Substantiation of outburst danger automated monitoring on amplitude frequency characteristic median of the operating equipment noise and methane concentration in the mine working medium

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Abstract. Basic requirements to the methods of current outburst danger prediction are formulated. The methods must be applied in the process of mining not interfering with the works and taking into account basic factors that cause the outbursts and they should have scientifically grounded methodology for fast definition of outburst danger criteria under certain mining, geological and engineering conditions. It is shown that geophysical prediction methods can meet the first requirement. Rock pressure, in-situ gas pressure and coal strength are taken as basic factors of outburst danger. Some well-known geophysical method such as a method of acoustic emission, a spectral-acoustic method, a gas analytical method and a temperature method taken separately do not satisfy the second and the third requirements. That is why it is suggested controlling rock pressure by spectral-acoustic method, gas pressure by means of gas analyser on methane concentration at the face of the working while mining coal and coal strength should be measured by a strength measuring device. To improve the accuracy of the prediction a version of spectral-acoustic method based on dependency of amplitude-frequency characteristic median of mining operating equipment noise on average stresses at the section between the source of the noise and geophone. The criterion of outburst danger is substantiated and the algorithm for arranging automated monitoring of coal seam outburst danger is offered.

1. Introduction
Due to the growth of the depth and intensity of mining works the stresses in a coal face spaces grow too. It brings about the danger of dynamic phenomena manifestation and one of the most dangerous one among them is sudden coal and gas outburst [1-4]. To prevent them different means and methods of regional, local and current types of prediction are being worked out. [5].

Methods of current prediction of outburst danger should meet three basic requirements: their application should not interfere with the mining process, they should take into account basic factors that may cause outburst and they should have scientifically grounded methodology for fast definition of outburst danger criteria under certain mining, geological and engineering conditions.

At present in coalmines of Russia and abroad (Ukraine, Kazakhstan, China, Australia, Poland, SAR etc.) several instrumental (based on analysis of coal samples and in-situ gas samples while drilling controlling boreholes) and geophysical methods of current coal seam outbursts danger prediction are applied. These methods differ by physical basis of rock mass controlling approaches together with accuracy and duration [6-9].

Geophysical methods of prediction where the controlled parameters are functionally connected with basic factors of outburst danger meet the first requirement Instrumental methods do not meet the first requirement as they can be performed only in a halted face space.

The accuracy of the method is higher if basic outburst danger influencing factors are adequately taken into account. The analysis of well-known sudden outburst danger prediction models witnesses that the basic outburst danger factors of coal seams with moisture less than 5-6 per cent are: rock pressure, gas...
bearing capacity, gas permeability and desorbed gas pressure in fractures and pores of the coal together with its structure and strength [10-13]. If the coal moisture went over 6 per cent than no outburst would take place in Russian coalmines as the moisture blocks gas in micro-pores and coal becomes plastic and the zone of high rock pressure moves gradually rather deep into the rock massif for initiating the outburst [2]. However, geophysical methods firstly make the predictions using only one factor of outburst danger; secondly, do not have sufficient scientific grounds for methodology of defining outburst danger criteria under certain mining, geological and engineering conditions.

Thus, as an example, a method of acoustic emission which is applied for predicting gas and coal outburst and rock bumps is based, basically, on experimental fact that in the samples of a solid body loaded nearly on 70 per cent of compressive resistance cracks start to be developed and with the increase of the pressures their growth intensifies to the extent of crushing the sample. However, performing mining works includes destructing coal seam selvedge that is why cracks are to be formed and grow. Moreover, as far as the working face moves many new sections of a coal seam with their new crack formations join to high rock pressure zone. This is the difference between the destruction of a coal seam edge and the destruction of a sample. In this situation either abnormal growth of acoustic emission or abnormal growth of acoustic emission impulse energy or spectral content of acoustic emission impulses peculiarities are tried to be identified as a marker of outburst danger [14-17]. Thus, the outburst danger criterion is tried to be defined on the bases of statistic processing of acoustic emission impulses registered before the dynamic phenomena in certain coalmines. The accuracy of such prediction is very low. That is why the prediction made by this method is a necessary condition but not sufficient one for initiating sudden outburst.

