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SUDDEN OUTBURST OF COAL AND GAS – FAILURE OF NATURAL COAL AS A SOLUTION OF METHANE IN A SOLID SUBSTANCE

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A sudden outburst of coal and gas is a catastrophic natural phenomenon that occurs during the underground working of coal deposits. Scientific research on this phenomenon has been conducted for several decades; its nature, however, is still not entirely clear. Among other things, there are various notions concerning relationships between the forces of mine pressure, and the free and sorbed gas in the failure of coal in stages preparatory to and during the outburst.

At the present time, the model of the layered separation of coal in a seam outcrop by gas compressed in the pores, and the model of the failure of coal by mine pressure, as well as their combination ([1, 2], where corresponding references are available), are dominant in Russia and the countries of the Commonwealth of National Governments. Certain critical facts regarding the failure of coal cannot, however, be explained within the framework of these models, for example, the formation of "mad flour," and the grinding of coal into minute particles, whose diameters may be smaller than one tenth of a millimeter.

If, in effect, the coal had been fractured by mine pressure and free gas alone, or by mine pressure alone, the orientation of the cracks induced in the mass and in the discarded coal would be sufficiently expressed, as occurs in practice during outbursts of sandstone and gas [3], and salt and gas [4], and follows from the theory of the separation of compressed rocks, which corresponds to the above-mentioned models [5]. Such failure, however, occurs only in very small coal outbursts, with a volume of several cubic meters [6].

On the other hand, only about 5% of the methane in gas-bearing coal is in the free state in the pores and 95% in the sorbed state. Taking the corresponding density value of the surface energy for coal, it is easy to calculate and demonstrate that the energy of the free methane in, and the elastic energy of, a compressed cubic meter of coal is simply inadequate for the failure of this volume of coal to the "mad flour" state with particle sizes of 0.05 mm.

In mathematical models of sudden outbursts, the gas (methane, carbon dioxide), which is in the sorbed state, has been considered only in connection with the motion of the unloading wave or the gas-coal mixture during bursts, for example, [7, 8]. Sorbed gas is not considered in models of coal failure [1, 9,10]. It is considered that as a result of the relatively extended time required for desorption, it cannot play an active role in crack development.

The Institute of Problems of the Complex Exploitation of Mineral Resources, Russian Academy of Sciences [11-13] has developed a concept relating to in-situ coal as a solution of methane in a solid coal substance (concept of a "solid solution"). The solution of methane is distinguished from absorption (bulk filling of micropores) by the fact that in the first case, the methane molecules, being interstitial, separate the coal substance, creating micropores, and, in the second case, fill the micropores already existing in the coal "skeleton" [11].

The solution concept makes it possible to isolate the stable and metastable states of the methane-coal and to examine dynamic phase transitions of the methane from the dissolved to the gaseous state. According to this concept, a sudden outburst is a result of instability in the state of the methane/natural-coal system when the seam is subjected to man's activity; in that case, it is precisely the dissolved methane that is considered the principal motive force involving changes that lead to failure of the coal in the seam.

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The concept of a "solid solution" has also evolved in Poland. Litwiniszyn [14] examined a model of the metastable state of the methane-coal system, which is separated into the phases at the beginning of motion. This will lead to the appearance of discontinuities in the form of shock waves, with which the outburst is also explained. This is undoubtedly an important step in mathematical investigations using the "solid solution" concept; it is also necessary, however, to develop other models that should utilize not only a deeper understanding of the mechanism of the rapid manifestation of a large amount of free methane, but also proposed relationships that make it possible to judge the outburst capacity of a coal seam.

In our study, we investigate the possible manifestation of the instability of the solid solution of methane in a coal substance from positions of fracture mechanics (theory of cracks). A model is constructed so as to permit analysis of the condition of the dynamic failure of the coal-methane solution, for example, the formation of "mad flour." The proposed model does not contradict previously developed models that take into account only the free gas in the failure, but only supplements them, incorporating a factor that has not been previously examined.

1. Physical Premises of Construction of Failure Model. The solution is a homogeneous system with a uniform distribution of one substance in the medium of another. The solubility of a substance, which exists in the gaseous state under normal conditions, in liquid or solid substances will depend, above all, on the temperature and pressure (T, p). The concentration of soluble substance may vary with these parameters: either additional absorption of soluble substance, or its release from the solution will occur.

