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Comparison of outburst danger criteria of coal seams for acoustic spectral and instrumental forecast methods

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Abstract. Outburst danger criteria for the two methods of current coal seam outburst forecast are considered: instrumental – by the initial outgassing rate and chippings outlet during test boreholes drilling, and geo-physical – by relation of high frequency and low frequency components of noise caused by cutting tool of operating equipment probing the face area taking into consideration the outburst criteria correction based on methane concentration at the face area and the coal strength. The conclusion is made on “adjustment” possibility of acoustic spectral forecast method criterion amended by control of methane concentration at the coal face and the coal strength taken from the instrumental method forecast results.

1. Introduction

Safety rules of Russia’s coal and shale mines prescribe to equip the mine openings with the systems and means providing the safe mining operations. These systems must be combined into multifunctional safety systems (MFSS) which are to perform among other operations the gas-dynamic phenomena (GDP) [1] control and forecast.

One of the most dangerous GDP types is sudden outbursts of coal and gas. The current outburst forecast can be fulfilled by two groups of methods:

- instrumental, based on the face area control with a test borehole, and
- geo-physical which evaluates the condition of the face area by probing it with acoustic or electromagnetic waves.

The widespread introduction of geophysical forecasting methods is constrained by the difficulty of substantiation of geophysical outburst criterion for specific geological and mining conditions.

The aim of the present work is to show that the most comprehensive technological solution will be to “adjust” the outburst danger criterion of geophysical acoustic spectral method, amended with the gas factor and coal strength control, according to the results of instrumental method, the initial outgassing rate and the chippings outlet during test borehole drilling.

2. Outburst danger criteria of instrumental and acoustic spectral methods of outburst danger forecast

When developing methods to predict coal and gas sudden outbursts, their signs determined during multi-year study of their manifestation, are taken into account. They include [2]:

- excessive pressure on the mine opening support;
- shocks, crackles in the rock mass;
- coal face peeling, squeezing out, coal pieces peeling and pouring out from the coal face;

- jamming of the drilling tool, its pushing out or pulling inside the borehole;
- coal strength reduction;
- increase of gas inflow while drilling or coal cutting works.

Outburst signs analyses proves that the main factors determining the outburst danger are stressed condition, inter-bedding gas pressure and the coal strength. To control these parameters at Russian mines direct (or instrumental) and indirect (geo-physical) methods are used.

Among instrumental methods the most reliable forecast at the mines in eastern Russia is provided by the method based on the interval measurement (in 1 m) of the initial outgassing rate and the chippings outlet as a result of control holes drilling [3]. Wherein the initial outgassing rate characterizes gas factor of the outburst danger and the chippings outlet – the stressed condition of the seam and coal strength. The outburst danger criterion at current forecast using this method at Kuzbass mines, which is based on a long-term processing of experimental data, is described by the following equation [3]:

$$R_1 = (S_{max}-1.8)(i_{max}-4) - 6 = 0, \quad (1)$$

where S_{max} is the maximum value for the chippings outlet, l/m; i_{max} – maximum value for initial outgassing rate, l/min·m. This dependence graph is shown in Figure 1.

