

The factor of outburst hazard of coal seams zones, conditioned by coal particles size

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Abstract

Introduction. Parameters and features of coal seams which experienced coal and gas outbursts are actively studied to specify the mechanism and develop the methods of forecasting and preventing coal and gas outbursts. Outbursts emit from weak, crumpled coal members.

Research aims to investigate the influence of coal seam grains size on the development of coal and gas outbursts with the account of possible modification of coal strength and filtration properties.

Methodology. Theoretical analysis of coal particles size and the size of incipient cracks influence on the formation of coal and gas outbursts.

Theoretical part. The research has shown that with the reduction of coal particles average size, the flow of gas which develops from the internal volume of coal into the free form increases, the coefficient of permeability decreases; it leads to the growth of gas pressure gradient in the marginal zone. The size of particles depends upon the conditions of coal development and occurrence. In certain geological periods coal breaks up when a part of a massif is broken by the forces of rock pressure. The size of coal particles influences the range of equilibrium conditions, under the violation of which coal and gas outburst develops.

Results. Based upon the conditions of balance of a minute volume of coal with oriented cracks, the criterion of coal and gas outbursts development has been formulated; it shows that with the reduction of cracks size as a power function, the probability of coal and gas outbursts increases, when other conditions remain constant.

Summary. The factor of coal and gas outbursts generation has been formulated, expressed in terms of coal particles size to the power of 2.5 whereby the probability of outburst generation linearly increases under the grow of coal seam gas content, methane diffusion ratio out of the internal chamber to the surface of coal particles and under coal strength reduction.

Key words: gas-dynamic events; marginal zone; coal; methane; coal and gas outburst; cracks; breakdown; size of grain; filtration.

Introduction. Three main factors determine the development of coal and gas outbursts at the seam compartment: stresses redistribution in the marginal zone, strength and physical-chemical properties of coal and gas pressure [1–5]. Despite rather evident set, it is generally difficult to determine a definite critical value and quantitatively assess the effect on the probability of coal and gas outbursts development for each of the enumerated factors [6–10]. For example, gas factor can be expressed through coal seam gas content and the original velocity of gas yield, each of these values influences the size of the measured gas pressure in different ways [2, 6, 8, 10].

Currently used methods of forecasting and preventing coal and as outbursts allow significantly reducing the probability of their manifestation, but do not fully prevent

from the development of this hazardous gas-dynamic event. Modern researches are oriented to the specification of the mechanism of coal and gas outburst as well as determining the parameters appropriate for their forecast [2–8]. At the present time, for the latest estimate of outburst hazard, the integrated criteria are being worked out, which take into account the influence of several parameters characterizing mining and geological conditions, stress-strain state and the sequence of coal seams mining. An example of such criterion [6, 7] is the criterion developed by V. I. Murashev. An approach proposed by V. N. Puzyrev [2] is also applied, which is based on the monitoring of the original velocity of gas emission from the drilled well, as well as the volume of rubble coming from every meter of a well when drilling an outburst-prone member.

Research aim. The structure of coal occurring in the outburst-prone member is called an earthy-grainy structure. The term agrees with the actual state of coal which contributes to outbursts development [1–3]. Quantitative characteristics of granularity are rarely used to estimate the aptitude of certain coal seam compartments to outbursts. However the size of grains can influence both strength and gaseous properties of coal. Coal aptitude to breakdown and the limit of deformations depend on the concentration of the beginnings of cracks, the distance between the cracks and their size [11–16]. The space between the grains forms the filtration capacity of a coal seam, i. e. the capacity accessible for free gas. The size of coal particles determines the total of coal solid, accessible for gas absorption and adsorption [8, 9, 16–18]. The present work studies the influence of coal seam grain size on the formation of coal and gas outbursts with the account of possible modification of strength and filtration properties of coal.