Some liquids are good solvents for gases. Carbon dioxide, the oxygen that fish breathe, and other gases are dissolved in water even under ordinary conditions. The amount of dissolved gas depends on its saturation pressure. For low concentrations, this relationship is described by Henry's law, which states: the mass of dissolved gas per unit volume of liquid is proportional to the saturation pressure of the free gas

$$m / V = sp. \tag{1}$$

Here, m is the mass of gas in a volume V of liquid, p is the saturation pressure, and s is Henry's constant. If the saturation pressure drops (for example, to a value p_*), some of the gas escapes from the liquid. The mass of gas Δm that goes off from the liquid can be found from the equation

$$\Delta m / V = s(p - p_*). \tag{2}$$

The solution of gas in a liquid takes place rather slowly; in that case, it usually occurs in accordance with the mechanism of the diffusion of molecules from the interface between the free gas and liquid. Conversely, the liberation of gas from a liquid may, under a sharp drop in saturation pressure, be violent and proceed in accordance with the mechanism of bubble formation *in the entire* volume of liquid, as occurs, for example, when a bottle of sufficiently warm champagne is opened.

Minute gas bubbles, which are generated in the microheterogeneities of the liquid, will grow, primarily due to the discharge of molecules of dissolved gas into bubbles. As a result, a pressure sufficient for surmounting the pressure of the liquid and counteracting its surface tension is maintained in the bubbles, despite the manifold increase in their volume.

A violent growth of bubbles in a liquid whose pressure drops suddenly (below the pressure of the dissolved gas) occurs during the phenomenon of hydrodynamic gas cavitation in a liquid flow [15]. The pressure in the liquid falls below a certain critical value due to a local increase in flow velocity.

One of the fundamental equations in the mathematical description of cavitation is the state equation of an embryonic bubble. From the equation, it is possible to determine whether or not a bubble will develop under specific conditions. If growth is possible, cavitation is possible in the moving liquid.

By analogy with the solution of a gas in a liquid, it is logical to assume that in the solid solution of gas, which may be a certain rigid body, the formation of internal "bubbles" of free gas is also possible under a sudden drop in the external saturation pressure of the gas and the pressure on the rigid body. As in the case of the solution of gas in a liquid, the following required conditions should be fulfilled for the appearance of free gas in the solid solution (within the rigid body): 1) the existence of embryonic "bubbles" (pores, microcracks, etc.), where the gas may escape; and, 2) the pressure of the free gas in these "bubbles" should be sufficient for their growth, i.e., to separate and fracture material with the formation of a new free surface in the latter.

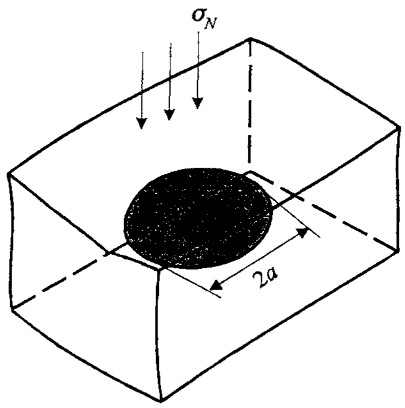

Fig. 1. Model disk-shape crack in solid solution.

It is clear that in the solid solution, a crack in the solid substance may be a "gas bubble." Investigation of the possibility of the escape of dissolved gas in the form of "bubbles" within the rigid body can therefore be reduced to assessment of the conditions under which separation cracks grow in the solid solution under the action of the free gas formed when dissolved gas flows out into a crack. If crack growth is dynamic in the solid solution, the escape of dissolved gas from the solid solution may be defined as violent.

Assessment of the growth of a crack as dissolved methane flows into it should be a key element in investigating the role of dissolved methane in the failure of natural coal during outbursts. If we establish that the crack evolves dynamically, the process of coal failure will be violent and dynamic. In that case, the dissolved methane must be accounted for in the analysis of coal failure during sudden outbursts of coal and gas. If a separation crack does or does not develop quasi-statically under the action of the free gas that appears in it, the dissolved methane can actually be disregarded.

