

Research Article

Characteristics of Pressure Relief Gas Extraction in the Protected Layer by Surface Drilling in Huainan

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To study the behavior of gas extraction from the protected layer by surface drilling, the common characteristics of gas extraction concentration and gas extraction quantity are summarized through the collection of key parameters of surface drilling and a combination of data and figures, with the background of 11⁻² coal protection 13⁻¹ coal in the Huainan mining area. The research results show that the flow of pressure relief gas extraction of the protected layer by surface drilling has three stages: a rising period, stable period, and decay period. When the extraction processes of multiple surface wells on the same working face are coordinated, the extraction flow is superimposed, and the extraction volume of surface drilling shows an increasing trend and fluctuates with the location of the drilling. The extraction flow rate before ground drilling is relatively small, and the extraction flow rate increases after ground drilling. This behavior is further confirmed by field observation of mining changes in the protective layer and the expansion and deformation of the protected layer. The periodic variation in the surface drilling and extraction quantity is affected primarily by the mining movement of the working face of the protective layer. Specifically, it is affected by factors such as the mining progress of the working face of the protective layer, mining height, degree of compacted goaf, degree of pressure relief of the protected layer, original gas content, and other measures taken to extract the protected layer.

1. Introduction

China is rich in coal resources and coalbed methane (CBM) resources. According to the second national coal resource prediction results, the volume of the reserves of CBM buried at depths less than 2000 m in China is $3.68 \times 10^{13} \text{ m}^3$, equivalent to $4.2 \times 10^{10} \text{ t}$ standard coal [1]. China's coal mine methane (CMM) resources are less plentiful than those of Russia and the United States, ranking third in the world, accounting for 13% of the total CMM resources in the 12 countries richest in CMM. In 2012, 3284 high gas outburst coal mines were distributed in 26 major coal-producing provinces, mainly in the southwest and mid-eastern regions. China's coal mine safety regulations stipulate that the coal seam must be predrained before mining so that the gas

pressure and gas content are reduced to 0.74 MPa and 8 m³/t, respectively. Otherwise, it is easy to cause coal and gas outbursts, excesses of gas in the working face, and gas explosion accidents [2–5]. In addition, the damage to the ozone layer and the greenhouse effect caused by gas emission into the atmosphere are 7 and 21 times greater than that of CO₂, respectively [6]. However, coalbed methane is a clean and efficient energy source, and its calorific value is 2–5 times that of general coal [7].

Coal seam permeability enhancement mainly includes protective layer mining, hydraulic fracturing, hydraulic cutting, hydraulic punching, presplitting blasting, shock wave fracturing, liquid CO₂ blasting, and other hole fracture reconstruction technologies. At present, hydraulic fracturing, hydraulic cutting, and hydraulic flushing have made

great progress in increasing the production of shale gas and CBM [8–11]. However, these methods also introduce some problems. When water enters the microhole fracture of the coal body, under the influence of “water lock,” gas desorption decays rapidly, resulting in poor water injection. It is difficult to ensure that fracturing water is evenly distributed in the fine cracks and pores of the coal seam, and it cannot fully wet the coal. Hydraulic technology requires high water consumption, which has become a problem in areas such as Texas, North Dakota, and Kansas [12]. In addition, the water and groundwater used by the hydration technology return to the ground; this water can contain hydraulic additives or harmful substances.

Presplitting blasting has made some achievements in increasing the permeability of coal seams and strengthening gas drainage [13]. However, it is extremely difficult to deal with abnormal conditions such as “dumb blasting” and “blind blasting” when using explosives. In addition, explosives cause the coal and rock mass to be crushed during the blasting process, and the crushed coal will hinder the propagation of the blasting wave, resulting in higher energy consumption. The fracture circle area is small, and the crushed coal and rock mass can easily block the fracture, making extraction ineffective. Shock wave fracturing of coal seams is an innovative technology for enhanced permeability gas drainage [14]. The coal reservoir is reconstructed through breaking, tearing, and elastic acoustic wave disturbance, which have the basic characteristics of segmentation and frequency bands. This basic feature is combined with the fatigue effect of repeated loading, which makes controllable shock wave technology advantageous in reservoir reconstruction technology; however, large-scale underground applications have not yet been realized.