Theoretical part. Based on the theory by S. A. Khristianovich [19–21], and in correspondence with the developed model by V. I. Murashev [6–7], the gradient of gas pressure is the impelling force (active force) of coal and gas outburst. The gradient of gas pressure and the intensity of gas emission determine the magnitude of the impelling forces contributing to coal breakdown, bringing a part of coal seam into a suspended state and its travel across the mine working. Forces restraining the outburst are called passive. Active forces F_a are applied along the whole cross-section of face S , while passive forces F_p act along the perimeter of coal seam P which borders upon the enclosing rock, and partially within the seam. The magnitude of active and passive forces is calculated for a unit thickness of a coal layer towards the inside of the mine working:

$$F_a = \frac{\partial P}{\partial z} S \lambda; \quad (1)$$

$$F_p = \tau P = (k_0 + \sigma \operatorname{tg} \varphi) P, \quad (2)$$

where $\partial P / \partial z$ – the gradient of gas pressure; S – cross-sectional area of the mine working; τ – tangential stresses; P – the perimeter of a mine working. The limiting value of tangential stresses along the perimeter of a coal seam according to Coulomb-Mohr friction law can be expressed through the coefficient of cohesion k_0 , the value of normal stresses σ and the tangent of internal friction angle $\operatorname{tg} \varphi$: $\tau_m = k_0 + \sigma \operatorname{tg} \varphi$. Condition $F_a \geq F_p$ determines the probability of coal and gas outburst, it is equivalent to the following expression:

$$\frac{\partial P}{\partial z} \lambda \geq (k_0 + \sigma \operatorname{tg} \varphi) \frac{P}{S}. \quad (3)$$

In (1), (3) coefficient λ is equal to the ratio of the cross-sectional area of the seam compartment under consideration, which the pressure gradient acts on, to the total area of face projection. The given coefficient is connected to the porosity of a seam. The obtained formula characterizes the macroscopic section of a marginal zone of a coal seam where the gradient of rock and gas pressure is oriented along the axis of the mine working from the face towards the inside of the coal seam. Linear dimensions, which reveal perceptible change of coal seam stress state, are significantly larger than the typical size of grains which make up the coal of the outburst-prone member, larger than the size of the cracks and the distance between the cracks.

Coal and gas outburst originates in the marginal zone of a coal seam some distance from the face, coal disintegrates according to the mechanism of laminar separation with cracks propagation under the action of high gas pressure within the coal seam. The condition similar to the macroscopic condition (3) of the equality of active and passive forces can be applied to a separate crack as well [11, 12, 15]. The given proposition implies that changing external conditions leading to the growth of one crack will cause the growth of all the cracks, which are under similar conditions in the coal seam, at once. The balance of a certain crack, where disruptive pressure P_0 acts, is disturbed under the following condition:

$$P_0 \geq \sqrt{\frac{Eg}{(1-\nu^2)\pi L}}, \quad (4)$$

where E – Young's modulus; ν – Poisson ratio; g – Griffith's parameter; L – half-width of a crack. Formula (4) is written for a standard problem of crack propagation, P_0 – the pressure which can be conditioned by the presence of gas inside the crack or the action of mechanical disruptive forces.

The state of a coal massif, which coal and gas outburst is possible from, is characterized by the high concentration of cracks, so it is necessary to take into account the interaction between the neighboring cracks. It has been shown earlier [15] that if two cracks are situated opposite each other at a distance of $a \ll 8L$, then the condition of cracks stability follows from the expression:

$$P_0 \geq \sqrt{\frac{2\sqrt{2}Eg}{a}}. \quad (5)$$

In the condition when the development of an outburst-prone situation is possible, i. e. under high concentration of cracks, the average size of cracks is approximately equal to the distance between the neighboring cracks $L \approx a$, it means that formulae (4) and (5) are equivalent. In its turn, the value of the average distance between the focuses of cracks is determined by the size of separate grains making up the massif. Assume the typical size of particles is similar in size to the average distance between the planes of cracks which, in its turn, is similar to the size of the developing cracks.

The forces, disrupting the crack, originate by means of the difference of gas pressure in the neighboring cracks, which can be expressed through the gradient of gas pressure and the average distance between the planes of the neighboring cracks:

$$P_0 = a \frac{\partial P}{\partial z},$$

in this basis the condition of cracks propagation (5) is reduced to the following:

$$\frac{\partial P}{\partial z} \geq \frac{\sqrt{2\sqrt{2}Eg}}{a^{1,5}}. \quad (6)$$

The smaller the distance between the cracks (6) and their size, the larger must be the gradient of gas pressure, which ensures meeting the threshold of separate cracks growth.