In the following paragraph, let us examine a mathematical model of crack development under the action of dissolved methane that escapes into a crack with certain simplifying assumptions.

2. Model. Let us examine a disk-shape separation crack of radius a (Fig. 1) in a solid coal, which for simplicity of mathematical calculations, will be considered an elastic homogeneous isotropic medium with an elastic modulus E and Poisson's ratio ν. The pressure of the free methane in the crack is denoted by p. Let the principal stress in the coal, which acts at a distance perpendicular to the plane of the crack, be σ_N.

For the notations introduced, the volume of the crack can be written in the following form:

$$V_T = 16(1-\nu^2)a^3(p-\sigma_N)/3E. \tag{3}$$

To simplify the analysis, the state equation of the gas in the crack will be described by the Clapeyron–Mendeleyev equation

$$pV_T = MRT/\mu, \tag{4}$$

where M is the mass of the methane in the crack in g, $\mu = 16$ is the molecular weight of methane, R = 8.31 is the universal gas constant in J/(mole·K), and T is absolute temperature.

Consider that all free methane in the crack was in the dissolved state prior to the latter's formation. During a short time interval defined by the rate of advance of the crack, the dissolved methane can obviously proceed into the crack only from a very thin surface microlayer, whereupon a rapid flow of dissolved methane from the very thin surface microlayer should proceed not in accordance with the diffusion mechanism, but in accordance with the mechanism of an "outflow from the surface." Let us dwell on this in greater detail.

Let us, above all, point out that on the scale of material microheterogeneities, the surface of a separation crack is heavily "cut" in a zig-zag manner by many induced microfractures. This is readily apparent on photographs taken under the microscope by many experimenters investigating crack formation.

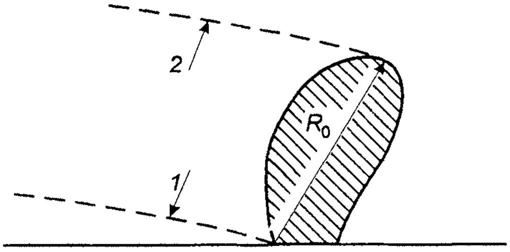

Fig. 2. Local plasticity zone (hatched) near tip of equilibrium crack: 1) upper edge of crack; 2) boundary of plasticity zone during crack development.

In granular materials, such as rock, a zone of surficial microfractures in the form of induced channels and microcracks may extend for a certain distance into the material. The stress field is actually nonuniform near a static crack. More vigorous excitations occur with respect to stresses near the crack tip, where a local plastic zone in which the material experiences inelastic shear deformation is formed (Fig. 2). In granular materials, it is accompanied by loosening of the material (dilatancy) [16].

The tip of the crack is displaced as it develops. In addition to this, irreversible shear deformation and the loosening that accompanies it are retained in the region of its previous position. As a result, a loosened microlayer with numerous channels and microcracks of a higher order should form near the surface of the crack.

The maximum thickness of this layer can be estimated within the framework of crack mechanics, proceeding from the length of the plastic zone near the separation crack in limiting equilibrium. If K_{1c} denotes the material's crack resistance, and τ_0 is the yield point in shear, it follows from Kondaurov et al. [17] that the length R_0 of the local plastic zone near the crack tip can be calculated using the relationship

$$R_0 \sim 0{,}064 K_{1c}^2 / \tau_0^2. \tag{5}$$

In such materials as coal, the extent to which the surficial microlayer is loosened and its effective thickness can be determined under a powerful microscope, and appropriate analytical developments for investigation of the microstructure of coal used.

Examining the flow of dissolved methane into the crack, we will therefore assume that it occurs not only from the surface of the crack, but also from microcracks in channels that penetrate the loosened surficial microlayer. In other words, the discharge of dissolved methane is accomplished in accordance with the mechanism of an outflow from the surface, the effective area of which is many times larger than the visible surface of the crack. The rapid dynamic flow of dissolved methane in accordance with the mechanism of an outflow from the surface will hereinafter be called "instantaneous" in contrast to the rather prolonged discharge of methane (several hours or more) in accordance with the diffusion mechanism.

