Research and Application of Pressure Relief Gas Drainage Technology by Long Borehole Drilling along Large Diameter From Roof Fracture Zone

Jianwei Wang
No. 55, Sancun, Shangqiao, Shapingba District, Chongqing, China
*Corresponding author’s e-mail: wjwmky@163.com

Abstract. Aiming at the problem of gas prevention and control in upper corner of U-type ventilation system under the condition of close-range high gas seam group mining, based on the theory of strata movement and the analysis of gas emission source in fully mechanized mining face, the technology of pressure relief gas extraction by long boreholes with large diameter roof strike is put forward, and the principle of pressure relief gas extraction in working face is expounded. Field engineering practice shows that the application of large diameter roof to longhole pressure relief gas extraction technology to control the gas concentration in upper corner is remarkable. The gas purity in the effective area is stable at 2~4 m³/min, and the gas concentration in the upper corner of the working face does not exceed the limit, thus realizing the safe and efficient mining of working face under the condition of close-range high gas seam group.

1. Introduction
Coal mine gas is a gas that is mainly composed of methane, which is found in coal and coal-bearing strata. It is one of the main threats to mine safe and efficient production [1]. Protective seam mining and coal seam gas drainage are commonly used in the coal industry in China to control mine gas disasters, and have achieved remarkable application results in field practice. As the mining intensity of the underground coal mining face continues to increase, especially for mines in the conditions of close high gas coal seams, the gas emission from the adjacent seam increases greatly due to mining influence, which easily causes gas concentration accumulation in the upper corner [2-3], and seriously threatens the safety of mine production. Many technologies have been formed to control upper corner gas, such as buried pipe gas extraction, high-level borehole relief gas extraction, etc [4]. However, due to the complex movement law of working face rock under the condition of close-range coal seam group mining, the application of traditional upper corner gas controlling technology in such mines is becoming more and more popular. There have been some limitations in the past. With the development of underground drilling technology in China [5-6], directional long borehole has been widely used in the pre-drainage of underground coal seam gas in our country. Although some scholars have applied directional drilling technology to extract pressure-relief gas from mining face, and achieved certain results, there are few application examples for the treatment of gas in the goaf under the condition of close-range high gas seam group mining.

In view of this, aiming at the problem of gas control in upper corner of "U" ventilation system under the condition of close-range high gas seam group mining, based on the engineering background of
Wanfeng Coal Mine, Shanxi Province, and based on the theory of strata movement and the analysis of gas emission source in fully mechanized mining face, pressure relief gas drainage technology by long borehole drilling along large diameter from roof fracture zone is proposed, and the working principle of the pressure relief gas in the pumping face is expounded.

2. The principle of pressure relief gas drainage technology by long borehole drilling along large diameter from roof fracture zone

The voussior beam theory holds that the overburden strata along the advancing direction of the working face will go through three different zones: the support-affected zone, the separation zone and the re-compaction zone. From the bottom to the top, the overburden strata in the goaf can be divided into three different zones: (1) The caving zone where the fractured rock blocks collapse and arrange very irregularly. The coefficient of looseness is relatively large, generally up to 1.3-1.5. (2) The fractured zone is located above the caving zone, where the rock blocks are still arranged neatly after the strata are broken. (3) The bending zone where the rock strata do not rupture any more, but only produce normal bending under the action of self-weight. The rock mass maintains its original integrity well, as shown in Figure 1.

![Diagram of "Transverse Three Zones" and "Vertical Three Zones" of overburden strata movement](image)

A—the support-affected zone (a—b); B—the separation zone (b—c); C—the re-compaction zone (c—d); I—the caving zone; II—the fractured zone; III—the bending zone

Because the caving zone is connected with the air leakage zone, so the gas concentration is low, it is not appropriate to adopt borehole extraction. Fractured zone is located above the caving zone. The farther from the caving zone in the vertical direction be, the smaller the fissures are. Along the horizontal direction of the working face, the fissures grow more and more from the stage coal pillar to the middle of the working face; along the direction of the goaf, the fissures develop from small to large to small. Therefore, when designing the high-level drilling of the roof, the drilling layer should be gradually raised along the orientation of the working face. The principle of pressure relief gas extraction technology by long borehole with large diameter roof strike is to use roof fissures formed by mining pressure in working face as a channel to extract gas, effectively intercept the pressure relief gas influxed into mining face from adjacent coal seams.

