Outburst danger criteria for acoustic prediction methods at the initial and final stages of preparing sudden coal and gas outburst

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Abstract. Two stages of preparing coal and gas outburst are studied in the article. At the first stage the cracks which create a coal block structure are being developed ahead of the moving workings in a zone of high rock pressure. At the second stage the crashing of a narrow coal layer in the mouth of starting outburst cavity and its outsqueezing into the workings takes place. The control of cracks development is fulfilled by acoustic emission method. For controlling the rock pressure spectral-acoustic method is applied. The outburst danger criterion of spectral-acoustic method is corrected depending on the coal strength and in-situ pressure and they are estimated according to the methane concentration in the workings atmosphere. The results of outburst danger criteria comparison for different variants of spectral-acoustic method in a form of relation between high frequency and low-frequency amplitudes of the operating equipment “noise” spectrum and in the form of current and critical values of amplitude-frequency characteristic medians of noise are introduced. It is demonstrated that a crack development criterion and the criterion of a coal layer outsqueezing coincide if there is no gas in a coal seam. With the increasing of methane concentration at the face the crack development criteria decrease much faster than outsqueezing criterion. It is concluded that the result of the outburst danger prediction made by acoustic emission method is a necessary but not sufficient condition for initiating the outburst. The prediction, made by acoustic emission method supplemented by controlling methane concentration and coal strength allows estimating outburst danger within the whole process of outburst preparation.

1. Introduction

With contemporary tempos of mining the seams exposed to coal and gas sudden outbursts and with the purpose to avoid the reduction of working tempos, current outburst danger prediction is fulfilled applying geophysical methods without sampling the drill holes. The most frequently applied are the prediction method on acoustic emission (AE) and spectral-acoustic one.

The predicting method on AE, which is sometimes called as acoustic emission or micro seismic one, is based on analyzing dynamic crack development process. Different variants of this method take into account abnormal growth of AE activity, sometimes AE source location is added or a spectral content or/and AE pulse power are used [1-6].

The given method of the outburst danger prediction was created by analogy with the method of non-destructive examination on AE, which is applied, for estimating the strength of materials and objects. The acoustic-emission method of non-destructive examination on AE is based on the principle
that starting from a certain load (presumably 70 percent of breaking limit) the cracks start propagating in a jump-like mode in a sample [7]. Thus the intensity of this process (the number of AE impulses per unit time) while increasing the load grow to a certain degree and then it decreases and the process culminates with propagation of the main cracks which brings about the destruction of the sample [7-9]. And it is experimentally registered that there is a certain time dependence of AE impulses sum while destructing both the rock samples and technical objects (see for example [10-12]). This principle is valid for all samples and products of limited form: rock, metal and composite material samples, body frames of the objects and constructions etc. [6-13].

In contrast to the experimental samples, a coal seam is a semi-infinite medium where one of the sides undergoes destruction. And at a certain distance from the working face a zone of high rock pressure, where the cracks could appear and grow, is formed. The process of the cracks propagation there is more intensive when the active stresses are higher. That is why the activity level of acoustic emission in stopes is higher than in the development workings and strongly depends on the size of the roof hanging over the developed space. With destroying the face space the shifting of the area with high rock pressure into the depth of the massif takes place and another part of it undergoes destruction. If the shifting process goes evenly and with a constant speed then AE activity keeps nearly to a constant level. If, for some reasons, a sharp shifting of high rock pressure takes place then the AE activity could exceed that nearly constant level, though the real outburst danger could decrease due to the shifting of the maximum bearing pressure into the depth of the massif. As we think, the majority of type 2 errors (false danger of dynamic phenomenon) while predicting sudden outbursts and rock bumps using AE method is conditioned by the increase of AE activity while the shifting of high rock pressure zone.

