

The study of coal tectonic disturbance using multifractal analysis of coal specimen images obtained by means of scanning electron microscopy

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Annotation. The possibility of using a multifractal approach to study the tectonic disturbance of coals has been investigated. The relationship between the coal disturbance and the asymmetry of fractal spectra of coal images obtained by means of scanning electron microscopy (SEM) is revealed: it has been established that undisturbed coals are characterized, as a rule, by a symmetric fractal dimension spectrum, and the disturbed coals are described by a fractal spectrum with some degree of asymmetry. It is shown that if fractal spectra of images have a symmetric appearance, then brightness distributions of these images are well fitted by a lognormal curves and parameters of these fittings can be estimated through characteristics of the fractal spectra. By using multifractal analysis of images for more than 140 test coal specimens from the quiet zone of a seam and the outburst zone, differences in the brightness distributions for images of coals with various degrees of disturbance were revealed. The basis of the research is the assumption that differences in the structure of disturbed and undisturbed coals are reflected in histograms of the brightness distributions for images of coal specimens. According to the results of multifractal analysis of images for the test coal specimens, it was established that the brightness distributions for images of the surface of undisturbed coal specimens are lognormal, while the brightness distributions for images of the surface of highly disturbed coal specimens, in most cases, deviate from the lognormal one. The conducted studies allow us to conclude about the applicability of the multifractal approach for assessing the degree of coal disturbance using digital images of coal specimens.

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1 Introduction

The causes of methane explosions and many other accidents in coal mines are, as a rule, sudden and rapid destruction of coal seam (rocks) in mines. In this regard, we can conclude that the prediction of the destruction of rocks and rock masses requires a more in-depth study of the destruction process, taking into account large-scale heterogeneities and structural features of the geological environment. Thus, the study of the tectonic disturbance of coal seams and its influence on the physicommechanical, filtration, sorption and gas-kinetic properties of coal is of particular importance.

In recent years, in Russia and abroad, fractal approach [1–5] is increasingly used to study coal disturbance. Given approach have allowed to identify characteristic scales of blocks of disturbed coal elements, to explain the origin and development of a cascade of defects in the process of loading rocks, to describe the change in the geometry of cracks in the process of rock deformation. It was also established that with increasing degree of disturbance of coals their permeability decreases noticeably and, accordingly, the fractal dimension of the pore space surface decreases from 2.98 for undisturbed coals to 2.25, 2.16, 2.13 and 2.12 in coals of I, II, III and IV degrees of disturbance, respectively [1]. The decrease of the fractal dimension of the pore space of coals indicates a more complex process of methane extraction, since its diffusion occurs, as a rule, in individual macrofractures.

However, the studies have shown that the fractal approach has a number of inherent shortcomings. So, for example, as shown in [1], coals of different degrees of disturbance can be characterized by close values of the fractal dimension of their pore space. Hence, it can be concluded that single fractal dimension is not enough to characterize the structural features of the coals of different degrees of disturbance. Moreover, as noted in [5], the fractal approach does not take into account the fact that the spatial distribution of defects (micropores, cracks, etc.) in coals is usually extremely heterogeneous. The non-uniform nature of the distribution of defects in coal entails a heterogeneous distribution of loads: some structural blocks of coal are overloaded, while others remain underloaded or do not any load at all.

In this regard, to characterize the structure of coals with various degrees of disturbance, it seems appropriate to use a multifractal approach, which is a natural generalization of the fractal approach and allows us to move from studying scale-invariant properties of defects cascades to studying a measure, reflecting the spatial distribution of various kinds of defects in coals. Thus, in the case of using the multifractal approach, the configurations of disturbed coal elements can be characterized using not a single, but a whole spectrum of fractal dimensions, the number of which in some cases reaches infinity.

The aim of this work is to demonstrate a progress in developments and experimental verification of a multifractal approach to assessing the degree of coal disturbance from SEM-images of coal specimens.

2 Methodology of research

In this study, we relied on the results of [6], which made it possible to conclude that there is a relationship between the degree of coal outburst and the asymmetry of multifractal spectra calculated from images of coal specimens. In [6], the degree of asymmetry was estimated using a coefficient $R = (\Delta_L \alpha - \Delta_R \alpha) / \Delta \alpha$, where $\Delta_L \alpha$ and $\Delta_R \alpha$ are ranges of values of Holder exponents α at the left and right sides from α_0 , and $\Delta \alpha = \Delta_R \alpha + \Delta_L \alpha$ (hereinafter, this indicator will be denoted as R_α). The value of R_α , as was shown in [6], it can be successfully used to quantify asymmetry of Legendre singularity spectra [7] having a