3. The overview of test working face

Wanfeng Coal Mine locates in the eastern part of Fenxiao Mining Area, Huoxi Coalfield, Shanxi Province. The test working face is 1201 fully mechanized mining face, which is located in the middle of the mine, with a strike length of about 1125m and an inclination length of 155m. No. 1 coal seam is mined. The gas content of No. 1 coal seam in test working face is 6.5 m³/t. The working face is shown in Figure 2. The occurrence characteristics of coal seams are shown in Table 1.

4. Gas emission analysis of test working face

1201 working face began to be mined in the middle shift on January 22, 2018, and forced roof caving measures were adopted in the middle shift on January 29, 2018. Thereafter, with the caving of the 1-up
coal seam, gas from the upper adjacent seam began to flow into the goaf and gradually increased. Therefore, calculating the daily gas emission data from the mining face to the mid-shift period of January 29, 2018. At this stage, the gas emission quantity $Q$ of working face is equal to the gas emission quantity $Q_a$ of mining face.

\[ Q = Q_a + \sum_{i=1}^{n} C_{2i}Q_{2i} - C_{1i}Q_{1i} \times 1440 + Q_{cc} \]  \hspace{1cm} (1)

$Q$—the gas emission of working face, $m^3/min$; $Q_a$—the gas emission of mining face, $m^3/min$; $C_{2i}$—the average gas concentration of working face on day $i$, %; $Q_{2i}$—air volume of working face in return roadway on day $i$, $m^3/min$; $C_{1i}$—the average gas concentration of inlet air roadway on day $i$, %; $Q_{1i}$—air volume of inlet air roadway on day $i$, $m^3/min$; $t_i$—time of statistical gas emission, min; $Q_{cc}$—The drainage gas amount of working face, $m^3/min$.
Because the average gas concentration of inlet air roadway is approximately 0, the formula (1) can be simplified, and the gas emission of mining face $Q_a$ is:

$$Q_a = \sum_{i=1}^{n} C_{Q_i} \times 1440 + Q_{cc}$$  \hspace{1cm} (2)

In the early stage of 1201 fully mechanized mining face, gas emission of mining face was the main factor. After adopting forced roof caving measures, the upper adjacent layer of gas gradually flowed into the working face, and gas emission began to increase significantly. Before that, the average gas emission of working face was $Q_a$. According to the statistical data and formula (2), it can be concluded that the average gas emission $Q_a$ is $3.77 \text{ m}^3/\text{min}$ and the maximum gas emission is $3.94 \text{ m}^3/\text{min}$.

Goaf gas mainly includes three parts: gas emission from adjacent strata, gas emission from mining residual coal and gas emission from surrounding rock, especially from upper and lower adjacent strata. The distance between No. 1 coal seam and adjacent strata is small, and the gas emission from adjacent strata affected by mining is large; the mining rate of 1201 fully mechanized mining face is higher than 95%, the amount of coal left behind in goaf is small, and the gas emission is negligible; according to the situation of coal seam roof and floor exposed during 1201 inlet air roadway and return roadway trench driving, the roof and floor of No. 1 coal seam in 1201 working face are sandy mudstone and mudstone. According to the gas emission of main roadways in Wanfeng Coal Mine during the excavation, the gas emission from the compact surrounding rock can be neglected. Therefore, it can be considered that the gas emission from the upper and lower adjacent layers is the main source of 1201 goaf.

After 1201 fully mechanized mining face was forced to cave the roof, as the working face continues to advance until the main roof begins to collapse, a large number of gas from the upper adjacent layer poured into the working face. At this time, the working face gas is composed of the gas form mining-coal bed and upper adjacent layer. At this time, the gas emission from the working face includes the gas emission from the coal seam $Q_a$ and the gas emission from the upper adjacent seam $Q_b$, calculated according to formula (3):

$$Q_b = Q - Q_a = \sum_{i=1}^{n} C_{Q_i} \times 1440 \frac{t_1}{t_2} + Q_{cc} - Q_a$$  \hspace{1cm} (3)

$Q_b$—gas emission from upper adjacent seams,$\text{m}^3/\text{min}$; $t_2$—the time between forced caving of the roof and first weighting of main roof,$\text{min}$.