Thus, nor acoustic emission method nor gas-analytical (on methane concentration at the face of the working) method nor temperature (on decreasing the coal face temperature due to the expansion of the gas emitted out of coal) method satisfy the second requirement as they control mainly one outburst danger factor: either a rock pressure or a gas factor [18].

While conducting comparative tests on geophysical methods of prediction [18] the best accuracy was shown by spectral-acoustic method, which in the Instructions on dynamic phenomena prediction in coalmines was named as “On the parameters of artificial acoustic signal”. However, multiple researches made on coal mines of Donbass, Kuzbass, Karaganda and Pechora coal basins showed that outburst danger criteria, experimentally defined initially for this very method on the basis of experimental data statistically processed by AK-1 apparatus, were valid only for certain mining technologies and mining geological conditions they had been captured in [19, 20]. It can be explained by the fact that not the whole range of outburst danger factors were taken into account and this very method controls mainly a rock pressure factor. As far as there are no unambiguous numerical outburst danger criteria while controlling rock massif by this method “The Instructions” suggests that initial definition of threshold value of the outburst danger criteria should be done on the parameters of the operating mining equipment “noise” received at the section of the active workings marked as “non-dangerous” [5]. But if the section is marked as non-dangerous one then the outburst danger indicator corresponds to non-dangerous degree of danger too. Thus, the real danger threshold value can be many times higher than the one received at the non-dangerous section, and the way of its defining is not explained by the “Instructions”.

Traditional options of a spectral-acoustic method define outburst danger indicator as the ratio of high frequency part amplitude of the spectrum to low frequency one [19]. Thus, if the outburst danger factors manifest themselves in unutilized part of the spectrum then the prediction will be false. That is why we suggest the variant of spectral-acoustic method on amplitude-frequency characteristic median of the operating equipment noise which uses the whole spectrum of the signal [21].

The purpose of this paper is to substantiate the methodology for experimental definition of outburst danger basic factors for the option of spectral-acoustic method based on outburst danger prediction on amplitude-frequency characteristic median of the operating equipment noise and to offer the algorithm for organizing automated monitoring of the coal seam outburst danger.

2. The dependence of outburst danger criterion on the parameters of the stressed gas-saturated coal massif
It is known that attenuation of the sound in solid body in the first approximation is directly proportional to frequency and inversely proportional to average stresses [19]. Using this proposition in paper [21] it is demonstrated that amplitude frequency characteristic median of the operating equipment noise grows together with the growth of stresses. (Under the amplitude frequency characteristic a harmonic frequency is understood and this harmonic frequency divides the noise spectrum into two parts in the way that
amplitudes sum of all harmonics with lesser frequency equals to the amplitudes sum of all harmonics with larger frequency). That is why the outburst danger indicator \( K_c \) in the form of relation of the current median \( f_{m,c} \) to its critical value \( f_{m,l} \), when the conditions for initial sudden coal and gas outburst starts to form have been introduced. In other words \( f_{m,c} \) corresponds to the equality of average current \( \sigma_c \) and limited \( \sigma_l \) stresses. Moreover, this indicator is connected with the relation \( \sigma_c \) and \( \sigma_l \) by the following ratio [21]:

\[
K_c = \frac{f_{m,c}}{f_{m,l}} = A \frac{\sigma_c}{\sigma_l},
\]

Thus to define \( K_c \) it is necessary to know \( f_{m,c} \) and \( f_{m,l} \). And if the values \( \sigma_c \) and \( \sigma_l \) which define it are set without taking into account the in-situ gas pressure then \( K_c \) will indicate only the coefficient of relative pressures. If \( \sigma_c \) and \( \sigma_l \) are set considering in-situ gas pressure and coal strength then \( K_c \) will stand for outburst danger indicator.