In recent years, domestic and foreign researchers have carried out numerous liquid CO₂ blasting tests in major coal mines [15]. The field results show that the technology has a significant effect on coal reservoir reconstruction and coal seam methane recovery, but the range of influence is small. Wen et al. [16–24] proposed liquid CO₂ permeability enhancement and gas displacement technology in coal mines, carried out several underground engineering tests, and achieved good results. However, these studies had problems such as small test areas and difficulty of CO₂ transportation. Protective layer mining is the most effective regional measure for preventing and controlling gas disasters. Protective layer mining changes the deformation degree of the coal skeleton, destroys the stress state of the overlying coal and rock mass, effectively improves the permeability of the protected layer, and promotes desorption, flow, and discharge of pressure relief gas [25–28]. In addition, Jin confirmed that the protected areas generated by protective layer mining were larger than those predicted theoretically [29], but the technology was greatly affected by geological conditions. With the deepening of mining depth year by year, there are fewer and fewer coal seams or low outburst-prone coal seams with an interlayer spacing of 20–50 m. Therefore, the protective layer mining method is greatly affected by the occurrence characteristics of coal seams.

The typical geological feature of the Huainan mining area is the high occurrence of coal seam groups, and the protective layer mining strategy has been fully implemented. In the process of mining the protective layer, the stress field and fracture field evolution caused by mining action are used to relieve pressure, increase the permeability of gas, and improve the storage and transportation of pressure relief gas. The pressure relief gas of the protected layer is efficiently extracted, and coal and gas are mined together to eliminate the risk of coal and gas outbursts in the protected layer.

Pressure relief gas extraction methods mainly include underground roadway extraction, coal pillarless borehole extraction, and surface drilling extraction [30]. Gas extraction by surface drilling is a type of green mining technology that does not interfere with the normal operation of the mine from the surface construction, reduces the amount of underground engineering technology, and is conducive to safe operation of the mine. This process is generally divided into predrainage before mining, mining-induced drainage, and goaf drainage. Surface drilling technology has been applied in Huainan, Huaibei, Jincheng, Lu'an, and other high gas mining areas and has become increasingly effective [31–37]. Based on the drainage results of surface drilling of a typical working face during the exploitation of the protective layer in the Huainan mining area, the characteristics of relief gas extraction from the protective layer by surface drilling are summarized.

1.1. Application of Surface Drilling for Pressure Relief Gas Extraction in the Huainan Mining Area. Since the successful application of pressure relief gas extraction technology by surface drilling in the 2352(1) protective layer working face of the Panyi Coal Mine in 2002, more than 100 wells have been tested in the Pansan Coal Mine, Xieqiao Coal Mine, Zhangji Coal Mine, and Guqiao Coal Mine. The geographical distribution of coal mines is shown in Figure 1. Surface drilling in the Huainan mining area is mainly used for pressure relief gas extraction during the mining of the 11⁻² coal protective seam face, that is, the construction of surface drilling before the 11⁻² coal mining. With the mining of the 11⁻² coal protective layer, the overlying coal and rock layers continue to collapse, crack, and sink, causing the pores and cracks of the originally closed geological body to proliferate and open, and the air permeability coefficient of the surrounding rock and its coal seam greatly increases, as shown in Figure 2. The mining of the protective layer promotes full pressure relief of the protective and protected layers. The pressure relief gas of the protective layer, the gas flowing into the goaf, and the pressure relief gas of the protected layer flow into the well through the screen and are then pumped to the ground from the well.

2. Characteristics of Surface Drilling Types in the Huainan Mining Area

To adapt surface drilling technology for pressure relief gas extraction to various types of working faces of mining protective layers and improve gas extraction, Huainan