Since the forced roof caving, the gas in the upper adjacent stratum gradually pours into the working face. When the working face advances about 36 m, the main roof breaks, the gas in the upper adjacent stratum reaches its peak value, and the gas in the lower adjacent stratum begins to pour into the goaf gradually. Under the action of air leakage and gas concentration pressure difference in the goaf, the gas is poured into the working face or pumped into the gas pipeline in the goaf. According to the data of gas emission during the period from forced roof caving to main roof fracture, formula (3) shows that the average gas emission from the upper adjacent layer is $8.52 \text{ m}^3/\text{min}$, and the maximum gas emission is $9.67 \text{ m}^3/\text{min}$.

After the first weighting of the main roof, the gas emission from the upper adjacent stratum gradually stabilizes, accompanied by the redistribution of surrounding rock stress, the gas emission from the lower adjacent stratum increases slowly until the working face appears periodic weighting, and the gas emission from the lower adjacent stratum reaches its peak value. Because the mining rate of the working face is higher than 95%, the gas emission from the residual coal of goaf is very small, which can be neglected. During this period, the gas emission includes gas gushing from mining seam $Q_a$, gas gushing from upper adjacent seam $Q_b$ and gas gushing from lower adjacent seam $Q_c$, according to formula (4):
5. Application effect and analysis

In order to ensure the extraction effect, the drilling horizons are arranged vertically in the middle and lower part of the fracture zone, and along the inclination, the drilling holes are arranged in the middle and far part of the 10~40 m distance from the return roadway. With the increase of the distance along the inclined inner staggered return roadway, the corresponding horizon cracks are more and more developed. At the same time, in order to conveniently inspect the extraction effect of different horizons of boreholes, the designed borehole horizon is 12~15m in the upper part of No. 1 coal seam, and 20~40m along the inclined inner staggered return roadway.

When the distance between the return roadway and the Open-off Cut is 370m, the No. 1 directional drilling field is constructed on the side of the working face and No. 2 directional drilling field is constructed on 275m outside the No. 1 directional drilling field. Five φ96mm roof trending long drilling holes are designed and constructed in each drilling field. The overlap distance between two groups of boreholes is 85m. The drilling parameters are shown in Table 2.

Table 2. The drilling hole setting parameter of design and fact in 1201 return roadway

| Designed hole number | Inboard distance between return roadway(m) | distance between designed hole and roof(m) | The corresponding hole number in 1#drilling field | The corresponding hole number in 2#drilling field |
|----------------------|--------------------------------------------|-------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 1                    | 20                                         | 12                                        | 1-2                                              | 2-3                                              |
| 2                    | 25                                         | 13                                        | 1-1                                              | 2-1                                              |
| 3                    | 30                                         | 14                                        | 4-2                                              | 3-1, 2-2                                        |
| 4                    | 35                                         | 15                                        | 4-1                                              | 5-2                                              |
| 5                    | 40                                         | 15                                        | 5                                                | 5-1                                              |

During the construction process, due to borehole collapse and other factors, each directional drilling field will eventually construct three main holes, using the main hole branch hole to replace the long borehole with the designed horizon and internal dislocation distance. The arrangement of long boreholes along the roof of 1201 working face is shown in Figure 3.

$$Q_c = Q - Q_a - Q_b = \sum_{i=0}^{m} C_2Qzi \times 1440 t_3 + Qcc - Q_a - Q_b$$

$Q_c$—gas emission from the lower adjacent seam, m$^3$/min; $t_3$—the time between main roof breaking and working face periodic weighting, min.