It can be proved that parameter \( A \) in (1) is defined by the ratio:

\[
A = \frac{\ln \left( \frac{A_{m,c,0}}{A_{m,c}} \right)}{\ln \left( \frac{A_{m,l,0}}{A_{m,l}} \right) F(r)},
\]

where \( A_{m,c,0} \) and \( A_{m,c} \) are the harmonics amplitudes of amplitude frequency characteristic median current values at the source of noise and near geophone respectively; \( A_{m,l,0} \) and \( A_{m,l} \) are amplitudes of amplitude frequency characteristic median critical values at the source of noise and near geophone respectively; \( F(r) \) is the function which takes into account the diagram of signal source directivity (in our case, approximately, it may be considered that the source of the operating equipment noise has spherical diagram directivity and for this diagram \( F(r) \approx 1/r \)).

In paper [21] on the basis of alerting markers of outburst danger initiation analysis the usage of two stage model of sudden outburst preparation is offered. According to this model at the first stage the development of the crack in a face space takes place and a coal block structure is formed. At the second stage out of the mouth of the future outburst cavity several coal cobs (blocks) are squeezed out and sudden outburst takes place. This paper also defines outburst danger criteria for both stages according to equation (1).

Thus, for the stage of the crack development the following relation for defining current (for the given position of a face) critical values of the outburst danger indicator \( K_{1,l,c} \) is received:

\[
K_{1,l,c} = 0.1 \left( \frac{q}{110-q} \right) - \frac{\psi_{q,e} r}{3\sigma_0} P,
\]

where: \( q \) is non-dimensional indicator of coal strength, measured by strength measuring device constructed by Skochinsky Institute of Mining, c.u.; parameter \( \psi_{q,e} = k_1 \phi / k_1^{\infty} \); where \( k_1 \) and \( k_1^{\infty} \) - are the coefficients of stress intensity at the observing point (where the crack development takes place) and out of workings influence zone, respectively; \( \sigma_0 = 1 \) MPa is a normalizing factor conditioned by defining the limits of coal strength in MPa measuring unit through non-dimensional indicator of coal strength \( q \); \( P \) is free gas pressure in a crack, Pa.

For the stage of outqueezing the coal layer (cob) out of the mouth of the outburst cavity the following relation for defining critical value of outburst danger indicator \( K_{2,l,c} \) was received:

\[
K_{2,l,c} = 0.1 \left( \frac{q}{110-q} \right) - \frac{(1-\phi) r}{95\sigma_0} x_l P,
\]
where: \( \phi \in (0;1) \) is a coefficient that defines the surface area share of the outsqueezed section along which the crack sides that separate the section from the rest of the massif contact tightly; \( x_1 \) and \( r_1 \) the thickness and equivalent radius of the outsqueezed coal section, respectively, m.

As far as direct continuous measuring of the gas in-situ pressure during mining is impossible we will use the results introduced in paper [21], where it is shown that this parameter can be estimated according to gas concentration in the workings medium near the face applying the following expression:

\[
P = D \sqrt{\frac{Q\Omega}{\xi}},
\]

where \( Q \) – air flow rate of a booster fan, that ventilates the workings, m\(^3\)/s; \( \Omega \) – current value of methane concentration, measured by methane sensor at the face of the workings, %; \( \xi \) is a coefficient that takes into account the influencing degree (the share of freshly exposed face area) i-th equipment type (combined machine, coal pick-hammer, cutting size of a drilling rig etc.) on the face, 0 < \( \xi < 1 \).