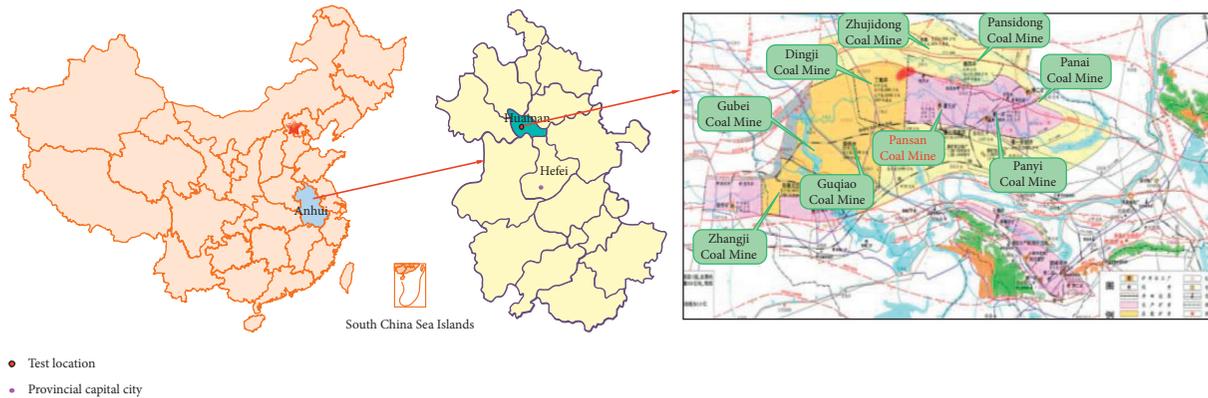


FIGURE 1: Geographical location of the study area and locations of the engineering test sites [17].

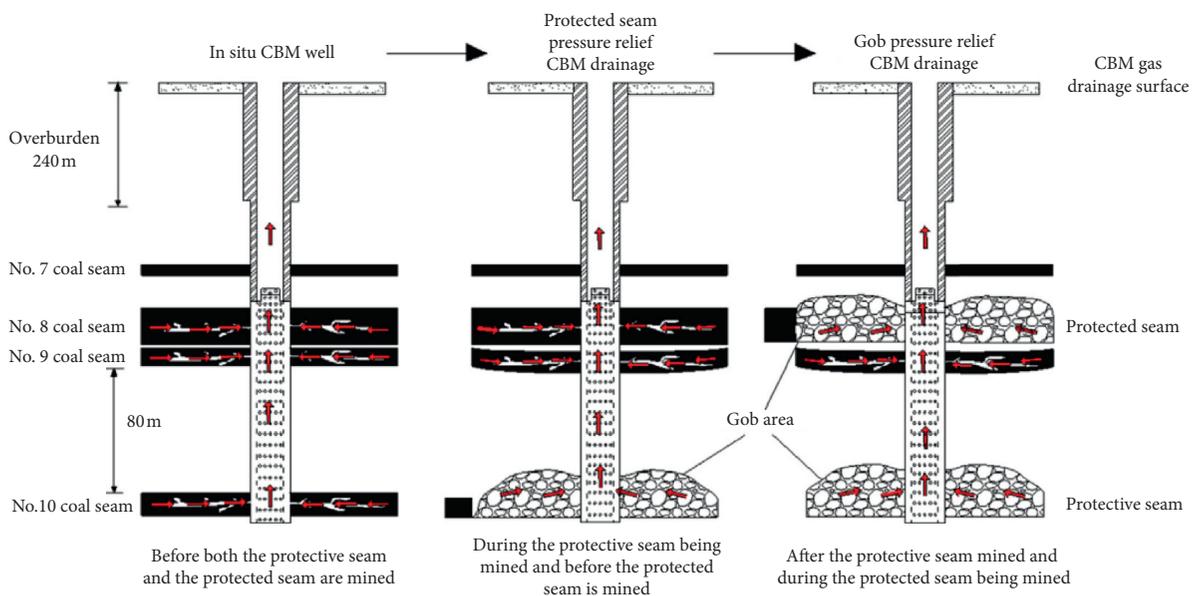


FIGURE 2: Different stages of pressure relief CMM extraction of the multipurpose well modified from the work of Wang et al. [38].

Mining Group has improved and innovated upon the drilling well structure, drilling construction technology, and drilling well location layout. The Huainan mining area successfully applied well structure types I, II, III, and IV, as shown in Table 1. Furthermore, the Huainan Mining Group formed a drilling well structure and drilling well location layout suitable for different mining conditions, mastered the key drilling construction technologies of different well body structures, and enriched the theoretical basis of pressure relief gas extraction in the protective layer.

