Designing In-Seam Gas Drainage Technology Based on Hydrodynamic Approach

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Abstract. The article presents science based technological solutions that are essential for the development of the country's coal mining industry in terms of ensuring safety and efficiency of underground coal mining on the basis of improving in-seam gas drainage technologies using hydrodynamic impact on coal seams. Experimental work on the in-situ testing and approval of the new holistic technology was successfully done in the production panels 24-58, 24-58, 24-60 and 24-62 at the Kirova mine. That included underground hydrofracture of the working seam carried out from the development headings. High effectiveness of the proposed in-seam gas drainage technology was confirmed by effective methane extraction from the working coal seam, reduction of gas content in longwall faces and significant cut-down of equipment non-productive time in areas covered by active in-seam gas drainage.

1. Introduction
Underground works in quite a few coal mines are seriously aggravated by gas factor. Therefore, there is a need to ensure gas-free environment for mining operations while increasing cost effectiveness of underground coal mining [1,2]. Rated performance at a number of Kuzbass mines (for example, those owned by JSC SUEK-Kuzbass) have already amounted to 20–30 thousand tpd and the trend is to ever higher production targets in the near future. However, gas release from working seams can reach critical values so that longwall productivity will be severely limited by gas factor [3]. Without a significant reduction of gas content in mine excavations which could be achieved through effective in-seam gas drainage it does not seem possible to ensure high rates of longwall production [4-6]. This means that to ensure highly productive and safe underground conditions a justified choice, improvement and development of an effective in-seam gas drainage technology is a top-priority objective [7-9]. Increasing the efficiency of in-seam gas drainage based on various downhole techniques is an issue of immediate interest and have always been widely covered in the media both in Russia and globally [10-15]

2. Methodology
Currently, various options of improving the in-seam gas drainage technology are being studied to provide conditions for safe and efficient performance. Various methods of coal seam hydrofracture (interval-based hydrofracture, oriented fluid fracturing, synchronous hydrofracture) [16-21], as well as various modes of gas-hydraulic pulse impacts on the coal seam, hydropercussion impulse, pneumatic and physico-chemical impact and a number of other techniques are of particular interest.
Under favorable mining and geological conditions (relatively shallow depth, high gas permeability of coal seams being drained, sufficient time allowed for gas drainage, etc.), the efficiency of gas predrainage can reach 40-50%. On the other hand, the increasingly complicated conditions in underground mining restrict the effectiveness of in-seam gas drainage. For example, in the Karaganda basin, it is at 10-15%, whereas in the mines of Kuzbass (i.e. the mines owned by JSC SUEK-Kuzbass) the average gas drainage is at 10-15% in case in-seam gas drainage holes are drilled downwards and below 15 ± 20% when horizontal and upward holes are drilled.

The unacceptably low level of in-seam gas drainage efficiency is though conditioned by the fact that up to 95% - 98% of all in-seam methane is in a bound state (retained gas). The transfer of methane to its free state and its migration to the drill hole requires significant time and energy as it demands substantial alteration of properties and condition of the coal seam.

Various modes of injecting the working fluid into the coal seam are known [20-22]. Two main modes of hydrodynamic impact can be recommended for intensive degassing of coal seams: hydrofracture and hydrojacking, the former creating new fractures and the latter opening the existing cracks. Both result in a significant increase of gas permeability of the coal seam.

It was found that working fluid injected into the coal seam should be retained there for a while to be able to replace methane in the sorption block, which results in reduction of the natural gas content in the area designed for hydraulic treatment. It is advisable to remove the working fluid from the seam to enable its further effective drainage, since water, as long as it resides in the fractures and pore space, significantly reduces relative gas permeability of the coal seam and impedes its liberation.

The key technological parameters of the underground hydrofracture method (PodzGRP) improved by our team have been defined and validated: pressure, rate of injection, amount of working fluid and the range radius of hydrofracture wells [16]. The preferred type of equipment to be used for injection of working fluid into the well is Hauhinco EHP plunger pump, AZE-5 (oil station for mine application) or their equivalent with a pumping rate of at least 5-10 l/s. It has been established that at fluid injection pressure of 8 to 30 MPa, filtration capillars are developed that remain open, with no need to support them by various kinds of proppants (quartz sand, etc.).