Spectral-acoustic method in a current “Instructions on dynamic phenomena prediction” is called “… on the parameters of artificial acoustic signal” [1]. It is based on the influence of a rock pressure on the spectral content of the operating equipment “noise” which propagates through the adjacent to the face coal space between the source and the receiver of the “noise” [14]. The method has several modifications which differ by the algorithm of acoustic signal processing [15].

Both abovementioned geophysical predicting methods do not have analytically and experimentally grounded methodology for defining outburst danger criteria. It is conditioned by the large number of parameters which characterize the stability of the massif and these parameters cannot be defined fast under mining conditions. This is the reason why the parameters of outburst danger are defined based on statistic processing of the experimental data about the values of the outburst danger indicators of the applied geophysical method. These values have been registered either before the dynamic phenomena in a controlled seam or when their dangerousness has been predicted by more reliable instrumental method.

The purpose of this paper is in comparing analytically defined, at different stages of preparing outburst, outburst danger criteria for spectral-acoustic predicting method and to estimate the accuracy of acoustic-emission and spectral-acoustic methods on their bases.

2. Outburst danger criteria for spectral-acoustic method based on the ratio between the amplitudes of high-frequency and low-frequency parts of the “noise” spectrum for two stages of preparing the outburst

Preparing sudden outburst goes gradually. In a simplified manner this process can be described as consisting of two stages which characterize the initiating and finalizing of the outburst preparation. The first stage corresponds to initiating and progressing the crack development in a face space and forming a block structure in it. The second stage corresponds to finalizing the sudden outburst preparation and it involves immediate destruction of a narrow coal layer in a mouth of the future outburst cavity (kind of micro rock bump) and outsqueezing the formed coal lumps into the workings that initiates the outburst as such.

For both stages in paper [16] the criteria of their accomplishment for outburst danger indicator are defined. It is done in the form of the ratio between the amplitudes of high-frequency and low-
frequency parts of the spectrum noise produced by operating mining equipment (for example, by tunneling machine). For the stage of the crack propagation this criterion is defined by the following equation [16]:

\[
K_{1,i} = \exp \left\{ -Cd \left[ \frac{\sigma_0}{0.1} \frac{q}{110-q} \sigma_0 - \psi \frac{x_{cr}}{x_{st}} \exp \left( -\frac{x_{cr}}{x_{st}} \right) \right] \right\},
\]

where: 
- \( C \) is a parameter that defines the attenuation of the sound at the section of a rock massif between the source and a receiver of the noise, m\(^{-1}\);
- \( d \) is a distance between the source and the receiver, m;
- \( \sigma_0 = 1 \text{ MPa} \) is a normalizing factor specified by defining the limits of coal strength through non-dimensional indicator of coal strength \( q \), measured by a strength measuring device constructed by Skochinsky Institute of Mining;
- \( k_1 \) and \( k_\infty \) are the coefficients of the stresses intensity in a place of observation (where the crack propagation takes place) and out of the zone of the workings influence, respectively;
- \( x_{cr} \) is a critical distance from the face of the workings where the jump-like growth of the crack is initiated, m;
- \( x_{st} \) is a distance from the face to the area of the massif where the gas pressure stabilizes, m;
- \( Q \) – booster fan air-outflow rate, m\(^3\)/s;
- \( \Omega \) – is a current value of methane concentration measured by a methane near the face of the workings, %;
- \( \xi \) is a coefficient which takes into account the degree of influence (a share of freshly exposed face area) of \( i \)-th type equipment (combined machine, hummer, cutting-size of a drilling rig) on the face, \( 0 < \xi_i < 1 \).

In Eq. (1) \( D \) parameter is defined as follows:

\[
D = m(k_0 \eta P_{at})^{1/2} \cdot (100S_f)^{-1/2}, \text{ Pa} \cdot \text{s}^{1/2} \text{ m}^{-5/2},
\]

where \( m \) – is constant, that characterizes coal strength; \( k_0 \) – is a coefficient that characterizes a coal seam gas permeability, m\(^3\)/Pa\( \cdot \)s; \( \eta \) – is a methane dynamic viscosity, Pa\( \cdot \)s; \( P_{at} \) is a gas pressure on the rock face equal to the atmospheric one, Pa; \( S_f \) – is face area, m\(^2\).