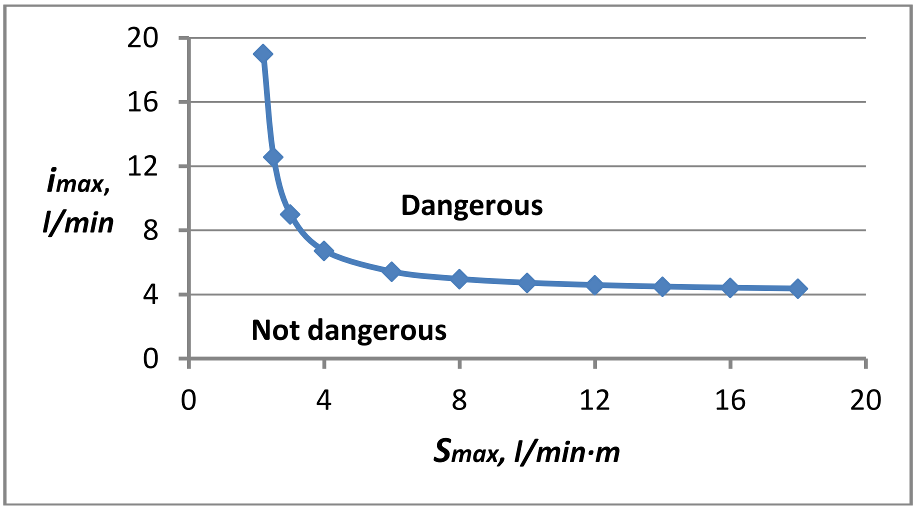

Figure 1. Dependency graph of outburst danger index $R_1 = (S_{max}-1.8)(i_{max}-4)-6=0$.

The main drawbacks of this method are periodical character of the forecast, long duration of the procedure during which the coal face operations need to be stopped.

The geo-physical methods are more advanced as they do not interfere with the mining operations. At present time three such main methods are known: the method of acoustic emission (AE) controlling the crack development process; gas analyzing method – by methane concentration in the mine atmosphere measured with air and gas control (AGC) instruments which control the factor of gas outburst danger; and acoustic spectral – by relation of high-frequency and low-frequency noise amplitudes of the operating mining equipment, which controls the stressed condition. The essence of the advantages and disadvantages of these methods are described in [4]. Their main disadvantage is the problem of justification of the geophysical outburst criterion for specific geological and mining conditions.

The simplest way to justify this criterion is to collect the experimental data while heading the galleries through the seam sections for which with the help of other methods the category "dangerous" and "not dangerous" was assigned. However, this approach seems to us time consuming and, therefore, not technological. A much more advanced is the method which quantitatively establishes the degree of outburst danger for the exact section by a reliable instrumental method and then according to this quantitative danger degree the outburst danger forecast of geo-physical criterion is "adjusted". To implement this approach we selected a acoustic spectral method which showed a high accuracy of the forecast compared with other geophysical methods at the coal mines in Donbass [5] and is in the process of implementation at some mines of JSC "SUEK-Kuzbass" in Kuzbass.

However, in this classic manner of application (by amplitudes relation of high- and low-frequency spectrum parts of operating equipment noise) this method only qualitatively controls the seam stressed state (at present there is no method for quantitative determination of outburst danger criterion). Therefore, we attempted to develop a correction procedure for the outburst danger index of a acoustic spectral method with regard to the gas ratio and coal strength, estimated by instrumental techniques of forecasting.

Outburst indicator of the acoustic spectral method was determined for the two main processes of outburst situation preparation: development of cracks at the face area and creation of coal block structure (the first process) and extrusion of coal blocks (lamps) into the working in the mouth of the future outburst cavity (the second process) in the following form:

$$K_c = \frac{A_h}{A_l} = e^{-C\frac{\sigma_l}{\sigma_c}d}, \quad (2)$$

where K_c – the current value of the outburst danger index; A_h A_l – amplitudes of acoustic noises, produced by the operating mining equipment, measured respectively at high and low frequencies; σ_l and σ_c respectively, the average limit and the current stresses;

$$C = \frac{\alpha_0 \beta (f_h - f_l)}{f_0}, \text{ m}^{-1}; \quad (3)$$

f_h and f_l – the characteristic frequencies from the ranges of upper and lower working frequencies of the acoustic noise source, Hz; α_0 – decay coefficient at a certain frequency f_0 which belongs to a range of registered frequencies, m^{-1}; β – the proportionality factor determined by the rock mass properties; d – distance between the noise source affecting the operating face (combine machine, coal plough, pick hammer, drill bit) and the receiver installed in the wall of the working at a certain distance from the face, m.

The obtained approximate expressions for the criteria determination of these processes are given in [4]. To improve the accuracy of determining the outburst criteria for acoustic spectral method the studies were carried out, the main results of which are as follows.