3. Experimental works
The key technological parameters of in-seam gas drainage using the PodzGRP technology were validated for Boldyrevsky coal seam (Kirova mine, JSC SUEK-Kuzbass) and included into the approved manual for hydrofracture operations:

- sealing depth at least 36 m;
- the expected pressure during hydraulic impact 10 ± 30 MPa;
- working fluid injection rate 5 ± 10 l/s;
- range radius of hydrofracture wells 25 ± 35 m;
- injected fluid volume 5 ± 100 m³;
- distance between PodzGRP holes 70 m;

The parameters of standard in-seam gas drainage (PPD) holes at this stage of research remain unchanged, though in the long term a reduction in the number of PPD wells to be drilled in PodzGRP areas is envisaged.

According to the results of exploratory experimental work, the mode of pumping working fluid into the Boldyrevsky coal seam was defined as **hydrojacking mode with cyclic microhydrofractures**. In this mode, the working fluid does not rupture the coal seam, it only removes some barriers on the working fluid flow and integrates fractures and pore space in the coal seam into a single gas drainage system of fractures directed towards the PodzGRP well.

The regime of the working fluid injection into the coal seam carried out at PodzGRP well No. 60/9 is provided in Figure 1. The graph characterizes general nature of the working fluid pumping process as hydrojacking with elements of micro hydrofracture (Gr1, Gr2, Gr3).
Figure 1. Change in pressure $P$ and temperature $t$ during hydrofracture through PodzGRP well No. 60/9.

The effect of hydrojacking (hydrofracture) in PodzGRP wells is confirmed by a sharp increase in methane yield from these wells after exposure and subsequent release of working fluid from the well. This increase in gas recovery intensity can be explained by increase in gas permeability of the seam, opening and formation of fractures, hence the increase of overall coal surface area related to these fractures.

The results of prospecting in-situ tests of the updated hydrofracture technology showed a 2–4-fold increase in methane yield and the total methane removal in the PPD wells drilled and functioning in zones of PodzGRP well influence (Figure 2: indicated at the abscissa axis are ordinal numbers of measurements that were taken 2 times per week within 6.5 month period).

Figure 2. Methane yield from a PPD well close to PodzGRP well (blue curve) and outside PodzGRP well influence (red curve).

According to the estimate, the main effect of methane extraction from the production face should not be expected directly from PodzGRP wells, it shall rather transpire in standard PPD wells drilled in hydrofracture zones in conditions of enhanced permeability of the target coal seam.

4. Discussion
In the process of prospecting, no correlation was found between the working fluid injection pressure and the effective length of the hydrofracture well (the size of the uncased hole section). Possibly, the injection pressure depends on some local mining and geological conditions in the block of the coal
seam subjected to hydrofracture, such as tectonic stresses in the coal–and gas bearing block (the presence of stress-relieved zones along with tectonically stressed ones).

The enhanced efficiency of in-seam gas drainage aimed at reducing gas content in longwalls in the PodzGRP zones is achieved both through the higher methane yield of the PPD wells, and also due to in-seam gas depletion resulting from the fact that PodzGRF wells were drilled from the development heading. It has been demonstrated that the drainage (liberation) of methane contained in longwall panel from the development heading is of no less importance than methane removal of by standard methane drainage DPS boreholes.

Significant rates of methane drainage from hydrofracture wells were recorded over an average period of up to 50-100 days. After this, the flow rate dropped, which, presumably, resulted from the depletion of the gas reservoir covering relatively small hydrofracture zone (according to actual estimates, fracture radius is approximately 25 to 35 meters). Then the flow rate values returned to those typical for undisturbed coal seam areas.

The average rate of PPD well yield in the Boldyrevsky seam at Kirova mine site is approximately 5 to 10 l/min (with 150m long boreholes). The rate of gas liberation from shorter PodzGRP wells was increasing during the test period from several units to 640 l/min. It is also important that no negative or critical information on the roof condition was reported in the zones that underwent hydrodynamic effects.

Studies have been carried out on reducing gas content in production panels and reducing downtime of mining equipment due to gas factor in PodzGRP areas. Correct and representative assessment of PodzGRP technology effectiveness was carried out in the course of coal production in longwall 24-58 (see data in Table 1).