For the second stage of preparing sudden outburst (starting the outqueezing of a coal layer from the mouth of the outburst cavity) the outburst danger criteria is defined by the following equation [16]:

\[
K_{2,i} = \exp \left\{ -Cd \left[ \frac{\sigma_0}{0.1} \frac{q}{110-q} \sigma_0 - (1-\varphi)10^{-2} \exp \left( -\frac{x_{1}}{x_{st}} \right) r_{e} D \frac{Q}{\xi_i} \right] \right\},
\]

where: \( r_{e} \) and \( x_{1} \) are effective radius and the thickness of the outqueezed coal layer, respectively, m; \( \varphi \) – is a coefficient which defines the size of the outqueezed section along which the crack sides that separate the area from the rest massif tightly contact with each other (\( \varphi \in (0;1) \)).

It is seen from Eqs. (1) and (3) that if there is no gas in a seam (\( \Omega = 0 \)) the criteria of the crack development (growth) and the criteria of initial outqueezing of the coal layer coincide as the second summand in denominators of the exponent value equal zero. Therefore, it can be supposed that for these conditions the prediction of dynamic phenomena preparation by AE method and spectral-acoustic method has nearly the same reliability.

Gas bearing coal seams with the growth of gas pressure have significantly different danger criteria for indicated outburst preparation stages. This difference reveals itself in other parameters which are included into the second addend of exponent value denominators, situated before \( D \) parameter.
Let us analyze the dependence of the criteria for accomplishing these two stages on the methane concentration $\Omega$ near the face of the workings, which characterizes gas factor of dynamic phenomena manifestation. To do it, at the beginning, it is necessary to estimate unknown parameters in equations for each stage.

Let’s suppose that when coal strength is $q=60$ c.u. (for this coal strength coal hardness coefficient according to Protodyakonov M.M. is $F=0.48$) the rock and gas pressure influence equally on outburst danger of the massif. Then, in equations (1) and (3) the summand in denominator of the exponent value equal to each other. Under this condition the equations for defining $D$ parameter either for the stage of the crack development (let’s call it $D_1$) or for the stage of coal layer outsqueezing ($D_2$) are defined as follows:

$$D_1 = \frac{0.1 \left( \frac{q}{110 - q} \right) \sigma_0}{\Psi_{cr} x_{cr} \exp \left( - \frac{x_{cr}}{x_{st}} \right) \sqrt{\Omega \Omega}}$$ – for the crack development stage, \hspace{1cm} (4)

$$D_2 = \frac{0.1 \left( \frac{q}{110 - q} \right) \sigma_0}{(1-\varphi)10^{-2} \exp \left( - \frac{x_1}{x_{cr}} \right) \sqrt{\Omega \Omega}}$$ – for a coal layer outsqueezing stage. \hspace{1cm} (5)

When: $\Psi_{cr}=5$; $x_{cr}=0.1$ m; $\Omega=1\%$; $\varphi=0.1$; $x_{cr}=0.1$ m; $\varphi=0.5$; $x_{cr}=0.1$ m; $r_e=0.5$ m; $Q=10$ m$^3$ we get: $D_1=0.07$ MPa $s^{1/2} m^{-5/2}$; $D_2=4.85$ MPa $s^{1/2} m^{-5/2}$. Comparing these values (they differ on three order) it can be concluded that a gas factor at the stage of cracks development has much higher value than the one at the stage of the outsqueezing.

Figure 1 demonstrates the graphs of outburst danger criteria dependency on methane concentration of type (1) – three curves and type (3) – one curve when $q=90$ c.u.