It is expedient to describe the "instantaneous" discharge of dissolved methane by a simple relationship: the relative change in the content of dissolved methane in the coal substance is proportional to the relative change in saturation pressure. Mathematically, the dependence is expressed by the linear relationship

$$(d_0 - d) / d_0 = \alpha (p_0 - p) / p_0, \tag{6}$$

where d_0 is the content of dissolved methane – the number of grams per unit volume of in-situ coal in which the saturation pressure is p_0, d is the content of dissolved methane in the coal substance under a saturation pressure p, and α is a proportionality factor (a constant of the model, which depends on the temperature and microstructure), which indicates what portion of dissolved methane remains in the coal substance, if the saturation pressure falls to zero.

Let us denote $\Delta d = d_0 - d$ as the mass of dissolved gas discharged from a unit volume; then, relationship (6) can be rewritten differently as:

$$\Delta d = (\alpha d_0 / p_o)(p_0 - p). \tag{7}$$

Expression (7) for the "instantaneous" discharge of dissolved methane corresponds to Henry's law (2) for the discharge of dissolved gas from a liquid. This indicates that the dynamic violent discharge of dissolved gas from a liquid during a drop in saturation pressure and the "instantaneous" discharge of dissolved methane from the wall of the crack that has formed are physically similar phenomena.

Denoting the thickness of the loosened surficial microlayer (otherwise known as the effective surface "thickness" of the crack) by h, the volume V_m of the microlayer from which dissolved methane is "instantaneously" released, can be written in the following form:

$$V_m = 2\pi a^2 h. \tag{8}$$

Using (8) and (7), the mass of methane in the crack can be represented by the expression

$$M = 2\alpha\pi a^2 d_0 h(p_0 - p) / p_0. \tag{9}$$

State equation (4) of the gas and simplest "sorption equation" (6) (or Eq. (9), which follows from (6)) are basic to the model. The condition of failure – a criterion of the limiting equilibrium state of the crack – is yet another basic equation. This criterion is written as

$$K_{1c} = K_1, \tag{10}$$

within the framework of Griffiths–Irwin crack mechanics [18], where K_{1c} is the material's crack resistance (strength parameter), and K_1 is the stress intensity factor at the tip of the crack (determined from solution of the corresponding problem of the theory of elasticity). For a disk-shaped crack and the notations adopted,

$$K_1 = 2(p - \sigma_N)(a/\pi)^{1/2}. \tag{11}$$

Equations (4), (9), and (10) in combination with (3) and (11) make it possible to determine the limiting equilibrium state of the crack, and also to define whether the crack will develop dynamically or quasi-statically.

3. Crack Behavior. Substituting expressions (4) and (3) and (10) and (11) in (9), it is possible to derive an equation for determination of the pressure of the free methane under which the crack is in limiting equilibrium:

$$\frac{pp_0}{(p_0 - p)(p - \sigma_N)} = \frac{3\alpha d_0 hERT}{2(1 - \nu^2)\mu K_{1c}^2}. \tag{12}$$

We will then assume $\sigma_N = 0$. This condition may occur as a seam is exposed, or in a coal lump severed from the seam; this is of interest to investigation of "mad flour" formation. From (12), we readily obtain

$$p = \left[1 - \frac{2(1 - \nu^2)\mu K_{1c}^2}{3\alpha d_0 hERT}\right]. \tag{13}$$

The crack should be open; therefore, p > 0 and the expression in the brackets will be positive. Consequently, the required condition of the existence of the crack's limiting equilibrium can be written as

$$\frac{\alpha d_0 h}{K_{1c}^2} > \frac{2(1 - \nu^2)\mu}{3ERT}. \tag{14}$$

The constants R and μ, and the parameters, whose variation from seam to seam is not very significant, are on the right side of the inequality. Conversely, the parameters, whose values may differ appreciably for different natural coals are on the left side. (We will hereinafter refer to relationship (14) as a required condition for the participation of dissolved methane in the dynamic failure of coal.)

The fulfillment of condition (10) implies only that the crack is in limiting equilibrium and *may* evolve. To answer the question whether this evolution will be dynamic, the variation in the stress intensity factor K_1 with increasing radius *a* of the crack must be investigated additionally; if K_I increases, the crack will begin to develop dynamically when condition (10) is met, and if K_I decreases, only a small increase will occur in the radius of the crack.