3. Characteristics of Gas Extraction in Pressure Relief by Typical Surface Drilling in the Huainan Mining Area

3.1. Measurement of Gas Extraction Flow from Surface Drilling. To extract pressure relief gas from the protected layer by surface drilling, an independent extraction system was established with sufficient extraction capacity and negative pressure of 20–50 kPa. The highly concentrated gas

extracted can be used directly as clean energy for gas power generation or civil use. During the extraction of surface wells, special personnel were deployed to maintain the extraction system. The gas extraction concentration, negative pressure, flow rate, temperature, and other parameters were measured daily. A daily extraction report was formulated, and the extraction effect of surface drilling was analyzed regularly.

3.2. Typical Characteristics of Pressure Relief Gas from Single Ground Drilling. The ground drilling No. 1 in the protective layer working face 2662(1) is a type I drilling structure, with a total of 214 days of extraction and 20.91 million m³ of gas extraction. Figure 3(a) shows that the gas flow of No. 1 surface drilling has a significant periodicity, which can be divided into a rising period, stable period, and decay period. The ground well (No. 1) passed 12 m through the mining face to begin the extraction; the gas extraction concentration was 20%, and the gas extraction rate was 2.99 m³/min. From that point, the gas extraction concentration and extraction

TABLE 1: Surface gas extraction wells of different structural types in the Huainan mining area.

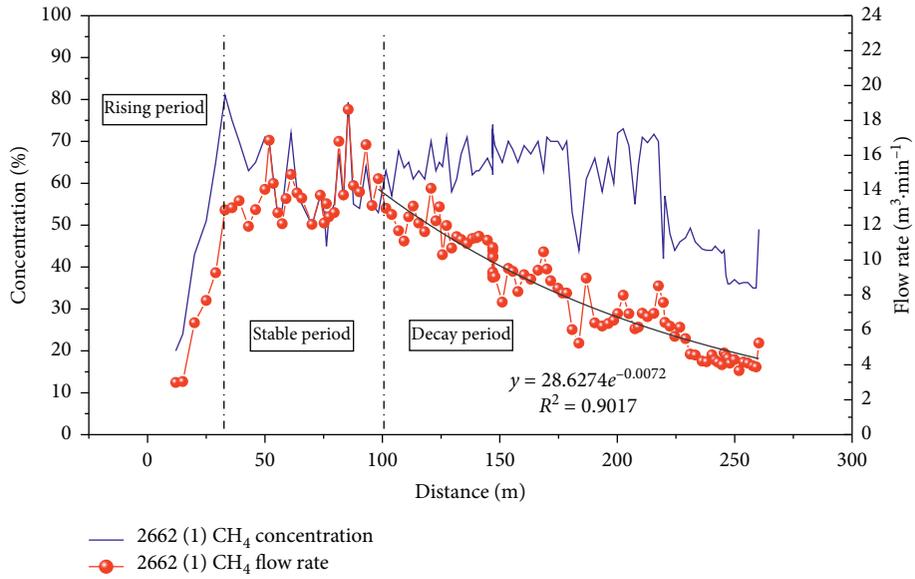
Type	Structural representation	Coal mines featuring successful application	Result
I		<p>Panyi coal mine, Xieqiao coal mine, and Pansan coal mine</p>	<p>The maximum single-well gas extraction volume is close to 1,000,000 m³</p>
II		<p>Dingji coal mine</p>	<p>The cumulative gas output of a single well is close to 1,000,000 m³</p>

TABLE 1: Continued.