After the main roof fracture, the gas emission from the upper adjacent layer reaches the peak value, and the gas emission from the lower adjacent layer gradually increases. When the working face advances to 70m, the gas emission from the working face reaches the peak value, and the maximum gas emission is 23.21 m$^3$/min. According to the data of gas emission from the main roof to the periodic weighting period of the working face, the average gas emission from the lower adjacent layer is 7.59 m$^3$/min and the maximum gas emission is 9.60 m$^3$/min.

In summary, the mining influence of 1201 working face will cause a large amount of pressure relief gas from the adjacent stratum to pour into the working face, and the absolute gas emission from the upper adjacent stratum is 9.67 m$^3$/min, accounting for 41.6% of the total gas emission from the working face. The absolute gas emission from the lower adjacent layer is 9.60 m$^3$/min, accounting for 41.4%.
From Figure 4, it can be seen that during the period of increasing gas extraction from long boreholes along the roof, the amount of gas exhausted by air in working face decreases obviously. Within the range of 83~210 m from the working face to 1#drilling field, the extraction effect of 1#drilling field is better, and the extraction purity is stable at 2~4 m³/min, averaging 2.85 m³/min. However, the mixing volume of 1 # main hole (1-1 # hole and 1-2 # hole) in 1#drilling field remains low, and the primary reason is that 1 # main hole collapsed. The 4 # and 5 # main holes have better extraction effect, the extraction purity of effective section is 1~2m³/min, but 4 # hole has two branches and 5 # hole has no branches. Therefore, it can be considered that 5 # main hole has the best extraction effect. Combining with its construction parameters, it can be seen that the effective section of 4 # and 5 # main hole corresponds to the drilling horizon which is 12~15m above No. 1 coal roof.

The drainage Gas amount of 1#drilling field shows that the higher the drilling layers be, the higher the gas concentration is. In No. 1 directional drilling field, the highest gas concentration is found in 5 # main hole, the second is corresponding to 4 # main hole (average extraction concentration is 32.59%), and the lowest is 1 # main hole (average extraction concentration is 27.81%). And the purity of gas extraction is greatly affected by the concentration of gas extraction, which decreases gradually in the middle and late stage of 4 # main hole extraction, and then decreases gradually; but the gas concentration decreases rapidly in the later stage of 1 # and 5 # main hole extraction (the working face advances to 86.6m away from No. 1 directional drilling field), which leads to a sharp decrease in the purity of gas extraction. 1.7m³/min (86.6m) →1.37m³/min (85.2m) →0.98m³/min(83m) →0.46m³/min (80.4m).
From Figure 4, we can also see that the gas drainage volume of 3 # main hole (3-1 # hole and 3-2 # hole) in 2#drilling field is very small during the whole extraction period, and the analysis shows that the borehole collapsed; the drainage effect is greatly affected by faults, there are many faults in the advance of the previous mining face, and the later working face is gradually advancing normally, and the drainage concentration shows a trend of "high-low-high" during the extraction period; The amount of gas extracted during the fault is small, with the normal advance of the working face, the purity of gas extracted increases gradually and stabilizes at 2.5~3.4 m³/min. According to the analysis of pumping effect during normal propulsion period, 2 # main hole pumping purity is 1~2.5 m³/min, 5 # main hole pumping purity is 0.9~1.5 m³/min, 2 # and 5 # main hole pumping effect is better (2# main hole effect is the best). According to its construction parameters, the corresponding drilling horizon is 10.5-14 m above the roof of No. 1 coal seam.

6. Conclusions
1) The mining influence of 1201 working face will cause a large amount of pressure relief gas from the upper adjacent layer to pour into the working face. The absolute gas emission from the upper adjacent layer is 9.67 m³/min, accounting for 41.6% of the total gas emission from the working face. The absolute gas emission from the lower adjacent layer is 9.60 m³/min, accounting for 41.4%.

2) The extraction effect of long boreholes along roof strike in directional drilling field is generally better, and the extraction purity in the effective area is stable at 2~4 m³/min. The effective zone is 10.5~15m in the upper part of No1 coal seam. Within a reasonable drilling arrangement, the gas extraction volume of long boreholes along the roof is generally stable. The higher the drilling arrangement level be, the greater the gas extraction purity is.

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