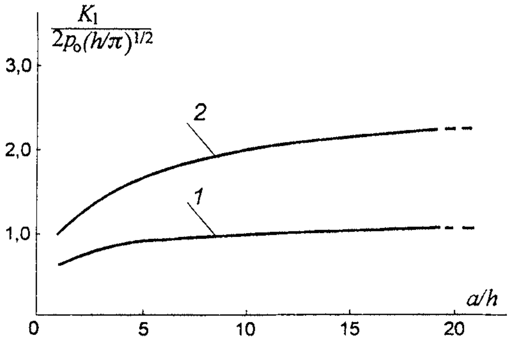

Fig. 3. Curves of stress intensity factor K_I versus crack radius a for different ratios of model parameters: 1) $\xi = 1$; 2) $\xi = 10$.

For the case in question, $K_I = 2p(a/\pi)^{1/2}$. Using (4), (9), (3), and (8), the pressure p in this relationship can be represented as a function of radius $p = p(a)$, and in turn, the relationship $K_I = K_I(a)$ can be constructed.

Calculations indicate that the stress intensity factor increases with crack radius. The $K_I(a)$ curve in dimensionless form is plotted as an example in Fig. 3 for two values of the dimensionless parameter $\xi = 3\pi\alpha d_0 ERT/[8(1 - \nu^2)\mu p_0{}^2]$. If, therefore, the crack begins to grow as dissolved methane flows into it, its growth will be dynamic as long as the external conditions are maintained.

When dissolved methane discharges into a crack, its dynamic development is a very important conclusion of the investigation. It indicates, among other things, that crack formation in natural coal, having begun on one scale level, may, without obstruction, proceed to larger scale levels. In this connection, let us point out that crack development under the action of free gas alone is different in principle: it should certainly be dwelled upon [10, 19].

4. Estimation of Parameters. Model Calculation. An accurate quantitative estimate of the quantities that enter into the model does not assume decisive significance, since our model, like many other mathematical models in geomechanics, is constructed with simplifications and assumptions. Generally speaking, it is sufficient to determine the order of the quantities that enter into the relationships.

As an example, let us investigate the possibility of the dissolved-methane-induced fracture of a coal lump severed from a seam during an outburst. Let us examine a methane-saturated coal seam at a depth of 500 m, where the natural mine pressure is approximately 10 MPa. The saturation pressure of methane in the in-situ seam is, in conformity with [20], the mine pressure: $p_0 = 10$ MPa. We will consider $T = 293$ K, $E = 5 \cdot 10^3$ MPa, $\nu = 0.2$, and $\sigma_N = 0$. The latter condition implies that the pressure of free methane in the working is negligibly small as compared with the mine pressure and the saturation pressure of the methane.

The methane content d_0 in the in-situ seam (in grams per 1 m^3 of coal) is easily determined, proceeding from the gas content of the coal. Considering that the gas content of the seam is 40 m^3/ton, we determine d_0 to be $3.4 \cdot 10^4$ g/m^3.

If data on the coal's crack resistance, which are cited in [10, 21, 22], are used, it is possible to set $K_{Ic} \approx$ (0.05-0.25) MPa·$m^{1/2}$. It should be considered, however, that in a natural gas-saturated coal, the effective crack resistance should be, as a minimum, two times lower than the crack resistance of an ordinary specimen of coal [23]. Let us examine three effective crack resistances in MPa·$m^{1/2}$: 1) $K_{Ic} = 0.025$; 2) $K_{Ic} = 0.075$; and, 3) $K_{Ic} = 0.125$.

The thickness of the loosened surficial microlayer can be estimated on the basis of two approaches: direct estimation and inverse analysis. In direct estimation, let us proceed from the thickness of the zone of inelastic deformations (5), where loosening of granular material may occur. For a conservative estimate, let us assume that the thickness of the loosened microlayer on the wall of the crack is several times smaller than the thickness of the plastic zone. Without generating a large error, the yield point τ_0 of the coal in shear can be set equal to 5 MPa. Having established the range of thickness of the plastic zone for the three cases under consideration $(0.16\text{-}4.0) \cdot 10^{-5}$ m using (5), let us set $h \sim 10^{-7}$ m (=1000 Å).