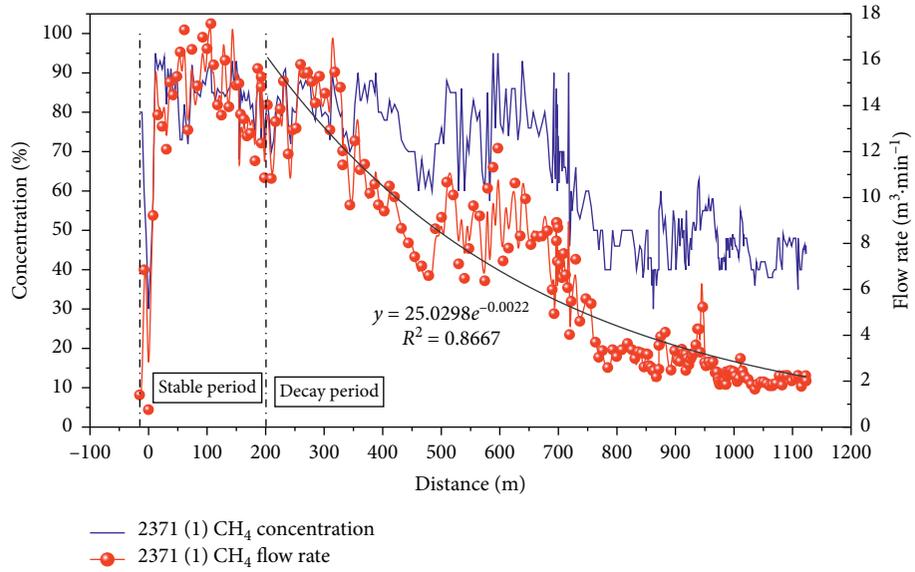
Type	Structural representation	Coal mines featuring successful application	Result
III		<p>Guqiao coal mine, as well as other coal mines in the Huainan mining area</p>	<p>The gas output of a single well is more than 1,000,000 m³, which solves the problem of gas extraction and pressure relief by rapidly advancing surface gas extraction drilling in complex geological and hydrogeological environments</p>
IV		<p>Pansan coal mine, as well as other coal mines in the Huainan mining area</p>	<p>The maximum single well gas extraction volume reached 7,500,000 m³</p>

rate were in the rising period until the mining face passed the drilling at 33 m; the gas extraction concentration was 81%, and the extraction rate was 15.89 m³/min. The working face

then passed through 33–109.2 m of drilling, and the extraction rate was stable during this period. The average gas extraction concentration was 64%, and the average



(a)



(b)

FIGURE 3: Continued.

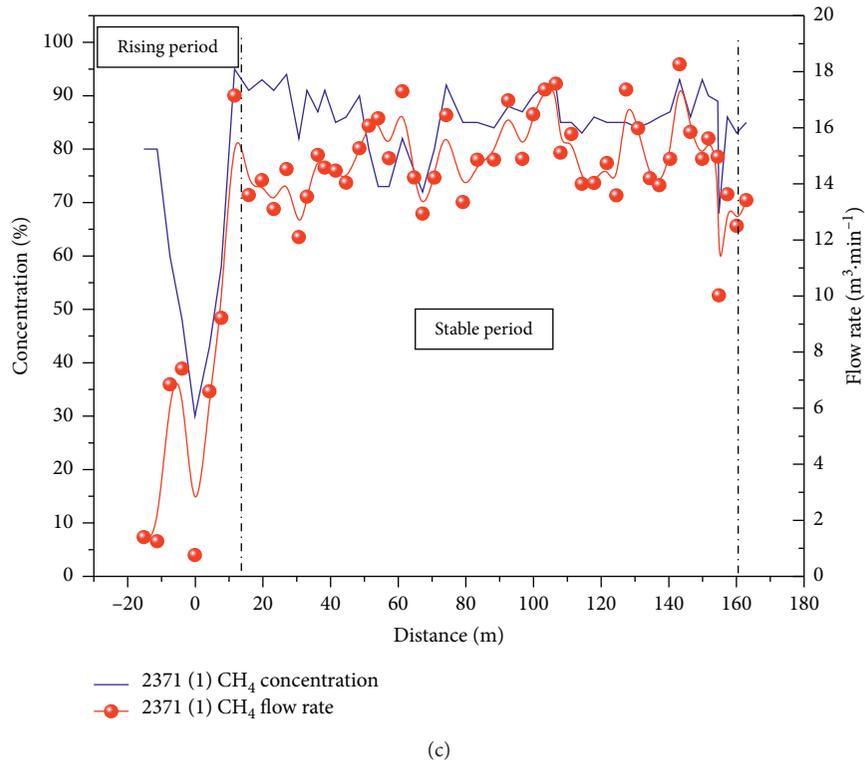


FIGURE 3: Diagram illustrating gas concentration and flow rate in gas extraction and pressure relief for typical single surface wells: (a) protective layer working face 2662(1), (b) protective layer working face 2371(1), and (c) protective layer working face 2371(1) rising period.

extraction rate was $11.84 \text{ m}^3/\text{min}$. After the working face passed the drilling (109.2 m), the extraction rate was in the attenuation period, and the extraction rate and mining progress (time) decreased exponentially.