dome-shaped form with a vertex at a point $(\alpha_0; D_0)$. However, as is known from the multifractal theory [8], the Legendre multifractal spectra are rough estimates of Hausdorff spectra, which are generally not dome-shaped. In view of these circumstances, it seems appropriate to introduce additional asymmetry criteria that do not require a dome-shaped form of the multifractal spectra. One such criterion, in our opinion, is the asymmetry coefficient, based on values of the areas of the figures, bounded by the multifractal spectrum graph, axis α and curves $y = \alpha_{\min}$ and $y = \alpha_{\max}$:

$$R_s = \frac{S_L - S_R}{S_L + S_R} = \frac{S_L - S_R}{S},$$

where S_L and S_R are areas under left and right branches of the graph $f(\alpha)$; $S = S_L + S_R$ is an area under the entire graph $f(\alpha)$. In addition, by analogy with the relative coefficient $r_\alpha = \Delta_L \alpha / \Delta_R \alpha$ it can be introduced the relative ratio r_s calculated by the following formula

$$r_s = \frac{S_L}{S_R}.$$

These coefficients can be used to estimate the asymmetry not only of the Legendre multifractal spectra, but also the large deviations spectra that are widespread today.

As also shown in [6], if the brightness distribution of specimen images under study is close to lognormal, then it can be argued that this image exhibits multifractal properties, and quantitative characteristics obtained using multifractal analysis allows to describe the behavior of the measure formed for the image. This dependency can be used as a reliable criterion for the applicability of multifractal analysis to studied digital images, but this does not exhaust its usefulness. In this paper, it is introduced a technique to evaluate the lognormal law of pixel brightness distribution using vertex coordinates for the singularity spectrum $(\alpha_0; D_0)$.

We assume that if the hypothesis of multifractal character of the measure μ formed on the image is confirmed, then the following relation is true:

$$N_\alpha(\varepsilon) \propto \left(\frac{\varepsilon}{L} \right)^{-f(\alpha)},$$

where ε is a linear size of covering elements of the image (cells), L is a linear image size, $N_\alpha(\varepsilon)$ is a number of cells with the size ε , which are characterized by the same index value α .

Normalizing values $N_\alpha(\varepsilon)$ by the total number of covering elements of the size ε , we obtain an expression for estimating the density distribution of the values of α :

$$P(\alpha) \propto \left(\frac{\varepsilon}{L} \right)^{D_0 - f(\alpha)}. \quad (1)$$

From relation (1) it follows that, the values of $f(\alpha)$ reflect the scaling behavior of the entire probability density of α . As shown in [8], the $f(\alpha)$ -spectrum near its maximum can be approximated by a parabola

$$f_A(\alpha) = \frac{D_0 - (\alpha - \alpha_0)^2}{4(\alpha_0 - D_0)}. \quad (2)$$

Therefore, if the entire spectrum $f(\alpha)$ from Eq. (1) is well approximated by $f_A(\alpha)$ defined by Eq. (2), then $f(\alpha)$ can be replaced by $f_A(\alpha)$. Substituting (2) into (1), we obtain that

$$P(\alpha) \propto \exp \left\{ -\frac{(\alpha - \alpha_0)^2}{4(D_0 - \alpha_0)} \cdot \ln \left(\frac{\varepsilon}{L} \right) \right\} \quad (3)$$

So, from the fact that the Eq. (3) is satisfied and $\alpha = \ln \mu / \ln(\varepsilon/L)$ it follows that

$$P(\ln \mu) \propto \exp \left\{ -\frac{(\ln \mu - \alpha_0 \ln(\varepsilon/L))^2}{4(D_0 - \alpha_0) \ln(\varepsilon/L)} \right\} \quad (4)$$

We can go from the distribution of measure values μ to the distribution of pixel brightness values I , using the fact that the measure μ_j for the j -th pixel of the image is determined by us as follows:

$$\mu_j = \frac{I_j}{I_s},$$

where I_j is the brightness of the j -th pixel and $I_s = \sum_j I_j$. Then we get that

$$P(\ln I) \propto \exp \left\{ -\frac{[\ln(I/I_s) - \alpha_0 \ln(1/L)]^2}{4(D_0 - \alpha_0)} \ln(1/L) \right\} \quad (5)$$

Taking into account the relation (5), we can write the following relation:

$$P(\ln I) \propto \exp \left\{ -\frac{[\ln(I - \gamma) - m]^2}{2\sigma^2} \right\},$$

where

$$m = \ln I_s + \alpha_0 \ln(1/L), \quad \sigma^2 = 2(D_0 - \alpha_0) \ln(1/L), \quad \gamma = \langle I \rangle - \exp\{m + \sigma^2/2\}.$$

The expression for estimating a parameter γ is obtained on the basis of the relation established in [9] between the average value of the lognormal distribution and its parameters m , σ^2 and γ .

