Substantiating topicality of injectable localizing and deactivation of coal seams prone to endogenous spontaneous combustion

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Abstract. The analysis for possible development of endogenous fires in coal seams prone to oxidation and spontaneous combustion is done. The coal free surface area is taken as a forecasting criterion for estimating the state of the zones of broken condition. The effectiveness of applying fracture plugging (cementing) technology for injectable localizing and deactivation of the massif is substantiated. The conception for further studying of the processes for controlling physical and chemical characteristics of a seam considering native properties of coal is formed.

1. Introduction
Despite the tendency of decreasing the coal share in total global energy balance it is still an important strategic energy source.

Growing speed and depth of underground development of the sheet deposits, their gas bearing capacity, and the presence of the unrecoverable reserves worsen the issue of the coal spontaneous-combustion. All these influence negatively on the state of a mine atmosphere, coal mining efficiency and safety, customer appeal of the products and the ecology of the resource region [1-15]. The development, preparation works and mining of the coal seam brings about inevitable progressing growth of its exposed surface area. The applied methods and techniques for defining incubation period of coal spontaneous-combustion, recommendations on preventing endogenous fires and safety mining of the coal seams prone to spontaneous-combustion [16-17] do not take into account extremely high initial reactivity of the native coal surface which has not been contacting to oxygen before (air, water, technological liquids). Due to all mentioned, applying geo-technologies without considering physical and chemical properties of coal in the process of preparing and mining coal seams worsen the issue of endogenous fire hazards of the mines.

2. Preliminary analysis
The danger of coal spontaneous heating appears when the speed of accumulating heat during oxidation exceeds the speed of heat removal. As soon as the temperature in the seam reaches the critical value spontaneous combustion takes place if special preventing measures are not applied.

Standard preventing measures on drill hole seam degassing or and wetting of a coal seam can result in its additional breaking and increasing gas bearing capacity of a fractured porous medium, uncontrolled activation of chemical reactions creating so called “reactor” for low temperature
oxidation and gasification with high level of heat release and low level of heat removal. When such high-temperature zones are formed in this “reactor” their contact with water can cause a steam-powered fissure of a coal seam, forming large fractures network and transferring hot particles of coal. Moreover, insulating constructions, isolation partitions, jackets, support systems applied near the contact with the coal seam practically do not meet the requirements of total sealing [18].

The above-described matter is being complicated by a well-known fact that coals of different origin and metamorphosis are able to oxidate actively even under low temperatures. A significant number of Russian and foreign scientific researches [19-38] are devoted to coal low-temperature oxidation processes considering different external influences, free-radical reaction behavior, changing inner micro-crystalline structure, formation of basic tracer gases and to the processes of coal low-temperature oxidation influenced by water [39-41].

All famous practice oriented researches are directed basically onto substantiation of spontaneous heating of coal residues not anywhere but in the mined-out workings (caving zone, roof caving zones) of the long pile mining system – longwall (LPM) [42-45] as a highly probable source of underground fire initiation. Considering the economical effectiveness, this technology is widely-practiced in Russia too and its productiveness is proved by underground mining volumes of SUEK Company in Kuzbass. It is well-known that the most hazardous zone for spontaneous combustion is a narrow zone with low heat-removal but sufficient oxygen concentration. For mined-out area three fundamental zones of disintegrated coal low-temperature oxidation are provided. They pass through isoline sections of oxygen concentration in the air (5-9 percent) dividing them into surplus oxygen zones and lack of oxygen zones [42-45].

Despite the fact that a greater number of endogenous fires takes place in mined-out parts of the mine workings the most unpredictable ones are the spontaneous heating zones in the mining seams because temperature location zone distribution in a seam is very complicated and unstable in time and space and a fractured-porous coal massif is characterized by complexity of detecting its physical state, sorption and desorption processes complexities and gas and liquid filtrating migrations in a seam. Moreover, the fractures in a seam are the basic collectors of gas – liquid migration of the oxidants (air, liquid solutions of technological chemical agents and suspended mixtures) towards chemically active coal structure. The reliable assessment of oxidant delivering kinetics to the coal opened surface and the assessment of heat and mass transfer in fractured porous medium (the condition of cooling reactive surface by gas flows or by technological liquid with oxidants) is a still an unsolved problem.

3. The results and comprehensive review of the problem
Qualitative and consolidated opportunity analysis for potential development of the endogenous situation in the process of mining the coal seam prone to oxidation and spontaneous combustion applying long-pile mining method (LPM) (as an example) is going to be done here.