**Table 1.** Production face parameters in PodzGRP area vs. those in reference (control) area.

| Parameter                  | Unit | Value | Reference (control) area | GRP area | Δ, % |
|----------------------------|------|-------|--------------------------|----------|------|
| Relative gas content       | m³/t | Max   | 1.37                     | 0.84     | 39   |
|                            |      | Mean  | 1.14                     | 0.80     | 30   |
| Mining equipment downtime  | min/day | Max | 129.9                    | 71.52    | 45   |
| due to gas factor          |      | Mean  | 122.39                   | 71.45    | 42   |
| Absolute gas content       | m³/min| Max  | 8.88                     | 7.81     | 12   |
|                            |      | Mean  | 8.29                     | 7.29     | 12   |
| Daily production           | t/day | Max  | 13007.14                 | 13350    | 3    |
|                            |      | Mean  | 10747.16                 | 13037.07 | 21   |

It can be stated that in hydrofracture zone of production panel 24-58 the average value of the relative methane content was reduced by 30%, the production of coal increased by 20% on average, and the downtime of mining equipment due to ventilation factor was cut down by over 40%. This allows to see the true value of the hydrofracture method and take the decision to apply the tested technology to the subsequent production panels at the Kirova mine.

Comparative parameters of the subsequent production panel 24-59 are shown in Table 2.
Table 2. Comparative parameters of production faces 24-58 and 24-59.

| Parameter                          | Unit     | Value  | Panel 24-59 | Panel 24-58 |
|------------------------------------|----------|--------|-------------|-------------|
| Relative gas content               | m³/t     | Max    | 12.4        | 26.5        |
|                                    |          | Mean   | 1.33        | 1.54        |
| Equipment downtime due to ventilation needs | min/day | Max    | 650         | 429         |
|                                    |          | Mean   | 103.3       | 112.61      |
| Absolute gas content              | m³/min   | Max    | 14.45       | 13.44       |
|                                    |          | Mean   | 8.68        | 8.3         |
| Daily production                   | t/day    | Max    | 24.3        | 18          |
|                                    |          | Mean   | 10.98       | 10.5        |

5. Conclusions
A number of conclusions could be made on the effectiveness estimate on PodzGRP technology application in longwalls 24-58 and 24-59:

1) Panel 24-58 was in operation for 8 months from 01.04.2016 to 30.11.2016 and the production amounted to 2.67 thousand tons of coal.
   Average monthly production was 321.5 Kt; daily average -10.5 Kt.
   Depth of the seam varied between 354 and 510 m (average – 401 m).
   Gas content was at 15 m³/t per dry ash-free mass.

2) Panel 24-59 was in operation for 9.5 months from 01.02.2017 to 13.11.2017 and the production amounted to 3.144 thousand tons of coal.
   Average monthly production was 331 Kt; daily average -10.98 Kt
   Depth of the seam varied between 354 m and 510 m.
   Average seam depth near GRP №13-18 borehole – 438 m.
   Average seam depth in reference (control) area – 385 m.
   Gas content 20 m³/t per dry ash-free mass.
   Obviously, panel 24-59 performed better than panel 24-58, where the technology effectiveness had been earlier adequately proved by addressing to reference (control) areas. In the case of panel 24-59:
   - Daily production increased by 5 % from 10.5 to 10.98 Kt/day;
   - Average downtime due to ventilation needs was reduced by 9.1% from 112.61 to 103.2 min/day;
   - Relative gas content dropped by 15.8 % from 1.54 to 1.33 m³/t.

It can be claimed that favorable technogenic reservoir of the degassed coal seam with increased gas permeability has greater dimensions and is not confined to the location of specific gas drainage PodzGRP wells. Apparently, in-seam gas drainage wells accept methane flowing from the entire production panel.

In the area near PodzGRF wells the lost efficiency in a number of parameters resulted from unsubstantiated increased effective length of PodzGRP wells, which excluded a very important factor in achieving efficiency associated with the degassing effect of the development heading from which PodzGRP wells were drilled (in fact, the in-seam heading may be regarded as a large in-seam gas drainage hole).

Nevertheless, all of the above confirms sufficiently high efficiency of holistic in-seam gas drainage technology that has been developed and successfully tested in production panels 24-58, 24-59, 24-60 and 24-62 at Kirova mine. This method includes hydrofracture and subsequent methane drainage using standard in-seam gas drainage wells (DPS) drilled from the development headings.
In 2019, the subsequent production panel 24-63 will be extracted in more difficult mining and geological conditions. It is there that an updated gas drainage technique is being successfully tested, which includes at the initial stage, in addition to the indicated technological operations, in-seam gas drainage by hydrojacking done through wells drilled from the surface, which should significantly increase the effectiveness of degassing work.

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