The Influence of Nonlinear Deformation-Wave Processes Induced by Seismic Effects on the Gas-Dynamic Activity of Coal Mines

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Abstract. Starting in 1834, the article gives a historical review of the influence of nonlinear deformation-wave processes, including those induced by seismic effects, on the gas-dynamic activity of coal mines. Hypotheses that differ in respect to the role of gas, rock pressure or tectonic stresses in the excitation and development of sudden outbursts in Russia and abroad, as well as the interpretation of these hypotheses from a modern point of view, are considered. It is shown that there is a deterministic connection between nonlinear deformation-wave processes induced by natural-technogenic earthquakes and propagating in rock masses in the form of packets of pendulum waves of the “quasimeter” (0.11 ÷ 1 m / s) velocity range, and modes of increased gas-dynamic activity coal mines of Kuzbass.

1. Introduction
The development of mineral deposits and coal, in particular, beginning with the first sudden emissions of coal and gas in 1834 in France (Isaac village, Loire basin) and in 1847 in Belgium was usually associated with catastrophic events of natural and technological character, where the role of the interaction between the "underground element" and man. At the end of the 19th century, there were more than 2000 such emissions in southern France (the Gard Basin). By this time, these phenomena had already become frequent in Germany (the Ruhr and Lower Silesia basins), England (South Wales), Hungary and Canada. There was an urgent problem of ensuring safety in the development of coal deposits. One of the most important solutions to this problem in 1890, the inventor of Marceau in Belgium, was the first to propose a shocking blast [1].

In Russia, the first sudden outburst was recorded on September 9, 1906 at the Novaya Smolyanka mine at a depth of 711 m. In pre-revolutionary times, sudden outbursts also occurred at the mines of Donbass. Their detailed description and analysis for the period from 1914 to 1925 given by prof. V. B. Komarov [2]. The few papers on sudden emissions of coal and gas published in Russia at that time mainly described the views of foreign scientists (Odiber, Arnold, Ruff, Rieber, Moren, etc.) on the causes and mechanism of sudden emissions [1]. These were hypotheses that differ in respect to the role of gas, rock pressure, or tectonic stresses in the generation and development of sudden outbursts. Often controversial, they were not directly related to practical measures to combat sudden emissions, among which shocking explosions remained the most common abroad.

In Russia, the opening and development of coking coal seams in the Donbass, the transition to deeper horizons led to an increase in the frequency and strength of sudden emissions. In this regard,
since 1932, the MakNII has begun the development of foreign experience and the introduction of shocking explosions in a number of mines. It was organized at the initiative of the Interdepartmental Mining Scientific Council at the People’s Commissariat of Labor (later - at the All-Union Central Council of Trade Unions). In 1933, the Commission on Sudden Methane Emissions was formed and a decision was made to introduce shocking explosions in the mines of Donbass. During 1933-34 it was possible to provoke several sudden emissions for the first time used in the USSR by this method.

At the same time, the physical and mechanical mechanism of shocking explosions remained incomprehensible to date. In MakNII prof. L. N. Bykov in 1933 [3] established some patterns that relate the strength and frequency of sudden outbursts to the stages of coal metamorphism, as well as to cracking and grinding of coal during tectonic processes. However, later prof. I. M Pechuk [4] believed that the cause of sudden emissions is the release of potential energy accumulated in elastic rocks, and that the gas released during the crushing of rocks by rocks plays only an auxiliary role. Open at present Corr. RAS V.N. Oparin's “piston mechanism” [5] fully confirms hypothesis [4] and describes the mechanism of release of potential energy and its transformation into kinetic energy of coal fractals. Received T.A. Kiryayeva, the experimental results on coal samples in the laboratory and field data in the mines of Kuzbass are also in good agreement with this hypothesis [6].

2. Studying the influence of nonlinear deformation-wave processes on the causes and mechanisms of sudden emissions of coal and gas

In the 50s of the last century, Acad. A.A. Skochinsky gave direct indications that when considering the phenomenon of sudden release, three main factors must be taken into account equally - gas, rock pressure, and the physico-mechanical properties of coal. In fact, he set the main lines of experimental and theoretical research to solve the problem of sudden emissions of coal and gas.