The gradient of gas pressure is determined by the value of gas flow which filtrates from the depth of the coal seam towards the free face. It depends on the seam pressure and on gas reserve which is in some connection with the massif. The value of mass flow G through the unit of surface area can be expressed through w – the filtration velocity and $\rho = PM/RT$ – gas density derived from Mendeleev-Clapeyron equation through the parameters of gas condition – pressure P , temperature T and its molar mass M :

$$\rho_w = -G, \quad \text{либо } P_w = \frac{-GRT}{M}. \quad (7)$$

Darcy's law describes the connection between the filtration flow rate and gas pressure gradient along the axis of the face:

$$w = -\frac{k}{\mu} \frac{\partial P}{\partial z}, \quad (8)$$

where k , μ – filtration coefficient and dynamic viscosity of gas correspondingly.

From (7), (8) we obtain the following expression for the gradient of gas pressure:

$$\frac{\partial P}{\partial z} = G \frac{\mu}{\rho k}. \quad (9)$$

The highest value of gas pressure gradient in a seam is reached near the periphery of the face, where gas density ρ is minimal. The size of coal fractions influences the filtration coefficient and the rate of methane development into the gaseous phase, i. e. gas flow rate. For earthy-grainy coal of outburst-prone members, the coefficient of permeability k is expressed through the typical size of particles r_0 , which make up the coal seam.

In correspondence with Cozeni-Karman model we can write:

$$k = \frac{m^3 r_0^2}{36c(1-m)^2}, \quad (10)$$

where m – effective porosity of a seam; c – Karman number which has meaning of a coefficient of form; the value of c for a close-packing of spheres is 5; porosity depends on the form and the character of particles packing, but it doesn't depend on the average size of particles.

In order to estimate the influence of particles size on the flow of gas percolating in the marginal zone, let us imagine that gas transfer from coal is determined by the rate of methane molecules diffusion through the coal particles to pores and cracks volume. The main part of methane in coal is in the dissolved state similar to the state of molecules

within the micropores of coal. The first step towards methane molecules development into the gaseous phase is solid diffusion. It is the slowest process that gas emission rate depends on. The typical time t of methane diffusion from the internal volume of a particle with radius r_0 to its surface can be associated with the coefficient of diffusion D on the grounds of dimensions and conformity theory: $Dt/r_0^2 \approx 1$, from which $t = r_0^2/D$.

Assume β – the mass of the liberating gas for a unit of coal volume V , kg/m³. Then the flow of gas from one coal particle, kg/s, can be assessed as follows:

$$G_0 = \frac{V\beta}{t} = \frac{4}{3}\pi D\beta r_0.$$

The concentration of coal particles we will express in terms of their dimensions and effective porosity as follows: $n = 3(1 - m)/4\pi r_0^3$. In this case, gas flow of in coal unit volume can be written as:

$$G = \frac{4D\beta(1 - m)}{r_0^2}. \quad (11)$$

The total flow of gas percolating through the marginal zone of a coal seam is proportional to the value which is determined by formula (11). Assume, parameter β has meaning of effective quantity of methane and includes the correction which determines the share of methane which takes part in filtration flow. Under such set of a problem, the gradient of gas pressure (9) is determined by an expression:

$$\frac{\partial P}{\partial z} = 720 \left(\frac{1}{m} - 1 \right)^3 \frac{D\beta\mu}{\rho r_0^4}. \quad (12)$$

Results. For numerical estimate according to (12) let us accept the following values: the coefficient of methane diffusion through coal solid $D = 10^{-13}$ m²/s; the mass of gas liberating from each cubic meter of coal, $\beta = 10$ kg/m³; methane viscosity under the filtration flow $\mu = 10^{-5}$ Pa · s; methane density in a seam near the face $\rho = 1$ kg/m³; coal porosity $m = 0.1$. In order to estimate the threshold value of gas pressure gradient, which causes the growth of cracks if exceeded, by formula (6), let us accept the value of Young's modulus $E = 10^8$ Pa, and Griffith's parameter $g = 1$ N/m. The results of the estimates are shown at fig. 1.