To estimate the broken condition of the coal seam during its mining a geometric criterion is taken. It will stand for assessing criterion for defining physical condition of the dislocated zones. The specific area of a coal free surface (for example $S_{sp}$, m$^2$) is in direct connection with the broken condition degree of coal seam unit volume. It is evident that the dependence of $S_{sp}$ value on the size of the irregularly shaped joints while destructing factual fractured porous medium of coal is more complicated, however, it is enough for understanding basic principles of physical processes development that take place during mining.

Developing further the works [38-41], four basic geometric zones of broken condition with different schemes of forming new free surfaces are defined (figure 1):
Figure 1. Principle scheme of high temperature locations in zones of broken condition.

0) initial, virgin (native) state of the coal seam with natural unrevealed dislocations in the structure which didn’t undergo any man-caused impact;

I) in the basic volume of the coal seam under heavy load a fracture network with formation of new nominally flat surfaces is built up (dimension m²);

II) dead part (caved workings) of the goaf with the coal remnants in the form of free joints and formation of new volume surfaces (dimension m³);

III) border zones of in-seam workings (sidewalls along the sections or protective pillars are hatched with a combined scheme of new surfaces formation along I and II (dimensions m² and m³).

The places, most hazardous on coal spontaneous combustion are numbered as: 1 – breakings and degassing well-bores connected with daylight surface; 2 – mining zone edge with a combined scheme of air delivery; 3 – mining zone behind longwall set of equipment with the air inflow out of the longwall; 4 – border zones of isolating partitions; 5 – mining zone edge of the earlier mined-out longwall; 6 – border zone of a seam; 7 – zone of air filtration through the fractures into the degassing bore-holes; 8 – zone of air filtration through the fractures into the degassing bore-holes connected with the surface; 9 – in-seam workings border zones; 10 – protective pillars border zones.

It is evident that in the process of preliminary development and stoping in the indicated zones 0-III the growth dynamics of the free surface specific area differ minimum by an order of magnitude. At the same time non-linear, progressive growth of $S_{op}$ under rock breaking which actively manifests itself under fraction size reduction less than 80-100 µm and under respective growth of $S_{op}$ over 300 sm²/g (power and exponential dependences) is widely known. Fine powder fraction is more actively formed in coal under rock pressure manifestation, particularly, in zone II, where, in fact, grinding of joints during roof caving takes place increasing $S_{op}$ of the coal even more.

Free surface area can be presented in a form of total aggregated coal free surface $S$, m², which contacts with air in the indicated zones 0-III. In the process of construction, preparation and exploitation of any coal mine two types of the mined-out areas are singled out. They radically differ by forming processes $S$: in the area of openings and stopes with the operational area – $S_{op}$ and in the mined-out area with unexploited underground workings – $S_{ex}$ (figure 2).
Figure 2. Qualitative graphical analysis of a coal free surface area development on the territory of operating an mined-out workings.

Respectively, $S_{op}$ has an active increment at the initial period of construction and is stabilized with a little general growth in time due to the increasing extension of the operating working (the share of the preliminary developments is limited by the project design of the underground mine). As for $S_{ext}$ – it starts forming from the moment of the face launching that shapes the mined-out area with significant remnants of disintegrated coal and it more actively and nonlinearly increments in the process of stoping. It is evident that exponential growth of the coal free surface $S_{ext}$ is relatively more active while mining the allotment.

Studying the relation between $S_{op}$ and $S_{ext}$, the crossing of the above-mentioned dependences is marked with point J and point B stands for the beginning of the period when a special control over operational parameters of the mine starts. Thus, time period of 0B is evidently larger than BC. Under current conditions of underground mining “lack of air” and increasing of the methane concentration in the operating coal working are balanced by adjusting operating mode of air ventilation system. In case of lack of capacities they are expanded by constructing new ventilation networks and structure. The attempt to level up the situation at the “point of no return” C with the dependence ending at infinity (figure 2) is economically unreasonable.

The reactive free surface area of coal is directly connected with the volume of oxidizing reactions in the underground mine. Ideal situation for mining coal is the following: minimum presence of oxygen in the mined-out space and the established standard for oxygen and methane presence in the operational space of the mine. Thus, understanding general principles of coal free surface area formation allows optimizing the mining technology and substantiate the necessity of timely carrying of coal seam preventive isolation as in the border zone so as in a massif.

3.1. Border zone of in-seam workings

Opening and preparing a coal seam to mining is done while carrying out in-seam workings which are connected with basic air (oxygen) mass-transfer. The most broken is a border zone with the developed system of drilling induced fractures and different range of fracture openings which is schematically presented in figure 3:

1 – MAXIMUM (out-squeezing zone $h_{os}$, is manifested by several overlaid fracture systems with opened from 5 mm to 20 mm, fracture cavitation 6–10 percent and practically linear distribution of the filtrating coefficient into the depth $h_{os}$, m);
II – HIGH (with filtrating coefficient changed according to quadratic law of distribution (V.A. Khyamyalyainen, V. G. Igishev);

III – Low (stable part of the massif, practically lacking of fracturing and air permeability).