The entire thickness of the rocks forming the lithosphere is in continuous motion. This is not only the thermal motion of the molecules that make up the Earth’s solid shell, but also the tectonic movement of the Earth’s plates and the processes of diffusion, filtration of liquids and gases in rock masses. Such a natural movement is enhanced by man-made human intervention. During mining, the stress state of the rocks in the massif changes: areas of high and low stress arise in which the rock is deformed, stratified and destroyed. In this case, the physico-mechanical properties of rock affected by the disturbance of their initial thermodynamic equilibrium change: fracture and porosity increase, gas permeability increases, bulk density decreases, and rock strength characteristics change. All this leads to a change in the sorption and filtration properties of the rock mass. The absence for many years of a sufficiently clear idea of the causes and mechanism of dynamic phenomena, including sudden outbursts, was largely explained by the desire to connect these phenomena with any one factor: geological (residual stresses of tectonic origin, coal seam preparation), mechanical (manifestation of rock pressure and the influence of the strength properties of rocks), mining, physico-chemical or gas-dynamic. Meanwhile, elucidation of the causes and mechanism of sudden outbursts is possible only with the objective consideration of all factors essential for their occurrence.

Prof. V.V. Hodot wrote: “In order to establish the real causes of sudden imbalances in coal seams, it is necessary first of all to know their physicochemical and mechanical properties, to study the sorption, filtration, and deformation characteristics of coal” [1]. He was the first to give the most complete description of sudden emissions of coal and gas, the main features of which are as follows: in most cases, sudden emissions occur starting from a depth of 250 m. With increasing depth of development, the frequency and strength of sudden emissions increase (table 1).
Table 1. An increase in the number and strength of sudden emissions with a depth of coal seam mining in the mines of Lower Silesia from 1909 to 1925. [1]

| Depth of development, m | The number of sudden emissions | The total amount of coal emitted, 10^3 kg | Amount of coal per emission, 10^3 kg |
|------------------------|-------------------------------|------------------------------------------|-----------------------------------|
| 0-100                  | 1                             | 5                                        | 5                                 |
| 100-200                | 4                             | 72                                       | 18                                |
| 200-300                | 130                           | 6 882                                    | 53                                |
| 300-400                | 179                           | 15 972                                   | 89                                |
| 400-500                | 123                           | 21 072                                   | 171                               |

Indeed, with increasing depth of mining operations, mountain pressure also increases. As shown in [7], with an increase in the stress level, when the deformations of geomaterials go beyond elasticity, nonlinear deformation-wave processes begin to develop inside the deformable body. Laboratory studies on coal samples under uniaxial “hard” loading to failure showed that almost from the very beginning of loading with a speed of ~ 3.3 · 10^-6 m / s, low-frequency internal microdeformation processes arise in coal samples generated by slow (quasistatic) force impacts. The amplitude of such deformation-wave processes increases with increasing stress level. In this case, the oscillatory movements of the structural elements introduce the “piston effect” [5] of alternating relative movements of the crack edges between these structural elements (fractals), which are completely or partially filled with liquid, gas, gas hydrates, or small solid fractions of geomaterials. In accordance with this “piston mechanism”, the gas flow through coal increases and, therefore, with a sudden release, the amount of coal and gas ejected should increase with depth.

Sudden emissions are often associated with geological disturbances, the technical preparation coefficient (the ratio of the power of packs of crushed coal to the thickness of the formation as a whole) of outburst hazardous formations is on average 3 times higher compared to non-hazardous formations. Although in [1] there were no significant differences between the composition and properties of the rocks enclosing the seams, hazardous and non-hazardous in sudden discharges, there are cases of increasing danger in sudden discharges with an increase in the strength of the enclosing rocks. So, for example, more durable sandstones as enclosing rocks are more dangerous in terms of sudden emissions compared to mudstones. In the Suchansky district in the Donbass, sudden emissions in coal seams are confined to a denser than usual, but fine-grained confluent sandstone; in the Gard Basin (France), sudden outbursts are often confined to coal seams occurring under sandstones or other hard rocks. In [1] it is also noted that in the Donetsk basin, productive formations that are hazardous in sudden releases are in most cases the least durable; they are characterized not so much by the low strength of the coal seam as a whole, but by the presence of broken, crushed bundles of coal or carbonaceous mudstone.

