Improvement of degasification efficiency by pulsed injection of water in coal seam

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Abstract. The authors discuss the known degasification methods and their efficiency. The ways of stimulating productivity of coal degassing are proposed. In particular, stimulation of methane recovery by water injection in coal seam in pulsed mode for generation of additional surface of gas release is described. Prediction of methane recovery relies on the modern knowledge on state of methane in coal.

1. Introduction
This article is concerned with low efficiency of pre-mine degasification. Solution of this problem will improve safety of mining by gas criterion. When addressing the problem of degasification inefficiency, it is necessary to advert to pre-mine degassing practice. In pre-mine drainage by hydraulic fracturing from crossing holes, by normative standards, the degasification ratio may reach 0.5 [1]. At the same time, this result to be obtained requires an appropriate technology and equipment for multi-stage hydraulic fracturing aimed to ensure uniform treatment of an extraction panel.

Currently Kuzbass mines extensively introduce directional degasification borehole drilling [2]. Volume of methane recovery with this method is two times as high as with conventional drilling patterns. The latter allow methane recovery at the level of 10 % relative to the total gas volume in coal seam. The matter is that an unloaded coal seam has low permeability and holds gas but this gas liberates in the course of mining operations, after unloading and formation of a new surface for gas release during coal cutting.

2. Coal properties and effect on methane release
The international experience [4], as well as the Russian practice [5] shows that permeability of a coal seam increases with its depth, and the most effective method to improve the permeability is extraction of covering layers, which results in decease of the geostatic stresses in the target seam. However, this method is not always applicable due to geological features of rock mass area being mined.

According to [6], long desorption allows higher permeability not only due to considerable expansion of the influence zone of borehole but also owing to retrogression of the mechanical strength of coal down to partial failure. Thus, improvement of permeability requires systematical disintegration of coal seams.

The foreign studies [7,8] into adsorption and desorption processes in coal and their effect on mechanical properties of coal during drilling say that as free gas pressure grows in cleavage, coal matrix undergoes compression and adsorption decreases as a consequence of stress redistribution. This
phenomenon is reflective of high influence of the gas pressure on permeability and, consequently on methane emission behavior on a microlevel.

In classification of coal saturation with water [9], it is mentioned that gravitational water in coal seams only fills large cracks and voids 0.5–5 micron in size and bigger (volume of voids is 10–15%). About 10–20% of the volume of voids is filled under the action of capillary forces (capillary saturation). Adsorption-bound water fills around 50–70% of voids. The adsorptive saturation of coal can take from a few seconds to a few days. Up to 10–15% of voids are entirely free from water owing to the uncontrolled nature of flow processes and due to presence of closed voids. According to the studies, transition of gravitational saturation to the capillary–adsorptive fill of voids in coal requires multiple injection of water at maximum density and needs formation of new waterway cracks by hydrodynamic impulses.

Regarding efficiency of degasification, it is necessary to take into account the modern knowledge [10] on the forms of methane occurrence in seams. Methane exists in three states: free, adsorbed and solid coal–gas solution (SCGS). On deeper levels, percentage of methane in the form of SCGS grows, and recovery of this methane requires relieving coal from mechanical stresses. In an unloaded seam, mostly diffusion of free and absorbed methane takes place, and the volume of gas release from coal can be correlated with the area of exposed surfaces in waterway cracks in coal. Consequently, gas pressure in cracks is governed by both their flow capacity and intensity of gas diffusion from coal. This ensemble of properties conditions low rate of methane recovery from boreholes. Decomposition of SCGS under destressing intensifies diffusion and increases the pressure gradient required for speeding up the permeation rate.

Metamorphism also influences coal permeability. Reduction in volatile yield increases volume of micropores and, thus, methane adsorption, i.e. improves gas flowability inside coal [11]. Theoretically, it is difficult to estimate gas flow in coal matrix due to the presence of water and owing to adsorption bonding between coal and methane [12].

The presented analysis [12] highlights the relevance and complexity of the problems connected with effectivization of pre-mine coal degasification and reminds on disastrous consequences of arbitrary decisions (1995–2005) on intensification of coal output with disregard of the fact that a seam is not only coal but coal-and-methane [13, 14].

### 3. Methods of coal seam treatment for stimulation of gas recovery

The analysis of the coal seam treatment methods aimed to intensify degasification shows that the best acceptable are the technologies meant to create high physical loads on a seam by water, air and various gases, as well as exposure to vibration waves, i.e. alteration of natural stress state of rocks. These methods differ in implementation, for instance, the treatment holes can be drilled both on the surface and in mine. For another thing, there are such methods to improve gas permeability of coal as undermining and overmining of a seam to be degassed, treatment of coal-and-methane seams with acids, or thermal and electrohydraulic effects.

The choice of a treatment technique is governed by the mining conditions. For example, the surface-to-borehole treatment is expensive, while application of overmining and undermining of coal seams depends on geological conditions. High capacity, at a proper approach, is a feature of the technology of high-presser coal humidification with hydraulic fracturing from gas drainage holes [1]. In this case, it is required to undertake pre-estimation of stress state of rocks in order to calculate optimal parameters for hydraulic fracturing of coal [5]. To this effect, it is possible to use the hydraulic stress measurement technique [16]. Efficient flow rate is achievable by hydraulic fracturing with proppant (sand) [17].