The asymmetry coefficient proposed in this paper was used by us to verify the conclusions from [6] about the separability of coals from the quiet zone and the outburst zone by means of their SEM-images. For this purpose, for each test coal surface image, spectra $f(\alpha)$ characterizing the coal surface structure were obtained by two methods: generalized local-global multifractal analysis (GLGMFA), implemented in the Geo-PC package (MIIGAIK), and fixed-mass multifractal analysis (FMMFA), implemented in the FracLab 2.2 package (INRIA — National Institute for Research in Computer Science and Automation, France). Then, for each multifractal spectrum $f(\alpha)$, its approximation by parabola (2) was restored and values of the asymmetry coefficient R_s were calculated. In the case when values of the coefficient R_s were close to zero, the lognormal distribution parameters were estimated according to the technique described above.

3 Source data

In this study, imaging of coal specimen surfaces was performed using scanning electron microscopes JEOL JSM 5910–LV and Jeol–6610–LV. The spatial resolution of the microscopes is more than 10 and 100 nm for secondary and reflected electrons, respectively. Low–energy secondary electrons are used in imaging surface topography. Natural–shape coal specimens were placed in a work camera via a gate. In the mode of registration of secondary electrons, the work camera was vacuumized (with $>10^{-6}$ mm hg vacuum). Secondary electrons were recorded by a standard detector, which a type of a sweeping–field photomultiplier tube connected to scintillator.

As the source data for this study was IPKON collection of coal specimens from the Zapolyarnaya mine (Vorkuta) and the Kirov mine (Leninsk–Kuznetsk), obtained from outburst–nonhazardous zones and outburst zones. For our research, we analyzed microstructure of coal surface in the images magnified 1000 times which showed coal grains with a characteristic size from 0.5 to a few microns. Methane can desorb from such grains, diffuse and flow in fractures as free gas [10].

The processed image regions were selected equal to 1024×1024 pixels. These sizes differ from the sizes of regions selected in [6], by reason of the limitation in the software implementation of FMMFA, according to which the linear size of the processed images should be equal to the power of the number two.

4 Research results

Based on the results of the analysis of calculated asymmetry coefficient values, it was established that undisturbed coals are characterized, as a rule, by a symmetric spectrum of fractal dimensions, and the disturbed coals are described by a spectrum having a certain degree of asymmetry (Fig. 1). This conclusion is in good agreement with the results obtained in [6], despite the different size of the analyzed regions and the range of sizes for covering elements (1, 3, 7, 15, 31, 63, 127, 255, 511 against 9, 19, 29, 39, 49 pixels in [6]). A logical consequence of this conclusion is that $f_A(\alpha)$ defined by Eq. (2) are well approximated $f(\alpha)$ –spectra only for coal specimens from the quiet zone (Fig. 2).

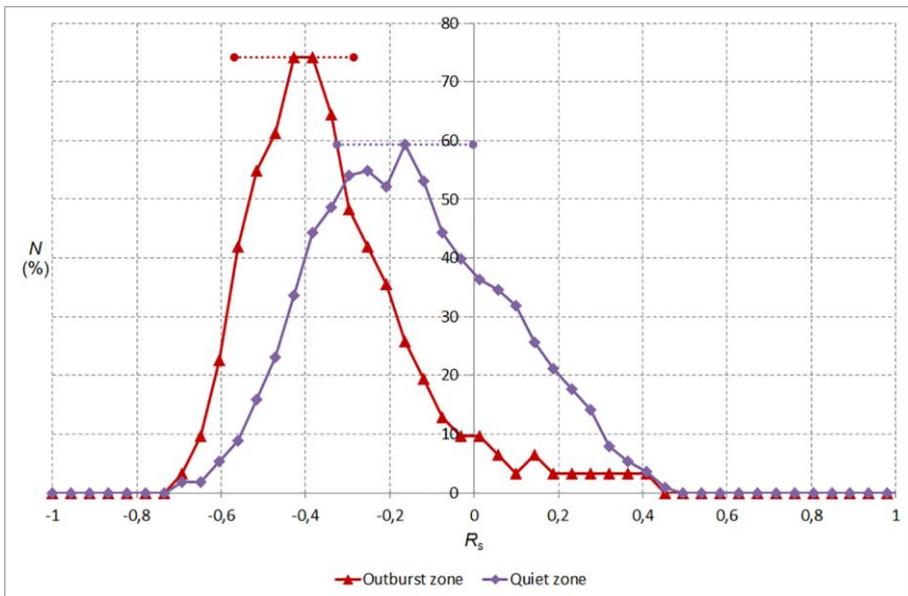


Fig. 1. Number N (%) of estimates for R_S , calculated for analyzed coal specimens (more than 140) by GLGMFA. The distance between centers of bins and the bin width for each histogram were chosen so that about 60% of all estimates for R_S fall into the ranges of the most likely values for R_S .