Promising models for describing the destruction of coal during gas evolution may be approaches based on the ideas of fractality of carbon materials [8]. The fractal approach allows us to interpret the effect of changes in strength in rocks, the reason for which is related to the fracture mechanism, structural and scale characteristics of the geomaterial, and the geometry of “defective sets”. The change in fractal dimension can be estimated, for example, from the parameters of the porous structure of coal. Sandstone is a sedimentary rock, which is a homogeneous or layered aggregate of clastic grains ranging in size from 0.1 mm to 2 mm (grains of sand) bound by a mineral substance (cement) [9]. Argillite is a clastic sedimentary rock formed as a result of compaction, dehydration and cementation of clays. These are cemented and compacted clay rocks of a layered or other texture. As a rule, they do not soak in water and are devoid of plasticity. Due to drying, the rock has lost the ability to absorb liquid. In the mudstones, oriented structures are observed — a parallel arrangement of elongated scales of clay minerals [10].

Disturbed, crushed packs of coal or carbonaceous mudstone can also be considered as fractal structures, but of a larger size. For example, prof. In [8], O. N. Malinnikova used multifractal analysis of digital images of the surface of coal samples obtained using a JEOL JSM 5910-LV scanning
electron microscope in the secondary electron recording mode to analyze the structural heterogeneity of fossil coal. The calculations showed that coals from outburst-hazardous strata are characterized by a wider range of structural heterogeneities, i.e., a wide scatter of fractal parameters and, as a result, are described by a wider range of fractal dimensions compared to coals of non-outburst strata having a narrower spectrum of fractal dimensions. It was shown in [8] that the formalized fractal approach allows one to interpret the effect of changes in strength in rocks, the reason for which is related to the fracture mechanism, structural and scale characteristics of the material and the geometry of defective sets, and the change in fractal dimension can be estimated from the parameters of the porous structure of fossil coals. Moreover, the porous structure of fossil coals, in turn, is an important characteristic of the gas-dynamic activity of coal seams.

In Russia, sudden emissions occurred and are currently occurring only with the participation of methane. But, for example, in the Silesian coal basin - with the participation of carbon dioxide, in the Gard basin (France) both methane and carbon dioxide are involved in emissions [2]. Sudden emissions involving nitrogen are known [11]. Of interest is the fact that sudden emissions involving carbon dioxide are superior in frequency and strength to those involving methane. In the Gard basin, out of 1,600 sudden emissions involving carbon dioxide, 361 were accompanied by the release of more than 200 tons of coal, 240 cases - from 200 to 500 tons, 89 cases - from 500 to 1000 tons, 32 cases - more than 1000 tons and 6 cases - more than 2000 tons ; while the maximum emissions of coal with methane did not exceed 275 tons. The average amount of coal per emission in the USSR in 1951-1954. with the participation of methane in all coal basins amounted to 40 tons [12]. Therefore, the physicochemical properties of the gas released during a sudden release and probably contained in the coal seam before the ejection play a significant role in mass-gas exchange processes in the coal seam. In this case, in relation to the study of the "piston mechanism", the problem can be formulated as follows. Considering that the mechanism of the occurrence of mass-gas exchange processes in coal samples is due to the oscillating movement of their structural elements (and, therefore, the edges of the cracks separating them) as a result of the transformation of the accumulated elastic energy into kinetic [7, 13, 14], the idea of a broad verification of the effect seems natural this effect in quantitative terms for coal samples in laboratory conditions for various gases (methane, carbon dioxide, nitrogen) and for the field conditions of the Kuzbass coal mines. The latter can be considered as “large coal samples” for methane emission from coal mines of the basin, but “perforated by a system of mine workings”, with a set of methane emission sensors that can be used to monitor both technogenic “background component” and induced by sufficiently large “shocking” geodynamic events (earthquakes) explosions.

With increasing humidity, the danger of a coal seam from sudden emissions decreases [1]. The authors of this article, when studying physicochemical parameters (porosity, humidity and methane consumption parameters of coals of the developed Kuzbass, Donbass and Lvov-Volyn basin deposits) from 15396 intersections of 11 Kuzbass and Donbass deposits, it was shown [15] that the specific energy of the expanding coal seam increases gas is proportionally reduced (Fig. 1).
Figure 1. Dependence of the specific energy $E$ of the expanding gas on humidity $W$ of coal seams [15].