Fig. 1 schematizes two dependences of gas pressure gradient on coal particles sizes (12) and on the size of cracks (6). Solid line indicates gas pressure gradient threshold value (6), excess of which causes the loss of crack stability, and crack growth becomes possible. In case the size is reduced, crack is difficult to disrupt, at the same time the concentration of cracks in a seam increases, the distance between the planes of cracks and the disruptive force, acting on every crack, decrease. Dashed line (fig. 1) indicates gas pressure gradient which develops at gas filtration through coal in the marginal zone (12). Particle size reduction increases the rate of methane development into the gaseous phase, and at the same time, even under the constant porosity of a seam, filtration channels cross-sections get narrow and filtration coefficient decreases, consequently, gas pressure gradient in the marginal zone grows. The intersection point of solid and

dashed lines at fig. 1 corresponds to the balance, and area to the left of this point corresponds to the unstable condition wherein the destruction of a massif starts.

With particles size reduction, gas pressure gradient grows according to the rule $1/r_0^4$, and the threshold value of a pressure gradient, which is sufficient for rock massif destruction, depends on the dimensions of cracks proportional to $1/a^{1.5}$. As it has already been said, cracks dimensions and the distance between the neighboring cracks are commensurable with coal particles dimensions. For a medium with strong granularity, cracks grow along the zones of weakening which mainly lie in the points of stronger particles contact, as well as along the sections with air pockets. The focuses of cracks beginning are usually the most weakened points of particles contact; that is why, depending on the conditions, the size of cracks can exceed the size of particles by one or two orders of magnitude. At the same time the point of balance at fig. 1 displaces rightwards into the area of larger particles – low gradients of gas pressure.

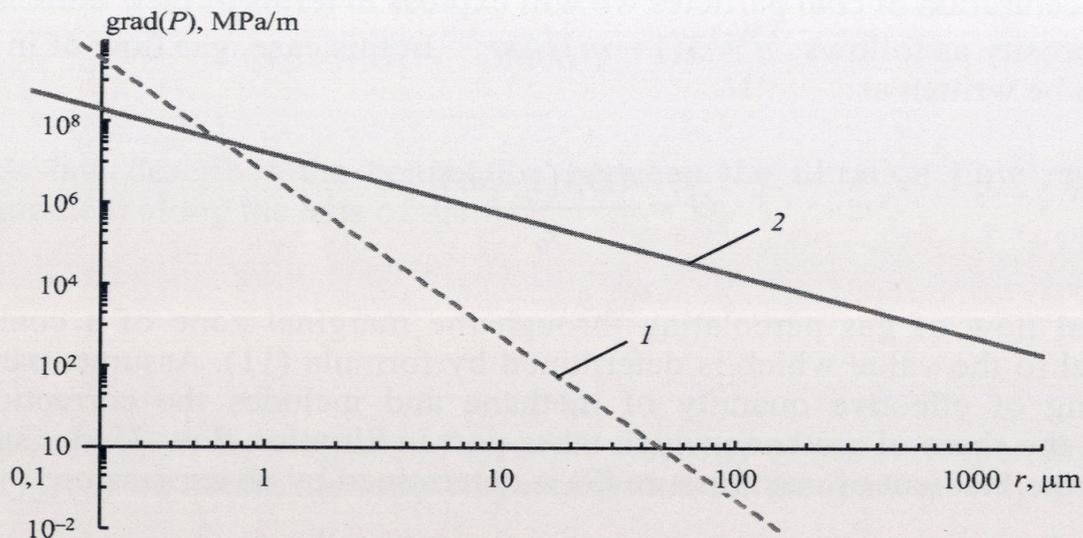


Fig. 1. Threshold value of gas pressure gradient (6) compared to gas pressure gradient (12) developing at filtration:

1 – dP/dz according to formula (12); 2 – dP/dz according to formula (6)

Рис. 1. Пороговое значение градиента давления газа (6), сопоставленное с градиентом давления газа (12), возникающим при фильтрации:

1 – dP/dz по формуле (12); 2 – dP/dz по формуле (6)