As a physical criterion of the outburst for the first process – a crack development at a distance x_{cr} from the working face, due to external compressive loads $\sigma_1(x)$ - $\sigma_3(x)$ (a plane problem) and internal gas pressure P , – the criterion, proposed by I.M. Petukhov and A.M. Linkov, was taken [6]:

$$\psi_{cr} \frac{P - |\sigma_3|}{\sigma_s} + \frac{|\sigma_1|}{\sigma_p} = 1, \quad (4)$$

where $\psi_{cr}(x_{cr}/l) = k_1 / k_1^{\infty}$; k_1 and k_1^{∞} are stress intensity factors at the observation point and outside the working zone influence; x_{cr} – critical distance from the working face, in the rock face of which the outburst develops (in this case a crack starts developing); l – the crack half-length; σ_p and σ_s are strength limits for compression and extension; $\sigma_1(x)$ и $\sigma_3(x)$ – main stresses.

The following expression was obtained for this criterion to determine the average stress limit σ_l depending on coal strength and in-situ gas pressure which cause the crack growth:

$$|\sigma_l| \simeq L \left| \left[\frac{0.3}{\psi_{cr}}\left(\frac{q}{110-q}\right) - P\right] \right|, \text{MPa} \tag{5}$$

where q is coal strength, determined with strength meter designed at A.A. Skochinsky Institute of Mining, $L = \frac{2+\lambda}{3\lambda}$ – the average coefficient of lateral thrust, λ – lateral thrust coefficient.

Using the dependence of gas flow from the face surface on the in- situ gas pressure proposed by V.V. Khodot [7] the expression was obtained relating the in-situ gas pressure P to the methane concentration Ω in the working atmosphere:

$$P = D\sqrt{\frac{Q\Omega}{\xi_i}}, \tag{6}$$

where: Q – local ventilation fan airflow, ventilating the working, m^3/s; ξ_i – coefficient taking into account the impact degree (proportion of fresh exposed face area) of i- type equipment (combine, plough, pick hammer, drilling bit diameter, etc.) on the face, $0 < \xi_i < 1$; Ω – the current value of methane concentration measured with a methane meter, %; $D = m\sqrt{k_0\eta P_{at}} \cdot x_{cr} \exp(-\varphi x_{cr}) / \sqrt{100 S_f}$, Pa·s$^{1/2}$ m$^{-3/2}$.

Substituting (5) and (6) in (2), we acquired the following expression for determining the current limit of outburst danger indicator (the initial stage of cracks development):

$$K_{l,c,1} = e^{-cd\left[\frac{1}{0.1\left(\frac{q}{110-q}\right) - \frac{\Psi_{cr}}{3} D\sqrt{\frac{Q\Omega}{\xi_i}}}\right]}. \tag{7}$$

Estimation of parameter D can be derived from the following considerations. The coal seams, dangerous due to their manifestation of the gas-dynamic phenomena could be related to the following three groups: dangerous because of rock bursts manifestation, dangerous because of sudden outbursts and rock bursts and because of sudden outbursts. The first group is characterized by high coal strength and high existing stresses, the gas pressure can vary within very wide limits. The second group on the contrary is characterized by low coal strength, high gas pressure with a rather high value of average stress. The third group is characterized by the mean values of coal strength with significant (sufficient) medium stresses and gas pressure. For the third group of coal seams, which are most typical for Kuzbass, we can suggest an approximately equal influence of rock pressure forces and in-situ gas pressure on the outburst danger index. Therefore, from the equality of common denominator members in the exponent (7), the parameter D is easily determined. We introduce the notation:

$$æ = 1/q. \tag{8}$$

Then from (7) we obtain an expression for determining a family of curves for different values $K_{l,c,1}$, connecting methane concentration with the reciprocal value of coal strength:

$$\Omega = \frac{9\xi_i}{\Psi_{cr}^2}\left[0.01\left(\frac{1}{110æ-1}\right)^2 + 0.2\left(\frac{1}{110æ-1}\right)\frac{cd}{ln K_{l,c,1}} + \frac{c^2 d^2}{ln^2 K_{l,c,1}}\right]. \tag{9}$$

The graph of the curves family in form (9) is shown in Figure 2.