\( D \) parameter in (5) equals:

\[
D = m \sqrt{k_0 \eta P_a \cdot x_{cr} \exp\left(-\frac{x_{cr}}{x_{st}}\right)} / \sqrt{100 S_f}, \text{ Pa} \cdot \text{s}^{1/2} \text{ m}^{-3/2},
\]

where \( m \) – is non-dimensional constant conditioned by the fact that not all the pressure \( P \) influence towards the workings but only its part that is in the pores and cracks (for solid body with pore-channels it is numerically close to coal porosity value); \( k_0 \) – is a coefficient that characterizes gas permeability of the seam, m\(^{-3}\); \( \eta \) – is a dynamic methane viscosity, Pa·s; \( P_a \) – is a gas pressure on the surface of the face equals to atmospheric one, Pa; \( x_{cr} \) – is a critical distance from the face of the workings in which plane the development of the crack that initiates the outburst takes place (for the first stage of outburst preparation) or the thickness of the outsqueezed coal layer (for the second stage of the outburst preparation); \( x_{st} \) – is a distance from the face to the section of the massif where the gas pressure stabilizes, m; \( S_f \) – is a surface area of the face workings, m\(^2\).

It is seen out of Eq. (3) and Eq. (4) that the outburst danger criteria structure for both stages of preparing outburst coincides: both have two summands defined to a significant degree by similar parameters of a rock massif. That is why it is possible to substantiate unified criterion. The first summands in Eq. (3) and Eq. (4), conditioned by the rock pressure and coal strength coincide. Thus, while lacking gas in a seam the criteria of the initial development of the cracks and squeezing the coal layer out of the mouth of the outburst cavity have identical values. The second summands are conditioned by gas factor and may differ much. That is why to avoid type I errors in the prediction (missing outburst beginning) in unified criterion \( K_{1,2,c} \), the second summand that has a greater value must be taken:

\[
K_{1,2,c} = 0,1 \left[ -\frac{q}{110-q} \right] - \Delta \sqrt{\Omega},
\]

where parameter \( \Delta \)

\[
\Delta = \max \left\{ \frac{\psi_{cr}}{3\sigma_0} \sqrt{\frac{Q}{\xi}} \right\} \left[ \frac{1-\phi}{95\sigma_0} \frac{r_1}{x_{cr}} \sqrt{\frac{Q}{\xi}} \right],
\]

In Eq.(8) \( x_{cr} \) parameter equals the thickness of the outsqueezed coal layer.

To compare the contribution of the second summands into the outburst danger criterion lets analyze the relation \( \psi_{cr} \frac{Q}{3\sigma_0} \sqrt{\frac{Q}{\xi}} \) to \( \frac{1-\phi}{95\sigma_0} \frac{r_1}{x_{cr}} \sqrt{\frac{Q}{\xi}} \) with the following approximate values of the parameters they cover: \( \phi = 0,1-0,9; \) \( \psi_{cr} \) changes in the limits from 1,2 (at the workings of the face) to 5,0 (in the depth of the massif) [22]; \( x_{cr} = 0,1 \text{ m}; \) \( r_1 = 0,5-1,0 \text{ m}. \) The estimation showed that the summand determining gas outburst danger factor in the criterion for cracks development approximately from 4 ( at the workings face) to 3300 times (in the depth of the massif) is larger than in the criterion for coal layer outsqueezing.
It proves one more time that the danger criterion on acoustic emission activity is only necessary but not sufficient condition for initiating sudden outburst.

Thus Eq. (7) and Eq. (8) show that the outburst danger indicator of the spectral-acoustic method of prediction depends on a large number of rock massif parameters which are impossible to be defined fast. That is why they were united into one integral parameter \( \Delta \), which should be defined experimentally. To use Eq. (7) in practice the methodology on defining \( K_{1,2,m,l,c} \) value and \( \Delta \) under mining conditions was worked out.