For the inverse analysis, let us proceed from the order of magnitude of the volume of methane discharging directly from the sorbed state during an outburst. It can be concluded from certain studies, for example, [24, 25], that from one to 10 m^3 of sorbed methane is released from 1 ton of fracturing coal in the first tens of seconds. In order that this volume correspond to the values generated by the proposed model, it is necessary to assume h = 3000 Å. Here, it should be considered

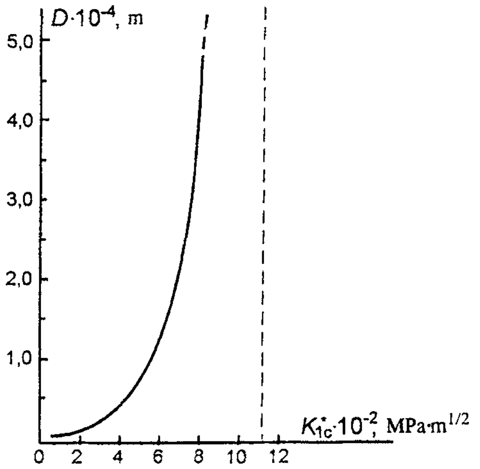

Fig. 4. Dependence of minimum diameter D of coal particles formed during outburst on effective crack resistance K_{1c}*.

that within the bounds of the surficial layer, all sorbed (in the model under consideration – dissolved) methane should go over to the free state, i.,e., it is also necessary to set $\alpha = 1$. (Confirming calculations will be presented below.)

Substituting the values assigned for the parameters in Eq. (13), we find the pressure in a crack of limiting equilibrium in each of three cases (1), (2), and (3). In the first case ($K_{1c} \approx 0.025$ MPa·m$^{1/2}$), it is 9.5 MPa. The maximum diameter $2a*$ of the corresponding crack, as follows from (10) and (11), is $1.2 \cdot 10^{-5}$ m. In the second case, the pressure in a crack of limiting equilibrium amounts to 8 MPa, and the diameter $2a* = 0.7 \cdot 10^{-4}$ m.

In the third case, it follows from Eq. (13) that $p < 0$, i.e., the crack cannot grow in a coal fragment. This means that for an effective crack resistance of 0.125 MPa·m$^{1/2}$, the dissolved-methane-induced failure of coal fragments that are severed from a seam (or already severed) is impossible. In other words, the crushing of coal to a state of "mad flour" is impossible. Conversely, the failure of coal lumps in the first two cases may continue successively right up to the formation of minute particles.

5. *Discussion of Results*. The conclusion that dissolved methane may or may not participate in the dynamic development of a separation crack can be drawn from the example under consideration. Relationship (14) serves as a determining condition for the participation of dissolved methane. If it is admitted that the participation of dissolved methane gives rise to a large-scale outburst, condition (14) is the simplest analytical condition of such an outburst.

The most significant parameters in condition (14) are on the right side, which can be represented as the generalized parameter $\beta = (\alpha d_0 h)/K_{1c}^2$; this defines the participation of dissolved methane in the fracturing of coal. The numerator of β reflects the amount of methane in the crack, and the denominator the crack resistance of the coal. The more methane released into the crack and the lower the crack resistance, the more favorable the conditions will be for participation of dissolved methane in the failure of the coal.

Generally speaking, this predictable conclusion has found quantitative expression in the model. The principal result of the model investigation consists in the fact that participation of dissolved methane predetermines unlimited dynamic crack development. Let us stress that a crack cannot sustain unlimited growth under the action of free gas.

The conclusion concerning the size of stable particles, up to which a coal lump severed from a seam may fracture during outbursts can be drawn from the lengths of cracks in limiting equilibrium. If, in effect, the characteristic dimension of a lump exceeds the diameter $2a*$ of a crack in limiting equilibrium, an unstable crack may form in the lump, and it should be separated. If the dimension of the coal lump is smaller than the length of the crack in limiting equilibrium, the formation of a crack in the lump will not lead to its fracture. Consequently, the order of magnitude of $2a*$ suggests the characteristic size of particles that may be formed during an outburst ($D \sim 2a*$).