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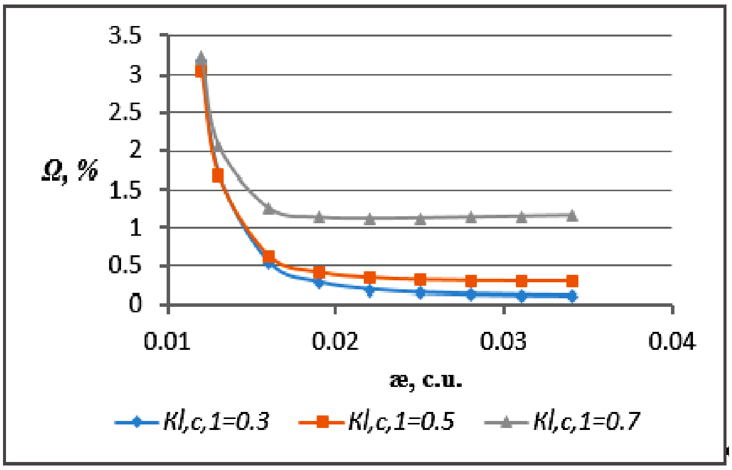

Figure 2. Family of curves $\Omega=\Omega$(æ) for values $K_{l,c,1}$=0.3; 0.5 and 0.7 in the process of crack development with the following parameters: ξ_i=0.1; Ψ_{cr}=5; Q= 10 м^3/s; α_0=1.3 m^1; β=0.07; D=0.01 MPa·s$^{1/2}$·m$^{-3/2}$; d=10 m; q=30-100 c.u.

Comparing the curves in Figure 1 and Figure 2, described respectively by expressions (1) and (9), we can see that the geo-physical outburst danger criterion of acoustic spectral method determined for the crack development process has the same character of dependence on gas factor and coal strength as well as the criterion of instrumental method by the initial outgassing ratio chippings outlet during test boreholes drilling. The main reason of differences is conditioned by the fact that in the function $i_{max}=f(S_{max})$ S_{max} parameter depends on the stress state and coal strength, whereas in function Ω = f(æ) æ parameter depends only on the strength of coal.

Similar studies have been conducted to establish the outburst danger criterion of acoustic spectral forecast method for the second preparation process of the pre-outburst state – coal blocks (lamps) extrusion into the working from the face surface in the mouth of the future outburst cavity. The following relationship was taken as the physical criterion of this process [4]:

$$K_{cr} = \frac{F_a}{F_p} = \frac{F_1 + F_2 \pm |F_3|}{F_4} \qquad (10)$$

In this criterion the active (triggering) in the numerator and passive (preventing) forces in the denominator forces are shown that press out the coal block into the working from the face. The first summand in the numerator of F_1 corresponds to the force of lateral thrust (horizontal component of normal stresses), the second summand F_2 – to the gas pressure force, the third F_3 – to the gravity of the pressed out coal block, and denominator F_4 – describes cohesion force and coal internal friction in the massif. To simplify the task it was assumed that the pressed out coal block has a cylindrical shape with the effective radius r_e and thickness x_1. The sign in front of F_3 depends on the working type – downward (-) or upward (+).

For this criterion, the following expression was obtained to determine the average stress limit σ_l, depending on the coal strength and in-situ gas pressure at which the coal block is pressed out into the working:

$$\sigma_l \lesssim \frac{L}{cos\delta}\left[9{,}5\left(\frac{q}{110-q}\right)10^6\frac{x_1}{r_e} - P \mp \gamma_c x_1 sin\delta\right], \qquad (11)$$

where δ – the angle of the opening axis to the horizon ; γ_c – coal specific weight.

Substituting (6) and (11) into (2), we received the following expression for determining the current limit value of the outburst indicator (the beginning of coal blocks pressing out):

$$K_{l,c,2} = e^{-C\left[\frac{10^8\frac{x_1}{r_э}\mp\gamma_y x_1\sin\delta}{10^7\left(\frac{q}{110-q}\right)\frac{x_1}{r_e}-D\sqrt{\frac{Q\Omega}{\xi_i}}\mp\gamma_y x_1\sin\delta}\right]d} . \qquad (12)$$

We find parameter D the same way as it was done for the criterion of beginning of crack development, but assume that in this process the gas factor affects the outburst approximately 3 times stronger than the factor of stress state.