The ground drilling No. 1 in the protective layer working face 2371(1) is a type II drilling structure, with a total of 427 days of extraction and 542.54 million m^3 of gas extraction. Figures 3(b) and 3(c) show that the periodic variation behavior of “rising period, stable period, and decay period” described previously is exhibited in this drilling system as well. The working face was 15.2 m away from the No. 1 ground drilling system, the gas extraction concentration was 80%, and the extraction rate was $1.25\text{--}1.4 \text{ m}^3/\text{min}$, which is the original coal extraction. When the working face was 7.5 m away from the No. 1 well, the gas extraction concentration was 60%, the extraction rate was $6.85 \text{ m}^3/\text{min}$, and the extraction rate was greatly increased, indicating that the protected layer 13^{-1} coal was released. When the working face was mined to the position of the No. 1 well on the ground, the gas extraction concentration was 30%, the extraction rate was $0.76 \text{ m}^3/\text{min}$, and the extraction concentration of ground drilling was significantly lower. Subsequently, the gas extraction concentration and extraction rate entered the rising period. When the working face passed a drilling depth of 11.6 m, the gas extraction concentration was 95% and the extraction rate reached $17.15 \text{ m}^3/\text{min}$. The working face passed through the drilling depths of 11.6–162.9 m, and the extraction rate was in the stable period. The average gas extraction concentration was

85.8% , and the average extraction rate was $14.86 \text{ m}^3/\text{min}$. After the working face passed the drilling depth of 162.9 m, the extraction rate entered the attenuation period, and the extraction rate and working face progress (time) decreased exponentially.

The structures of the No. 1 wells on the ground of the 2662(1) working face and 2371(1) working face are different, and the extraction time and amount are different, although both follow the periodic pattern of the “rising period, stable period, and decay period.” Therefore, after analyzing the extraction of surface drilling in the Huainan mining area, it was found that the typical characteristics of pressure relief gas extraction by surface drilling follow the periodic pattern of the “rising period, stable period, and decay period.”

3.3. Analysis of Gas Extraction by Multiple Ground Drilling Systems in the Same Working Face. The distance between ground drilling and extraction of pressure relief gas in the protective layer in the Huainan mining area is generally less than 300 m. Therefore, multiple drilling systems are arranged in the same working face. As shown in Figure 4, a total of five ground wells were arranged in the 1581(1) working face, and the ground well spacing was 230–260 m. After the working face was recovered from the No. 1 surface drilling system, the surface drilling extraction rate rose rapidly by $21.08 \text{ m}^3/\text{min}$, and after a short stable period, it entered a decay period. Before the working face mining to No. 2 surface drilling, the surface drilling extraction rate was

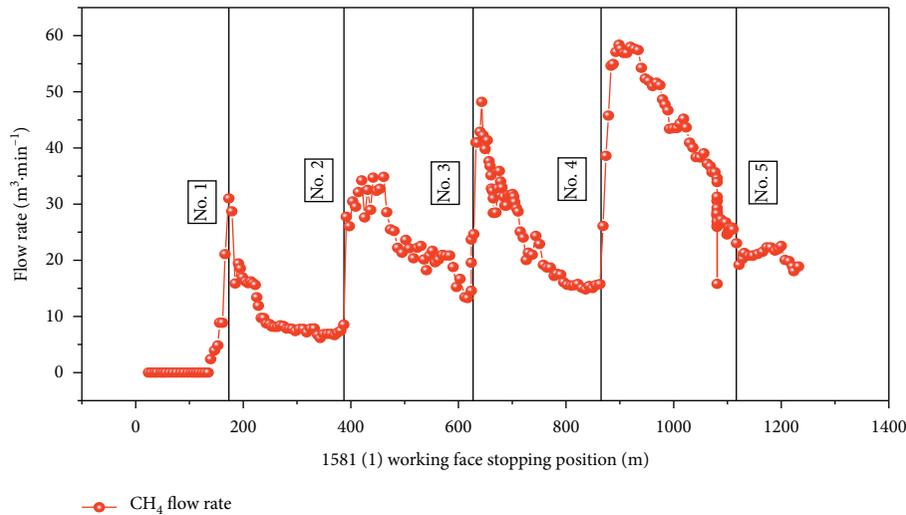


FIGURE 4: Cooperative extraction of five surface wells in 1581(1) working face.

attenuated to about $7 \text{ m}^3/\text{min}$, and the extraction volume of the working face recovered rapidly to $27.74 \text{ m}^3/\text{min}$ after the surface drilling of No. 2 was recovered. The extraction process of surface drilling at different positions in the same working face follows the periodic pattern of “rising period, stable period, and decay period.”