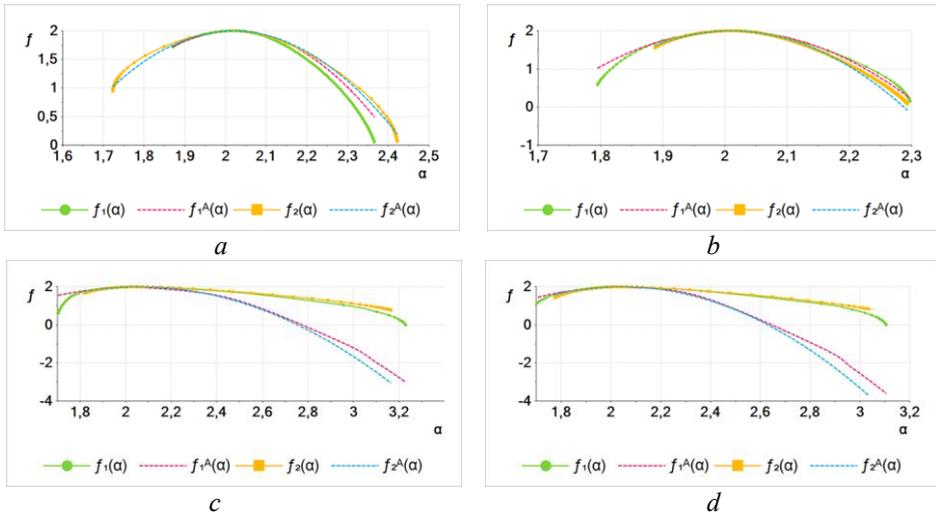


Fig. 2. Singularity spectra and their parabolic approximations obtained by GLGMFA ($f_1(\alpha)$ and $f_1^A(\alpha)$) and FMMFA ($f_2(\alpha)$ and $f_2^A(\alpha)$) for image regions of coal specimens from the quiet zone (a, b) and the outburst zone (c, d).

In Fig. 3, as an example, we show lognormal fittings for histograms of image regions, corresponding to approximations of multifractal spectra $f_1^A(\alpha)$ and $f_2^A(\alpha)$, which are shown in Fig. 2, a, b . As can be seen from Fig. 3, each of the restored lognormal curves approximates the histogram of the image brightness distribution quite well. To test all experimentally obtained lognormal curves, we used the Kolmogorov–Smirnov goodness-of-fit criterion and measured the "distances" between the experimental and theoretical distribution functions [11]. Based on the results of testing the hypothesis of the lognormal distribution, it was established that for most specimens from the quiet zone, the hypothesis is confirmed.

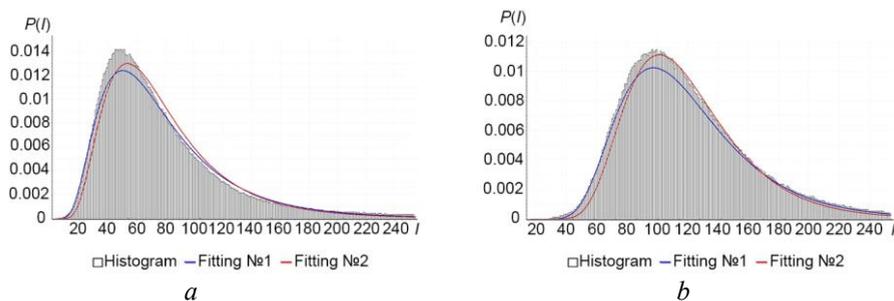


Fig. 3. Histograms of image regions of coal specimens from the quiet zone and their lognormal fittings obtained using $f_1^A(\alpha)$ (fitting №1) and $f_2^A(\alpha)$ (fitting №2).

Thus, it can be concluded that, in most cases, brightness distributions of images for coal specimens from the quiet zone are lognormal, while brightness distributions of images for

coal specimens from the outburst zone deviate from lognormal ones. This means that differences in the structure of coals from the quiet zone and the outburst zone are also reflected in the histograms of the brightness distribution of images of coal specimens from these two zones.

5 Conclusions

In this paper, we have shown that differences in the asymmetry of multifractal spectra for images of surface of coals from the quiet zone and the outburst zone do not depend on the chosen method of multifractal analysis and can be determined by various asymmetry criteria R_α , r_α and/or R_S , r_S . The observed differences are probably related to the different shapes of the brightness distribution functions for the analyzed images, which, in the case of specimens from the quiet zone, can be considered as lognormal functions with parameters m , σ^2 and γ defined using vertex coordinates of singularity spectra $(\alpha_0; D_0)$. The findings can be used in studies of tectonic disturbance of coals by their SEM-images.

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