From (12) for horizontal mine workings (δ=0) by simple transformations we obtain the expression for the family of curves for different values of $K_{l,c,2}$, connecting the methane concentration with the reciprocal value of coal strength:

$$\Omega = \frac{10^{16}\ \xi_i x_1^2}{D^2 Q r_e^2}\left[\frac{c^2 d^2}{ln^2 K_{l,c,2}} + 0.2\left(\frac{1}{110æ-1}\right)\frac{cd}{lnK_{l,c,2}} + 0.01\left(\frac{1}{110æ-1}\right)^2\right]. \quad (13)$$

The graph of the curves family of form (13) is shown in Figure 3.

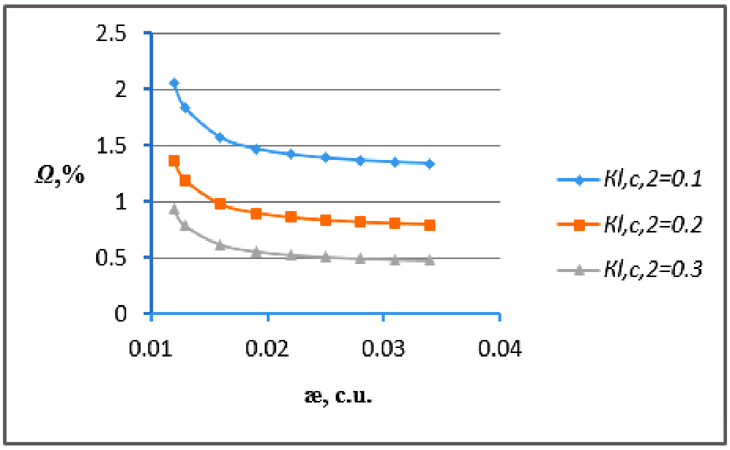

Figure 3. Family of curves Ω=Ω(æ) for values $K_{l,c,2}$ = 0.1; 0.2 and 0.3 in the process of a coal block pressing out with the following parameters: ξ_i=0.1; x_l=0.05 m; r_e=0,5 м; Q= 10 m^3/s; α_0=1.3 m^{-1}; β=0.07; D=1.0 MPa·s$^{1/2}$·m$^{-3/2}$; d=5 m; q=30-100 c.u.

Comparing the curves in Figure 1 and Figure 3, described respectively by expressions (1) and (13), we can see that geophysical criterion of outburst danger of acoustic spectral method, established for the coal block pressed out into the working from the face surface in the mouth of the future outburst cavity, has about the same character of dependence on gas factor and coal strength as the criterion of instrumental method for the initial outgassing rate and chippings outlet during drilling the test boreholes. The differences, obviously, are due to the same cause as the differences in the dependencies in Figure 1 and Figure 2.

3. Conclusions

The obtained results prove the following. Firstly, outburst danger criteria of the acoustic spectral method for two considered processes of preparation of outburst dangerous situation, although have the same character of dependence on the basic influencing factors, differ quantitatively.

Secondly, the character of dependence of outburst danger factor on the influencing factors for the instrumental technique of the forecast as well as for geophysical one is much the same and allows the range of influencing parameter values to be divided into two zones: outburst dangerous and not dangerous.

Thirdly, the compared instrumental and geophysical criteria have quantitative outburst danger estimation which allows the criteria to be compared and, as we think, it will make possible to “adjust” geophysical criterion in a specific working in accordance with the criterion readings of the instrumental forecast method.

The obtained results will be used for development of methods for determining the critical index of outburst danger by acoustic spectral method for specific conditions of mine workings.

As acoustic spectral- method controls the stressed state of the rock mass by the noise spectrum of a working combine, installing noise receivers in ventilation and haulage galleries at a small distance from the face makes it convenient to control the dynamics of stressed state in the face area while controlling roof using such method as a directed hydraulic fracturing among others.

4. Acknowledgements
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