If we accept that $a \approx r_0$ as a threshold estimate, then from formulae (6) and (12) we get the value of coal particles critical value, compared with the parameters of a seam:

$$r_0^{2.5} \leq 428 \left(\frac{1}{m} - 1 \right)^3 \frac{D\beta\mu}{\rho\sqrt{Eg}}. \quad (13)$$

If the right part of inequality (13) is greater than the left part, then it corresponds to the parameters of the coal seam which is coal and gas outburst-prone. The obtained ratio has been formulated based on the balance of physically small volume of the coal seam which contains growing cracks and is subject to the action of gas pressure gradient. Numerical coefficient 428 has a guide value; it has been obtained with a range of estimate values which were used to derive formula (12). However, the interconnection between the values which determine the outburst hazard of a coal seam is reflected reliable enough in formula (12). High coefficient of diffusion D , high concentration of gas in a unit of volume β , as well as low strength of coal, expressed through Young's modulus and Griffith's parameter \sqrt{Eg} , increase the probability of coal and gas outbursts. The main result lies in the fact that with the reduction of coal particles size,

the probability of coal and gas outbursts grows as a power function. Thus, the smaller the coal particles are, the higher the probability of coal and gas outbursts from the given area is. The later statement has been made as a hypothesis of invariability of coal gas bearing capacity and the coefficient of methane diffusion through coal.

Summary. In order to improve the methods of forecast and prevention of coal and gas outbursts, it is necessary to study the mechanism of outbursts hazard situations development and specify the properties of a coal seam which accompany coal and gas outbursts. The dimensions of grains in a coal seam determine the average distance between the beginnings of cracks and the dimensions of cracks in a state prior to outburst.

The speed growth has been determined of methane development into the gaseous phase and of filtration flow in the marginal zone due to the reduction of methane diffusion to the surface of particles, which is conditioned by the reduction of particles dimensions.

It has been shown that the reduction of an average size of coal particles and channels radius along which gas is filtered under the constant value of coal porosity, leads to the growth of gas pressure gradient in a coal seam.

The factor of coal and gas outbursts generation has been formulated, expressed in terms of coal particles size to the power of 2.5 whereby the probability of outburst generation linearly increases under the increase of coal seam gas content, methane diffusion ratio out of the internal chamber to the surface of coal particles and under coal strength reduction.

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Фактор выбросоопасности зон угольных пластов, обусловленный крупностью частиц угля

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Реферат

Введение. Параметры и свойства угольных пластов, на которых произошли внезапные выбросы угля и газа, активно исследуются с целью уточнения механизма и совершенствования методов прогноза и предотвращения внезапных выбросов угля и газа. Выбросы происходят из слабых, перемятых пачек угля.

Цель работы. Исследование влияния крупности зерен угольного пласта на формирование внезапных выбросов угля и газа с учетом возможного изменения прочностных и фильтрационных свойств угля.

Методика. Выполнен теоретический анализ влияния крупности частиц угля и размера зарождающихся трещин на формирование внезапных выбросов угля и газа.

Теоретическая часть. В работе показано, что с уменьшением среднего размера частиц угля увеличивается поток газа, переходящего из внутреннего объема угля в свободную форму, уменьшается коэффициент проницаемости, что ведет к возрастанию градиента газового давления в краевой зоне. Размер частиц определяется условиями формирования и залегания угля. В отдельные геологические периоды уголь измельчается при разрушении части массива силами горного давления. Размер частиц угля влияет на диапазон равновесных условий, при нарушении которых развивается внезапный выброс угля и газа.

Результаты. Исходя из условий равновесия малого объема угля с ориентированными трещинами сформулирован критерий возникновения внезапных выбросов угля и газа, который показывает, что с уменьшением размера трещин по степенному закону возрастает вероятность возникновения внезапных выбросов угля и газа при сохранении прочих условий.

Выводы. Сформулирован фактор возникновения внезапных выбросов угля и газа, выраженный через размер частиц угля в степени 2,5, в соответствии с которым вероятность формирования внезапного выброса линейно возрастает при увеличении газоносности угольного пласта, коэффициента диффузии метана из внутреннего пространства к поверхности угольных частиц, а также при уменьшении прочности угля.

Ключевые слова: газодинамические явления; краевая зона; уголь; метан; внезапные выбросы угля и газа; трещины; разрушение; зернистость; фильтрация.

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