3. Methodology on experimental definition of current critical value of outburst danger indicator \( K_{1,2,e} \), critical value of amplitude-frequency characteristic median of noise \( f_{m,k,e} \) and \( \Delta \) parameter

To simplify recording of the formulas we will determine \( K_{1,2,m,l,c} = K_{m,l,c} \). Defining the unknown values is meant to be done by comparing the results of prediction by the offered method on amplitude-frequency characteristic median of noise and by the quite popular and approved in Russian coal mines instrumental method of prediction on initial speed of gas saturation and output of drill cuttings while control borehole drilling. This comparison is possible as both methods are based on controlling basic factors of outburst danger, i.e. the initial speed of gas emission as well as the methane concentration at the face of the workings control the gas factor. The output of drill cuttings from a long-metre of the borehole in instrumental method characterizes a stress state and a coal strength. In spectral-acoustic method a coal strength, in addition to the strength itself, defines also a stress state. As far as the suggested instrumental method has a good scientific ground and empirical support for high accuracy of predicting results obtained from different large coal deposits in Russia we will use it as a reference method for substantiating outburst danger criteria for the introduced option of the spectral-acoustic method on amplitude-frequency characteristic median of noise.

According to this instrumental method the outburst danger criterion for coal mines in Russia is described by the following relation [5]:

\[
R = (S_{max} - 1.8) (g_{max} - \alpha) - b = 0,
\]

where \( R \) – is an outburst non-dimensional indicator; \( S_{max} \) – is a maximal value of drill cuttings output from the control interval, l/m; \( g_{max} \) – maximal value of gas emission initial rate from the control interval, l/min; \( \alpha \), \( b \) — are non-dimensional coefficients: for Vorkuta deposit: \( \alpha = 5 \), \( b = 21 \); for the rest coal basins and deposits of eastern region of Russia: \( \alpha = 4 \), \( b = 6 \).

When \( R \geq 0 \) the seam zone is referred to outburst dangerous one.

Experimental definition of \( K_{n,l,c} \) is realized as follows. Firstly, we select an experimental area. It can be a development entry which is worked out by a combined machine. In this case the combined machine would become a source of the wide-band sounding acoustic emission. At the experimental area step by step we undertake outburst danger prediction applying instrumental method which is characterized by high prediction accuracy and then we’ll apply the suggested option of spectral-acoustic method. In the process of defining outburst danger indicator (when combined machine works on coal) we also measure methane concentration \( \Omega \) at 2-3 m from the face of the workings and register the combined machine noise.

Using Eq. (9) we’ll define the critical value of the outburst danger indicator \( R_{cr} \) of the instrumental prediction method as follows:

\[
R_{cr} = (S_{max} - 1.8) (g_{max} - \alpha) = b,
\]

Further, using the results of drilling the control borehole using Eq. (10) we define experimental current value of outburst danger indicator \( R_{e,c} \) applying the following formula:

\[
R_{e,c} = (S_{max,c} - 1.8) (g_{max,c} - \alpha),
\]

where \( S_{max,c} \) and \( g_{max,c} \) – are current maximal values of drill cuttings output and initial gas emission rate registered from the one-meter control interval at the experimental area.

Further on, we define the coefficient of the relative outburst danger of instrumental prediction method \( R_{e,a} \) for the controlled zone as a ratio between current and critical values of outburst danger indicator:

\[
R_{e,a} = R_{e,c} / b, \quad (R_{e,a} \in [0; 1]).
\]
After that on the same seam area we define experimental current value of outburst indicator for our variant of spectral-acoustic method \( K_{m,c,e} \), when a combined machine is a source of sounding acoustic emission. For this indicator the coefficient of relative outburst danger will be written as the ratio of current \( K_{m,c,e} \) and current critical value (for a given moment and position of the face of the workings) \( K_{m,l,c,e} \) of outburst danger indicator:

\[
K_{o.e} = \frac{K_{m,c,e}}{K_{m,l,c,e}}, \quad (K_{o.e} \in [0; 1]). \tag{13}
\]