Because of the different locations and times at which surface drilling was conducted in the working face, the extraction rates of multiple surface drilling systems in the same working face were combined, the trend of the surface drilling extraction rate increased, and the extraction rate fluctuated with the position of surface drilling. When the working face was close to No. 4 surface drilling, the extraction volume decreased to $14.81 \text{ m}^3/\text{min}$. After the working face was recovered from No. 4 surface drilling, the surface drilling extraction volume rose rapidly to $58.38 \text{ m}^3/\text{min}$. After a short stabilization period, it entered the decay period. No. 5 surface drilling which was close to the retraction line of the working face; the recovery progress of the working face slowed down, the gas emission volume was reduced, and the combination of multiple surface drilling extraction rates was not obvious. In summary, when multiple ground drilling systems in the same working face perform extraction concurrently, the extraction rate of ground drilling increases with an increase in the number of drilling systems extracting simultaneously, and the extraction rate fluctuates with different ground drilling positions.

3.4. Analysis of the Causes of Surface Drilling Extraction Characteristics. In the mining process of the 11^{-2} coal protective layer working face in the Huainan mining area, the pressure relief gas extraction by surface drilling of the 13^{-1} coal protective layer was taken as an example for analysis. The influence of the mining-induced 11^{-2} coal protective layer on gas extraction in the goaf of the 11^{-2} coal face includes several main aspects. When the 11^{-2} coal working face passed through the ground drilling, the ground drilling system communicated with the 11^{-2} coal goaf, and

the air leakage in the goaf was large. With the 11^{-2} coal face advancing, the ground drilling and 11^{-2} coal goaf gradually compacted and the goaf air leakage was reduced and then gradually stabilized.

To determine the influence of mining changes in the 11^{-2} coal protective layer working face on the 13^{-1} coal protected layer, the expansion deformation rate of the protected layer working face was studied as an evaluation index, as shown in Figure 5. When the working face was 37.75 m away from the measuring point, the deformation rate of the 13^{-1} coal seam was 0. When the working face was 33.8 m away from the measuring point, the 13^{-1} coal seam expanded and deformed. When the working face was 0 m away, the expansion deformation rate of the 13^{-1} coal seam was 7.2% . When the working face passed the measuring point of 16.3 m , the expansion deformation rate of the 13^{-1} coal seam was 28.5% . After that, the 13^{-1} coal seam has contracted slightly, and when the working face passed the measuring point of 66.45 m , the expansion deformation rate of the 13^{-1} coal seam was 23.2% .

Before the surface drilling of the 11^{-2} coal face in the Huainan mining area, the protective layer of 13^{-1} coal generally began to unload pressure. When the working face passed through the ground drilling, the ground drilling communicated with the goaf of the 11^{-2} coal working face, the extraction volume was reduced, and the gas extraction concentration was generally at its lowest value. With the advancement of the 11^{-2} coal working face, the goaf of ground drilling and the 11^{-2} coal working face was gradually compacted, and the air leakage was gradually reduced. The expansion and pressure relief of the 13^{-1} coal protected layer in ground drilling and the amount of desorbed gas both increased, while the concentration and rate of gas extraction entered the rising period. With an increase in the goaf distance between the 11^{-2} coal face and the ground drilling, the goaf of the 11^{-2} coal face during ground drilling was basically stable. The range of the fully pressure relief zone of protected layer 13^{-1} extracted by ground drilling increased, and the amount of ground drilling extraction entered a stable period.