### 4. High-pressure humidification of coal seam with elements of hydraulic fracturing

Figure 1 shows a general plot of water feed pressure and flow rate in high-pressure humidification of coal seam with elements of hydraulic fracturing. The high-pressure feed of water in a seam creates a network of main fractures at stage 1, which results in formation of free gas pressure gradient in the
fractures and promotes free flow toward coal exposures. At stage 2, closed microcracks and micropores open (i.e. the mode of injection transforms mostly to the mode of water permeation), which reduces gas release both in the period of coal degasification and in the time of coal failure in mechanical breaking [18].

Figure 1. Variation in water feed pressure and flow rate during high-pressure humidification of coal seam with elements of hydraulic fracturing [19].

Figure 2 depicts schematically the change in the physical condition of coal-and-methane geo-material. On the left of the figure, there is a model of block structure of a coal seam in intact rock mass. On the right of the figure, there is the result of high-pressure humidification of coal seam with elements of hydraulic fracturing. The insignificant external impact on the coal–gas equilibrium opens pores and initiates propagation of cracks, which promotes migration of free and adsorbed methane toward surface exposure. Migration contributes to a slight decrease in the stresses as a consequence of reduction in gas pressure and shrinkage of coal substance, which initiates decomposition of SCGS. Later on, the process repeats cyclically with exponential dependence: decomposition of SCGS—desorption of adsorption gas and flow of free gas—decrease in stresses (shrinkage).

Figure 2. Schematic physical state of coal-and-methane geo-materials with changing porosity in coal seam before and after hydraulic fracturing: 1 – fracture created by water pressure; 2 – macropores; 3 – micropores; 4 – visible pores and cracks.
Low rate of gas liberation from coal blocks to a weakly developed system of natural pores (macropores) and fractures governs low output and short efficiency range of gas-drainage holes. On the other hand, high efficiency of methane recovery from boreholes can be governed by high gas permeability of bottomhole zone [20] due to increasing permeability of coal under mechanical unloading.

The increased efficiency of hydraulic fracturing toward high gas recovery from coal seam is achievable through:

- A series of hydraulic fractures created along a borehole [21], stage 2 excluded (Figure 1);
- Pulsed injection of water [22] to break surfaces of cracks;
- Increase in gas recovery of created fractures using proppant [17].

5. Features of water injection to coal seam in pulsed mode

Cyclic loading provokes active growth of fatigue fractures and an increased gas release from coal [23]. Internal defects, inclusions and initial cracks, which are typical of a coal seam, have considerable influence on initiation and propagation of the fatigue fractures.

The expected result of the pulsed mode in hydraulic fracturing is:

- growth of pores and cracks owing to their integration, which will intensify liberation of free and absorbed methane in the mode of flow;
- destruction of crack surface with removal of particles to borehole by water flow, which will enhance mechanical unloading of the crack surfaces.

Stress redistribution in rock mass is a cause of intensified methane release from coal. Physically, potential energy accumulated in rock mass is higher than the energy of external effects and only acts as an initiator of nonstationary processes in coal and adjacent rocks. In this manner, during hydraulic fracturing in the pulsed mode and (or) with proppants, the energy of the coal–gas system is activated, which contributes to coal disintegration, provides larger radius of opening of main cracks and creates more developed network of small cracks as compared with hydrofracturing in the conventional injection regime.

6. Results and discussion

With the generalized experience gained in coal hydrofracturing and based on the factual data on a standard drainage hole productivity from methane flow rate monitoring, the production output of degasification holes with hydraulic fracturing of coal seam in the pulsed mode and using proppant is predicted (figure 3).

![Figure 3. Diagram of methane inflow in standard degasification hole and after stimulation of gas recovery.](image-url)
Thus, it is possible to draw a conclusion that single hydraulic fracturing can form additional gas recovery area in coal, which will improve productivity of degasification borehole for a long period of time. The improvement will for the first turn be connected with release of huge volume of free and adsorbed methane. In 2–3 months, the methane recovery mode will change into the standard degassing regime of a borehole untreated by hydraulic fracturing. This means methane recovery due to gas release from coal in the form of solid coal–gas solution. Under high volume of water injection in coal seams, blocking of pores takes place, which, in the period of methane release form SCGS, will also decelerate coal seam gas recovery. This effect can affect total productivity of a degassing borehole with single hydraulic fracturing.

This effect is eliminated in hydraulic fracturing with proppant which wedges out the created fracture. Consequently, productivity of a standard drainage hole is added with extra volume of methane release from the new formed surface of gas recovery.

The most efficient variant of hydraulic fracturing is its implementation in the pulsed mode and with proppant. The present paper authors think, pulsed water injection will break surface of microcracks and will prevent closure of the cracks after depressurization. Proppant, in particular, sand, will promote methane flow in macropores.

7. Conclusions

1. The coal–methane system is the highly complex natural geo-material poorly studied from the viewpoint of permeability and deliverability. The research has yet to rely on the experimental mine data when developing measures aimed to reduce gas and gas-dynamic hazard.

2. The pulsed hydraulic fracturing with proppant is the most efficient approach to improvement of permeability and gas recovery of coal seams as against the other known methods of coal treatment aimed to increase productivity of gas drainage holes.

3. The change of the natural stress state in coal promotes transition of energy to the coal–methane system, which is required for activation of SCGS decomposition in the vicinity of hydraulic fracture. Further decomposition will partly be maintained by the dissipation energy of SCGS.

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