The estimation of $C$ parameter is done on the basis of the data introduced in paper [17].

Common parameters for these three curves are: $C=0.02$ m$^{-1}$; $d=10$ m; $q=90$ c.u. ($F=1.8$); $x_{cr}=10$ m; $Q=10$ m$^3/s$; $\varphi=0.1$; $D=1.7$ MPa $s^{1/2} m^{-5/2}$.

![Figure 1](image-url)

**Figure 1.** The dependence of crack development and coal outsqueezing criterion on the methane concentration in a face atmosphere when coal strength is $q=90$ c.u. for the variant, based on the ratio of high frequency and low frequency amplitudes of the noise spectrum.
The first curve of type (1) equation is built according to the supposition that the crack develops not far from the face at the distance of \( x_{cr} = 0.1 \) m. The parameter value \( \Psi_{cr} = 5 \) is taken for this distance. The second curve of type (1) equation is built according to the supposition that the crack develops at the distance of \( x_{cr} \approx 1 \) m from the face. For this distance the approximate parameter value is \( \Psi_{cr} = 1.2 \). The third curve of type (1) equation is built according to the supposition that the crack develops rather far from the face at the distance \( x_{cr} = 5 \) m. For this distance the parameter value \( \Psi_{cr} = 1.2 \) is taken. (The dependence of \( \Psi_{cr} \) on the ratio between the distance from the face and the length of the crack are taken from paper [17]).

The curve of type (3) equation is built according to the following values: \( r_e = 0.5 \) m; \( x_1 = 0.1 \) m; \( \varphi = 0.5 \). The rest of the parameters coincide with the parameters used for building curves of type (1) equation.

Figure 2 demonstrates similar dependences that are taken in figure 1, but the coal strength is \( q = 70 \) c.u. (\( F = 0.70 \)). Here only two curves of type (1) equation are presented as when \( \Psi_{cr} \approx 1.2 \) at a distance of \( x_{cr} = 5 \) m, methane concentration \( \Omega > 0 \) and when existing values of rock pressure (its value is considered in equation (1) through parameter \( q \) [16]) are used, the condition for the development is valid for all cracks.

![Figure 2](image.png)

**Figure 2.** The dependence of the crack development and coal outsqueezing criterion on methane concentration in the face atmosphere when the coal strength is \( q = 70 \) c.u. for the variant based on the ratio of high-frequency and low-frequency amplitudes of the noise spectrum parts.

As it is seen from the figures, with the decreasing of the coal strength the crack development criteria and coal outsqueezing criteria decrease. When there is no methane in coal and the coal strength is similar these criteria are equal to each other. With the increasing of methane concentration in the workings atmosphere near the face, the crack development criterion decreases along the exponential curve and with distancing from the face into the depth of the massif the criterion decreasing velocity increases. Herewith, the coal-outsqueezing criterion remains nearly constant for a large range of methane concentration changes.

3. Outburst danger criterion of spectral-acoustic method based on the ratio of current and critical values of amplitude-frequency characteristic medians of noise for two stages of outburst preparation

One of the weaknesses of variants for spectral-acoustic method of outburst danger prediction based on defining outburst danger criterion in the form of relation between high-frequency and low-frequency amplitudes of the operating equipment noise spectrum parts is in a possible type I error (outburst
danger situation skipping) when the noise spectrum change takes place in uncontrolled zone of amplitude-frequency characteristics. The second important weakness of these variants is the dependence of outburst danger criterion on the distance between the source and the receiver of the noise.