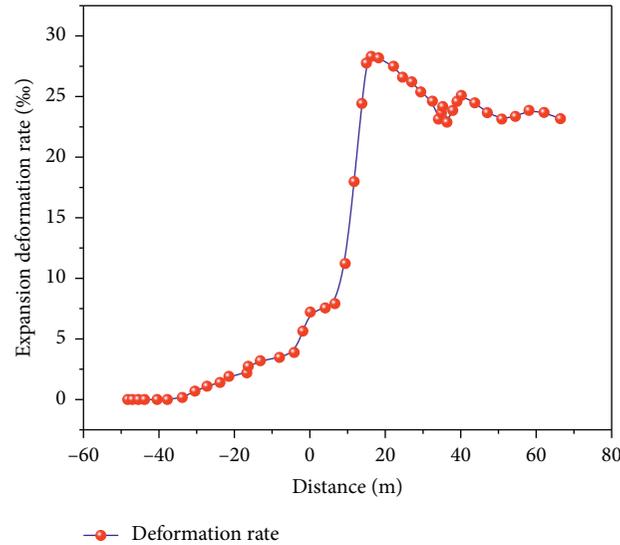


FIGURE 5: 1672(1) expansion deformation rate of the protected layer.

When the distance between the working face of the 11^{-2} coal seam and the ground drilling goaf increased to a certain range, the protected layer of 13^{-1} coal during ground drilling gradually entered the recompaction area from the fully depressurized area, and the gas content in the fully depressurized area decreased significantly, and the ground drilling pumping quantity entered the attenuation period. In summary, the periodic variation in the surface drilling extraction is mainly affected by changes in the mining of the protective layer working face. The rate of surface drilling extraction and the variation thereof are affected by the mining progress of the protective layer working face, mining height, degree of goaf compaction, degree of pressure relief of the protected layer, original gas content, and other measures for extraction of the protected layer.

After the protective layer working face passes through the drilling, the mined-out area is not fully compacted, and the air leakage is gradually reduced. Gas drilling occurs in the rising period, mainly manifested as an increase in the gas extraction concentration and extraction rate. The goaf of the protective layer working face is fully compacted, and the leakage is stable. Gas extraction by surface drilling occurs in the stable or attenuation period. The rate of gas extraction by surface drilling is mainly determined by the amount of pressure relief gas in the protective layer within the range of influence of surface drilling in the stable or decay period. In the range of influence of ground drilling, the amount of pressure relief gas in the protected layer is large, the gas extraction rate of ground drilling is stable, the fluctuation is small, and the trend line of the fitting curve is in a horizontal state, which represents the stable period of gas extraction from ground drilling. In the range of influence of ground drilling, the amount of gas released by the protective layer decreases, and the rate of gas extraction decreases.

The main feature of the surface drilling extraction volume from the rising stage to the stable stage is that the gas

extraction concentration reaches a maximum. Simultaneously, the variation trend of the extraction volume is considered. The fluctuation of extraction quantity in the stable period is small, the trend line of the fitting curve is in the horizontal state, and the gas extraction concentration is generally stable. The stable period transitions to the decay period mainly because the extraction volume begins to decline, and the extraction volume and stopping schedule or time in the decay period decrease exponentially.

4. Conclusions

- (1) Through the analysis of pressure relief gas flow and extraction concentration of protected layer extraction by surface drilling in different working faces, it was found that, after the protected layer working face was pushed through the surface drilling, the gas extracted by surface drilling showed a periodic variation summarized as the “rising period, stable period, and decay period.”
- (2) When multiple ground drilling systems were used in the same working face coordinate extraction, the extraction rate is superimposed, and the extraction rate increases with an increase in the number of drilling systems. The extraction rate fluctuated with different ground drilling positions. The extraction rate was small before the working face was pushed through ground drilling, and increased afterward.
- (3) The periodic variation in surface drilling extraction is mainly affected by the mining progress of the protective layer working face, mining height, degree of goaf compaction, degree of pressure relief of the protected layer, original gas content, and other protective layer measures. The rate of gas extraction by surface drilling is mainly determined by the amount of pressure relief gas in the protective layer within the influence range of surface drilling in the stable or decay period.

- (4) The main change from the rising period to the stable period is that the gas extraction concentration reaches the maximum value, considering the trend of the extraction volume. The main change from the stable period to the attenuation period is that the extraction rate begins to decline, and the extraction rate in the decay period decreases exponentially with the recovery progress or time.

Data Availability

The data used to support the findings of the study are all available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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