sigma'' \) and elastic \( \sigma' \) areas of the massif:

\[
\sigma'' = K\left(\frac{\pi}{2} + \frac{x-x_0}{h}\right),
\]

\[
\sigma' = \gamma H \sqrt{\frac{x}{x-x_0}} \quad (x_1 \leq x \leq \infty)
\]

where \( x_0 = \frac{hE}{\pi(1-v^2)\gamma H} \); \( K \) is an indicator characterizing the properties of coal, inverse plasticity, \( h \) is a half the thickness of the coal seam; \( E \) and \( V \) – modulus of elasticity and Poisson’s ratio of roof rocks; \( \gamma H \) – initial stresses at the depth of development \( N \); \( x \) is the coordinate of the considered point of the array (the origin of the coordinates is the junction of the footwall and roof rocks); \( x_0 \) – the fictitious position of the face, based on the elastic solution of the problem; \( x_0 \) – face position, taking into account the presence of a plastic face space; \( x_1 \) – the position of the maximum bearing pressure, taking into account the zone of plastic deformation adjacent to the face.

To determine the values of \( x_0 \) and \( x_1 \), we have the following relations:

\[
\sigma'(x_1) = \gamma H \sqrt{\frac{x_1}{x_1-x_0}}
\]

\[
\int_x^0 \sigma'dx = \gamma H x_0 \left[ \frac{x_1}{x_0} \left( \frac{1}{x_0-x_1} - 1 \right) + \ln \left( \frac{x_1}{x_0} - 1 + \sqrt{\frac{x_1}{x_0}} \right) \right]
\]

Relation (7) expresses the equality in the section \( x=x_1 \) of the load values obtained by elastic and plastic solutions, and relation (8) expresses the equality of the total load in the plastic zone of the fictitious load in the section from \( x=x_0 \) to \( x=x_1 \).

The system of equations (7) and (8) made it possible to find an expression for determining the stress concentration coefficient in the bearing pressure zone \( K_c \) (the ratio of the maximal stresses to the initial ones), which has the form

\[
\ln \frac{K_c+1}{K_c-1} = \frac{1}{K^* x_0} K^2_c - 2 \frac{K_c}{K^*_c-1} - \frac{\pi^2 K^*}{4 x_0^*}
\]

where \( K^* = K / \gamma H; x_0^* = x_0 / h \).

Equation (9) is transcendental. Its solution for various values of \( K^* \) and \( x_0 \) was obtained graphically. The known value of \( K_c \) also allows the value of \( l \) to be determined (the length of the plastic face space, referred to half of the seam thickness).

The results obtained made it possible to evaluate theoretically the effect of preventive wetting of coal seam on the length of the plastic zone and the value of stress concentration. It was found that a decrease in
a. an increase in the plactility of coal, causes an increase in l and a simultaneous decrease in $K_c$. It follows that the indicated change in the basic parameters of the bearing pressure zone should take place as a result of preventive wetting of the coal mass.

The noted regularities were confirmed during experimental studies of the stress distribution, which were carried out using hydraulic sensors in the untreated and treated sections of seams Volkovsky, Kemerovsky and Vladimirovsky in Kuzbass (figure 4).

So, if in the untreated section of the seam Kemerovsky the distance l from the bottom to the maximum of the bearing pressure was 2.8 m, and the stress concentration factor $K_c$ was 1.92, then in the treated section $l = 8–10$ m, and $K_c = 1.33$.

As a result of theoretical studies, an inverse relationship was established between the stress concentration coefficient and the length of the plastic zone near the face. The mathematical expression of this dependence is obtained:

$$K_c = Al_c^\beta,$$  

where $A$ and $\beta$ are parameters depending on a large number of factors and, in particular, on the value $x_0^*$. 

When processing the experimental data, the following values of parameters were obtained: $A = 2.5; \beta = 0.333$. Taking into account the indicated values, expression (10) can be written

$$K_c = \frac{2.5}{2l_c} = 2.5\sqrt{\frac{m}{2l}},$$  

where m is the seam thickness.

The obtained during the measurement of stresses the change in the indicators of hydraulic sensors, when the works in the face are stoped, indicates the continuation of the stresses redistribution process in time. Let us introduce the following notation:

- $l_b$ – the distance from the face to the maximum bearing pressure at the initial moment of time (immediately after the regular advancement of the face);
- $l_c$ – the same for a steady case (after the end of the rheological process under consideration);
- $l_t$ – the same, at time $t$ (the countdown is from the stop of the face).