To eliminate these weaknesses the variant of spectral-acoustic method based on the relation of current and critical values of amplitude-frequency characteristic medians of noise is offered [18]. For this variant the equations for defining outburst danger criterion for two abovementioned stages of outburst danger preparation are $K_{m,1,c}$ and $K_{m,2,c}$ respectively [18]:

- The criterion for the crack development stage:

$$K_{m,1,c} = 0,1 \left( \frac{q}{110-q} \right) \frac{\Psi_{cr}}{3\sigma_0} x_{cr} \exp \left( -\frac{x_{cr}}{x_{st}} \right) D \sqrt{\frac{Q\Omega}{\xi_i}} .$$

(6)

- The criterion for coal outsqueezing stage:

$$K_{m,2,c} = 0,1 \left( \frac{q}{110-q} \right) \frac{(1-\varphi)}{95\sigma_0} r_c \exp \left( -\frac{x_1}{x_{st}} \right) D \sqrt{\frac{Q\Omega}{\xi_i}} .$$

(7)

Figures 3 and figure 4 demonstrate the dependences of crack development criterion and coal outsqueezing criterion calculated by the equations of type (6) and (7), with the coal strength $q=90$ c.u. and $q=70$ c.u. respectively. Parameter $\Psi_{cr}$ (three values), $\sigma_0$, $x_{cr}$, $x_1$, $x_{st}$, $D$, $Q$, $r_c$, $\varphi$ and $\xi_i$ are the same as for those in figures 1 and 2.

Figure 3. The dependence of the crack development criterion and coal outsqueezing criterion on methane concentration in the workings atmosphere when coal strength is $q=90$ c.u. for the variant based on the relation between current and critical values of amplitude-frequency characteristic medians of noise.

As it is seen from pictures 3 and 4 the dependence of crack development criterion and coal outsqueezing criterion on methane concentration is equal at a significant degree for the variant of spectral-acoustic method in the form of the ratio between current and critical values of amplitude-
frequency characteristic medians of noise. However, if the coal strength decreases the criteria values also decrease. And for both variants if there is no gas in coal then the crack development and coal outsqueezing criteria coincide. When coal contains gas, with the increasing of its pressure and methane concentration in the workings atmosphere, consequently, the value of crack development criterion is getting less than the value of coal layer outsqueezing criterion. This tendency grows stronger with distancing from the face workings.

![Figure 4](image)

**Figure 4.** The dependence of the cracks development and coal outsqueezing criteria on methane concentration in the mine working atmosphere when the coal strength equals $q=70$ c.u. for the variant based on the ratio between current and critical values of amplitude-frequency characteristic medians of noise.

Comparing figures 1 – 4 we see that the dependence of cracks development criterion and coal outsqueezing criterion on methane concentration in the variant of method on the relation of amplitudes is significantly higher than in the variant of relations of medians. It can be explained by the fact that in the first case the power law dependence (degree) on methane concentration is placed into the indicator of the exponential dependence, which defines the criteria values. While in the second case, the criteria dependence on methane concentration has only a power-law character.

Summing up the results, it can be concluded that acoustic emission and spectral-acoustic methods of dynamic phenomena prediction must show similar reliability only in case complete absence of gas in coal. The seams prone to sudden coal and gas outbursts marked up with high gas-bearing capacity. Under this condition, acoustic emission method can predict only the initial stage of sudden outburst preparation, whereas spectral-acoustic method accompanied with controlling methane concentration and coal strength can control the whole process of the outburst preparation.

**4. Conclusions**

- Outburst danger criteria dependence of both variants of spectral-acoustic method on in-situ gas pressure, basically, coincides. However, the variant in the form of relation between the current and critical value of amplitude-frequency characteristic medians excludes the failure due to non-considering the parts of spectrum for mining operating equipment cutting unit noise.
- The danger criterion of the variant in the form of the relation between the current and critical values of amplitude-frequency characteristic medians in contrast to the variant in the form of the relation between high frequency and low frequency parts of the noise spectrum does not depend on the distance between the source and the receiver of the noise.
- The acoustic emission method strictly controls the initiation of the first stage of outburst preparation where the spectral-acoustic method controls the stress increasing process along the first stage to the second stage of its preparation namely to the outqueezing of a coal layer from the outburst cavity mouth.

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