It is noteworthy that crack resistance raised to the second power enters into the parameter β; this confirms its significant role in the fracture of coal by dissolved methane. The dependence of the diameter D of the particles being formed on the effective crack resistance K_{1c}* is shown in Fig. 4 (for the above-cited values of the model parameters).

The value of $K_{1c}^* = 0.11$ MPa·m$^{1/2}$ in the example under consideration is critical for the participation of dissolved methane in the dynamic fracture of coal. For sections of a seam, where $K_{1c} > K_{1c}^*$, dissolved methane should not assume an active part in outbursts.

It follows from the calculations and Fig. 4 that for small crack-resistance values ($K_{1c} < 0.045$ MPa·m$^{1/2}$), which apply to coals classed as IV and V in terms of degree of breakdown (shattered and ground coal, crushable ores [26, 27]), the particle diameter corresponds to the particle diameter of "mad flour" ($D < 5 \cdot 10^{-5}$ m) with respect to order of magnitude. It is important to stress that this result is obtained without consideration of the coal's microstructure.

For the sake of correctness, it must be pointed out that calculation of a crack length of the order of 10^{-5} m is derived in the face of possible application of crack mechanics. Use of fracture mechanics for very small crack lengths assumes significance as an investigation of the tendency of possible failure on the microlevel from the standpoint of fracture energy.

Let us now estimate the volume of methane that goes over from the dissolved to the free state during the fracture of 1 ton of coal to minute particles. The particles can be represented by cubes with a face length D. Let us examine the two cases that were dwelled upon above.

The first of these cases corresponds to an effective crack resistance $K_{1c}^* = 0.025$ MPa·m$^{1/2}$ for coal with a particle dimension $D \approx 2a* = 1.2 \cdot 10^5$ m. In this case, we have: a particle volume $V_d = D^3 = 1.728 \cdot 10^{-15}$ m^3; the number of particles $N \approx 5.79 \cdot 10^{14}$ in 1 m^3 of coal, and the volume of that part of 1 m^3 of coal from which dissolved methane was discharged "instantaneously" (on failure) $V* = 6NhD^2 \approx 0.15$ m^3; the mass of "instantaneously" liberated methane (under a pressure $p \approx 0.1$ MPa in the working) $M = \alpha d_0 V*(p_0 - p)/p_0 \approx \alpha d_0 V* \approx 5.1 \cdot 10^3$ g; and, the volume that the methane instantaneously liberated from 1 m^3 of coal occupies in the working $V = MRT/(\mu p) \approx 7.9$ m^3. Assuming the density of the coal to be 1.3 tons/m^3, we can arrive at the desired result: in the first case, approximately 6.1 m^3 of dissolved methane was liberated "instantly" from 1 ton of coal.

In the second case, the linear particle dimension $D \approx 2a* = 7 \cdot 10^{-5}$ m. Performing similar calculations, we deduce that in this case, 0.95 m^3 of dissolved methane is liberated "instantaneously" from 1 ton of coal during an outburst. The order of the volume of dissolved methane that is liberated instantaneously therefore corresponds to experimental and analytical estimates cited in [24, 25].

Mine pressure was not considered in the example; this is justified for the mechanism adopted for the formation of "mad flour." In the general case, σ_N should be introduced to the calculation. The problem of that critical stress redistribution in the seam for which dissolved methane may take part in seam failure in the stage preparatory to an outburst may be solved in this connection.

In conclusion, let us stress that crack growth in coal under the action of dissolved methane may be interpreted as one of the mechanisms responsible for the escape of methane from the solid solution with a critical reduction in its mechanical stresses. The mechanism in question, which is similar to the discharge of bubbles from a liquid, may also act in both a coal seam and in individual coal fragments severed from the seam. This is explained by a rapid release of dissolved methane during outbursts.

BASIC CONCLUSIONS

1. The methane dissolved in natural coal may participate directly in the dynamic failure of the coal during sudden outbursts.

2. The following are factors determining the participation of dissolved methane in the failure of coal during outbursts: a high natural methane content, the fracture microstructure of the coal, and its low crack resistance.

3. It can be stated that it is precisely the dissolved methane that predetermines the formation of "mad flour."

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