Figure 3. Border zone of in-seam workings (1 – out-squeezing zone line at the depth of h₀, 2 – stable part of the massif line at the depth of h).

Considering high level of man-caused breakings and fractures in in-seam workings it is important to create modern complex of mutually reinforcing technologies connected to the coal seam structurally and spatially: building isolation partitions with plugging (cementing) the adjacent border zone, sprayed insulating covering of the mine working line, injectable-saturated plugging (cementing) of outsubseezing border zones of a coal seam along the mine workings. The above-mentioned methods unite the filtration processes of active suspended mixtures (technological liquids) in in-seam workings border zones. Modern geo-technologies for plugging (cementing) coal seam by active suspended mixtures take into account low-pressure flat-radial filtration modes. Upon this the required density, strength and stability of the plugging (cementing) line of the coal seam is ensured.

3.2. Coal seam massif prone to oxidation and spontaneous heating

Areas of the most dangerous spontaneous heating in a seam are connected with filtration channels of air flows through main crack-collectors of air supply (figure 1). It is obvious that there is a necessity for further scientific substantiation and development of the technology for injectable localizing and deactivation of deep-earth spontaneous heating sites of a seam prone to oxidation by suspended mixtures and protective agents. When applying cyclic hydraulic fracturing of a coal seam by suspended (liquid) protective agent it is important to take into account structural and physical and chemical characteristics of active fractured-porous medium of coal.

In the capacity of technological mixtures for creating thermal resistant anti-filtering barrier it is economically reasonable, to apply solidifying suspended mixtures made on the basis of man-made ash-slag residuals and cements.

However, when mixed with water this suspended mixtures become unstable and get sedimeted and in the process of hydration and changing the concentration these suspended mixtures reveal both Newtonian and non-Newtonian properties.

The given suspended-mixtures have not been used in plugging (cementing) the coal seam due to:
• high reactivity of newly formed coal surface right after destruction of the massif,
• water affinity (hydrophobic property),
• chaotic fracturing of a border zone,
• weak adherence of technological suspended mixtures to coal,
• high hydro-dynamic resistance of a coal seam.

The complexity of the coal seam plugging (cementing) technology for fulfilling protective measures on endogenous spontaneous combustion and the absence of scientific grounds for physical and chemical processes restrain the development of this important direction.

4. Conclusion

Thus, the conception for further research is developed.

The basic object of the research is a coal and methane seam active towards oxidation and spontaneous combustion. And this seam transfers from the native medium into activating fractured porous medium in the process of preparation and mining.

The subject of the research is low-temperature oxidation and water affinity of the non-contacting with air coal surface, interaction of unstable solidifying suspended mixtures with chemically active fractured porous surface of a native coal, the processes of controlling physical state of a gas-coal seam by means of constructing plugging deactivating curtains (barriers) considering the revealed filtrating effects of unstable solidifying technological suspended mixtures in chemically active coal fractured porous medium.

A scientific task on substantiating physical and chemical processes of injectable localizing and deactivation of low temperature oxidation zones of the coal seams prepared for further development is set up. Herewith the way of controlled coal seam plugging using chemically active unstable suspended mixtures is reviewed.

The current tasks are:
• To develop physical and chemical basis for filtrating mass-transfer of unstable dispersion medium in chemically active fractured porous medium of coal;
• To work out scientific grounds for the controlling the process of thermodynamic equilibrium of oxidation and spontaneous heating zones in the opened coal seam by constructing anti-filting deactivating injectable curtain.

The technology for injectable localizing and deactivation of endogenous areas is the most practical way to operate and control a physical and chemical state of the coal seam and to keep thermal equilibrium of “coal-oxidizing compound” system. It happens due to interaction of the cooling process, hermetic sealing and decreasing of fractured porous medium reactivity.

The researches, fulfilled by the Institute of Coal FRC CCC SB RAS, showed good perspectives for application of the controlled coal seam plugging for the purpose of preventing spontaneous combustion. The decrease and stabilization of the temperature in the activated coal seam is also proved. Hermetic sealing of the in-seam working contour and insulating structures using technological suspended mixtures also proved to be effective.

Substantiating the process of injectable localizing and deactivation of low-temperature oxidation zones by unstable suspended mixtures will allow developing the theory of fluid filtration (dispersed system) in reactive fractured porous medium.

The results of the researches and the obtained fundamental knowledges will make a scientific ground for further development of the ways for active remote operation and control of rock massif physical state. New technologies that are being developed now play an important role in the development of mining industry of successive technological paradigm.

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