The specific energy of relaxing gas equaled approx 200 kJ/kg at the moisture content of 1% while it nearly halved at the moisture content of 3%.

It has been found that zones of the increased coal and methane outburst hazard feature bifurcation in the values of porosity, moisture content and methane content in terms of coal under mining in the Kuznetsk, Donets and Lvov–Volyn Coal Basins. The laboratory-measured porosity of coal samples was six percent while the analytical moisture content was one to one point three percent. With that combination of physicochemical parameters Kuzbass coal seams with the limiting methane absorption equal to eighteen cubic meters of methane per tonne of coal have experienced the highest coal and gas outbursts since nineteen forty three up to this date. Coal seams possessing the methane absorption above or under the value of eighteen cubic meters of methane per tonne of coal but the same porosity and moisture content are less outburst-hazardous (from mine practice). However, in highly productive longwalls, gas releases from broken coal in the outburst hazard mode since the initial velocity of gas recovery is high. For this reason, in-mine gas drainage is required to be implemented. At the bifurcation points of the parameters included in the Langmuir equation (at the limiting methane absorption of eighteen for Kuzbass, Donets and Lvov–Volyn Basins coal), a coal seam is genetically able to generate a disturbing gas-dynamic impulse sufficient for self-destruction be initiate. These properties explain unexpected nature of coal and gas outbursts.

A large number of so-called “delayed emissions” were recorded, which did not occur immediately after a shocking explosion in mines (not after 5-8 seconds, as usual), but after several minutes and even hours [1]. According to the MacNII [15], in 1946–1953, out of a total of 289 cases of sudden emissions, 32% occurred with a delay of several minutes, 9% with a delay of more than 30 minutes. Currently, due to the large-scale technogenic impact of mining facilities of Kuzbass on its bowels, including the use of high-power technological explosions [16], there has been a noticeable intensification of the manifestations of rock shocks, shocks, sudden emissions of coal and gas, landslide phenomena, induced seismicity. There are different ideas about the possible impact of not only such manifestations, but also natural earthquakes on induced seismicity within the zones of influence of mines and mines in the processes of their development. It is important to know the real mechanism of such an influence, especially for the conditions of development of mineral deposits in the gas-dynamic (and seismically) active regions of Russia [17]. In [17], experimentally and theoretically, using the earthquakes of 2016–2019 and the gas-dynamic activity induced by them at the Alardinskaya and Osinnikovskaya mines, it was established that there is a deterministic connection between nonlinear deformation-wave processes induced by natural-technogenic earthquakes and propagating in rocky arrays in the form of packets of pendulum waves of the “quasimeter” ($0.11 \div 1 \text{ m} / \text{s}$) speed range, and modes of increased “oscillating form” of the gas-dynamic activity of the coal
In this case, the time from the moment of earthquakes (taking into account the distance from the earthquake to the measuring sensors in coal mines 8-36 km) to the start of a significant increase in gas-dynamic activity of the Kuzbass mines ranged from several hours to one and a half days.

Given the large difference between the propagation velocities of P and S waves, as well as pendulum waves (more than three orders of magnitude), qualitatively new methodological and methodological possibilities appear for predicting catastrophic events in the coal mines of Kuzbass, with the implementation of early withdrawal of miners from treatment faces and proactive measures to change the functioning of mining enterprises.

This fundamental research result is based on the theory of the interaction of geomechanical and physicochemical processes in oil and gas bearing and coal seams, which is being actively developed at the Chinakal Institute of Mining of the SB RAS, as well as the experimentally discovered mechanism of the occurrence of nonlinear mass-gas exchange processes when testing coal samples of various grades.

3. Conclusions

Thus, some of the main features of sudden coal and gas emissions given by prof. V.V Khodot [1], can now be explained using estimates of the influence of nonlinear deformation-wave processes induced by seismic effects on the gas-dynamic activity of the Kuzbass coal mines. Only comprehensive studies of the laws of interaction between nonlinear deformation-wave, physicochemical, and gas-mass exchange processes in coal seams of different stages of metamorphism in the changing fields of stresses, strains, and temperatures can offer new ideas not only about the processes occurring in a coal seam during shock rocking, but about the mechanism of sudden release of coal and gas in general.

4. References

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