Supposing that coefficients of relative outburst danger of instrumental and spectral-acoustic method are nearly equal i.e. \( R_{as} \approx K_{as} \), we find experimentally defined at the given section of the workings current critical value of outburst danger indicator of spectral-acoustic method \( K_{m,l,c,e} \):

\[
K_{m,l,c,e} = \frac{K_{m,c,e}}{R_{as}}. \tag{14}
\]

For registered combined machine noise we define experimental current value of amplitude frequency characteristic median of noise \( f_{m,c,e} \). Substituting it in Eq. (1) we will find current critical value of the amplitude frequency characteristic median of noise \( f_{m,l,c,e} \):

\[
f_{m,l,c,e} = \frac{f_{m,c,e}}{K_{m,l,c,e}}. \tag{15}
\]

Knowing \( K_{m,l,c,e} \), it is easy to define \( \Delta_e \) parameter out of Eq.(7):

\[
\Delta_e = \frac{0.1 \left( \frac{q_e}{110 - q_e} \right) - K_{m,l,c,e}}{\sqrt{\Omega_e}}. \tag{16}
\]

Using the given substantiation for methodology of defining critical value of outburst danger indicator for spectral-acoustic method the following algorithm of automated outburst danger monitoring was offered.

4. Algorithm for automated outburst danger monitoring for spectral-acoustic method on amplitude frequency characteristic median if the noise

The algorithm for automated outburst danger monitoring consists of two parts: algorithm of “tuning” the method and algorithm for automated monitoring.

The algorithm of tuning the spectral-acoustic method with the help of instrumental method if the following:

- A current value of outburst danger indicator for instrumental prediction method \( R_{as} \) is defined by the formula Eq. (11).
- Current limited value of outburst danger indicator for spectral-acoustic method \( K_{m,l,c,e} \) is defined according to the formula (14).
- Current value of amplitude frequency characteristic median of noise \( f_{m,c,e} \) is defined using the registered spectrum of combined machine noise by the method introduced in paper [21].
- A limited value of amplitude frequency characteristic median of noise \( f_{m,l,c,e} \) is defined by the formula (15).
- Experimental value of \( \Delta_e \) parameter is defined by the formula (16).

The value of \( \Delta_e \) parameter defined by the above introduced methodology is considered to be constant while mining the workings till reaching the seam section where anomaly of any parameter that characterizes basic outburst danger factors is registered. It may be thickening of broken coal block or increasing methane concentration while the combined machine operation. In this case it is important to “tune” the method to new conditions according to above introduced methodology and define new value of \( \Delta_e \) parameter.
After the spectral-acoustic method “tuning” procedure, the outburst danger automated monitoring of a seam using the following algorithm is fulfilled:

- Continuous control of methane concentration at the face of the workings by gas protection equipment is fulfilled and periodically the strength of the broken coal block is measured by strength measuring device constructed by Skochinsky Institute of Mining.
- According to the registered data the amount of the critical value of outburst danger indicator $K_{m,l,c}$ is constantly corrected according to formula (7).
- Current value of the amplitude frequency characteristic median of noise $f_{m,c,e}$ is measured continuously according to formula (15) and the critical value of amplitude frequency characteristics median of noise $f_{m,l,c}$ is corrected.
- Current value of the outburst danger indicator is defined according to formula (1).

5. Conclusions
1. The introduced methodology for defining outburst danger criterion by geophysical method on amplitude-frequency characteristic median of the operating equipment noise allows controlling basic outburst danger factors: rock and gas pressures and coal strength.
2. The methodology for "tuning" the criterion of geophysical prediction method according to the results of simultaneously fulfilled outburst danger prediction by instrumental method in the same mine working is substantiated.
3. The algorithm of organizing coal seam outburst danger automated monitoring including “tuning” the method according to the parameters of instrumental prediction parameters and continuous correction of outburst danger criterion according to methane concentration in the workings medium is introduced.
4. The methodology and the algorithm can be used for working out technical specification for constructing subsystem of outburst danger automated prediction for multifunctional safety system of the coal mine.

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