The section of the seam from $x = l_b$ to $x = l_t$ was considered as a solid, deforming in time according to the law

$$E(t) = \frac{1}{E}\left[\sigma(t) + \int_0^t \sigma(t, \tau) \sigma(t) d\tau\right].$$  

Here $\varepsilon(t)$ and $\sigma(t)$ – are the strain and stress corresponding to time $t$; $E$ is the deformation modulus; $L(t, \tau)$ is the core of the integral equation, reflecting the influence of the unit stress $\sigma(t)$ acting in a unit time interval $\tau$ on the strain at time $t$.

As a result of studies in which the equation kernel (12) was adopted exponentially

$$L(t, \tau) = \theta^{-\lambda(t, \tau)}$$  

the formula obtained

$$l_t = l_k - (l_k - l_b)e^{-\lambda t},$$  

where $\lambda$ is the rheological parameter.

Expression (14) represents the law of change in the magnitude of the zone of ultimate stress state in time. The parameters included in it are determined experimentally. Taking into account V.V. Khodot’s solutions, a special technique was developed for their determination by the time variation of the hydraulic
sensor readings located beyond the maximum of bearing pressure, and, in particular, the formula is proposed

\[ l_t = (r + x_2) \sqrt{\frac{K_c'' - 1}{K_c - 1}} - r, \]  

(15)

where \( r \) is the half of the working width; \( x_2 \) – the distance from the face to the place of sensor installation; \( K_c \) and \( K_c'' \) – stress concentration factors at time \( t \) at points with coordinates \( x_1 \) and \( x_2 \).

![Figure 4. Measurements of stresses \( \sigma \) at various distances \( x \) from the longwall faces: a – seam Kemerovsky; b – seam Volkovsky; c – seam Vladimirovsky (Kuzbass).](image)

As a result of an experimental study of the stresses redistribution of in front of the workings in the seams hazardous for dynamic phenomena, the values of expression parameter are obtained. For example, for the untreated section of the seam Volkovsky, \( l_c = 2 \text{ m}, \lambda_b = 0.4 \text{ m}, \dot{\lambda} = 0.4 \text{ h}^{-1}, \) and for the treated one \( l_c = 5 \text{ m}, \lambda_b = 2.8 \text{ and } \dot{\lambda} = 0.4 \text{ h}^{-1}. \) To determine the distance \( l \) from the face moving at a speed \( V \) to the maximum of the bearing pressure, the formula is obtained (the steady-state case of movement is considered)

\[ \bar{l} = l_k - \frac{V}{\dot{\lambda}}. \]  

(16)

From this formula it follows that the distance from the face to the maximum of bearing pressure depends not only on the speed of the face advancement rate, but also on the rheological parameter \( \dot{\lambda}. \) With
the increase in the latter, which occurs, in particular, as a result of wetting, the extent of the zone of the ultimate stress state increases and, consequently, the risk of manifestation of rock bursts decreases.

On the other hand, the analysis of expression (16) implies the possibility of increasing, by increasing the intensity of the flow of rheological processes, the safe rate of mining operations on the pre-wetted seams prone to rock bumps and sudden coal outbursts and gas releases.

5. Conclusions
It was established that the use of low-pressure water infusion makes it possible to significantly block the gas in the coal pores by the injected water. As a result, the gas recovery rate and the free gas pressure in the immediate vicinity of exposed surfaces are reduced. With appropriate water infusion parameters, the goal of preventing sudden outbursts of coal, gas releases and its accumulation in the workings is achieved.

The results of theoretical and experimental studies showed that the amount of potential energy of elastic deformations accumulated by coal is significantly reduced as a result of preliminary wetting of the coal massif with water or a fluid that changes into a gel state. The massif is becoming more plastic. When measuring the deformations of coal pillars with different humidity, it was found that with an increase in the latter both their absolute values and their transformation rates sharply increase.

Thus, a reduction in the rock-bump hazard of seams by the method of their hydraulic treatment is achieved as a result of a decrease in the elastic and strength characteristics and an increase in the plastic properties of coal, which, in turn, causes displacement of maximal stresses to the depth of the massif from the working.

The coal massif adjacent to the mine or contoured by several mine workings loses its capacity to brittle fracture, and the arising loads are largely realized in the form of plastic deformations that do not lead to a rock bump.

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