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Characteristics of mining gas channel expansion in the remote overlying strata and its control of gas flow

Liu Hongyong [a,b,c,d,*], Cheng Yuanping [a,b,c], Chen Haidong [a,b,c], Mou Junhui [a,b,c], Kong Shengli [a,b,c]

[a] School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, China
[b] National Engineering Research Center of Coal Gas Control, China University of Mining & Technology, Xuzhou 221008, China
[c] Key Laboratory of Gas and Fire Control for Coal Mine, China University of Mining & Technology, Xuzhou 221116, China
[d] Post-Doctoral Scientific Research Station in Shanxi Coking Coal Group Co. Ltd., Taiyuan 030022, China

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ABSTRACT

The technology of pressure relief gas drainage is one of the most effective and economic for preventing gas emissions in underground mines. Based on current understanding of strata breakage and fracture development in overlying strata, the current study divides the overlying strata into the following three longitudinal zones in terms of the state of gas flow: a turbulent channel zone, a transitional circulation channel zone and a seepage channel zone. According to the key strata discrimination theory of controlling the overlying strata, the calculation method establishes that the step-type expansion of the mining gas channel corresponds to the advancing distance of working face, and this research also confirms the expanding rule that the mining gas channel in overlying strata follows the advancing distance of mining working face. Based on the geological conditions of Xinjing Coal Mine of Yangquan, this paper researches the expanding rule of mining gas channel as well as the control action of the channel acting on the pressure relief flow under the condition of the remote protective layer, and got the distance using inversion that the step-type expanding of mining gas channel is corresponding to the advancing distance of working face, which verifies the accuracy and feasibility of theoretical calculation method proposed in this study. The research provides the theoretical basis for choosing the technology of pressure relief gas drainage and designing the parameters of construction.

1. Introduction

The technology of pressure relief gas drainage has developed rapidly in recent years, and has been successfully combined with coal bed methane extraction for pressure relief gas drainage and exploitation of both the protective layer and protected layer [1–3]. Many years' practice has proved that the technology is one of the most effective and economic ones, not only reducing problems with coal seam outbursts but also improving safety and reliability in preventing coal and gas outbursts. For this reason, coal supervision departments have promulgated many laws and regulations, and adopted the technology of exploitation of the protective layer and pressure relief gas drainage of the protected layer as the first-choice technology used for preventing coal and gas outbursts. The technology, which is used for the exploitation of the protective layer, has been proved by extensive practice and has been established in the form of laws and regulations to be the most effective method for preventing coal and gas outburst, and is widely used [2,3]. The purpose of mining the protective layer is to use the mining action to encourage stress unloading of the rock strata between seams and the protective layer and to induce fractures, which form the gas flow channel for mining. As a result, the air permeability increases and enables pressure relief gas drainage to be successfully carried out. Draining the gas can transform a high-pressure outburst-prone coal seam into a coal seam with low pressure and zero outburst risk, and realize the goal of co-extraction of coal and gas.

The technology, which is used for the exploitation of the protective layer and pressure relief gas drainage of the protected layer, involves the use of gas control in both the protective and protected layers. Many years' practice has found that pressure-relief gas in the protective layer working face and its adjacent layer can migrate to a specific gas drainage roadway as well as a high level suction roadway, or migrate to a specific gas drainage roadway of lower angle drilling as well as a high level suction roadway and thus be effectively controlled [4]. The pressure-relief gas in the protected layer and its adjacent layer can be captured by upward cross-layer drilling in the floor rock roadway and therefore to be effectively controlled. Stress unloading of overlying strata, along with the extent and height of damage fracturing, increases with an increase in distance of face advance. Therefore, gas control, which is used not only in the protective layer but also in the protected layer, plays a

* Corresponding author. Tel.: +86 516 83885948.
E-mail address: Lhyeven@163.com (H. Liu).

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role with an increase in advance in the mining layer. In order to improve the effectiveness of gas drainage and gas control, it is necessary to further study the characteristics of mining gas channel expansion in the remote overlying strata and its broad effect on the flow of pressure-relief gas, and to derive the rule that convergence and enrichment of pressure-relief gas changes with advance of the mining layer.

Many researchers have investigated the damage and deformation of overlying strata from the perspective of preventing excessive mine pressure and water inflow, and have determined that the lithology and occurrence conditions of the overlying strata have a great influence on the height of fracture development, the movement of rock and the deformation of the ground surface [5–9]. The research mentioned above achieved its aim of controlling mine pressure and water. Based on the above, some researchers discovered that fracturing of the overlying strata caused the pressure-relief gas to flow and converge [4,10–12]. However, very little attention has been given to the characteristics of mining gas channel expansion in the remote overlying strata and its broad effect on the flow of pressure-relief gas from the perspective of gas control. Thus, the application of the technology of pressure relief gas drainage is jeopardised, especially in terms of the choice of pressure-relief gas control method, the design of gas drainage parameters and the time limit of drainage. This severely impacts on the effectiveness, safety and economy of pressure-relief gas drainage and prevents the theory and technology of pressure-relief gas drainage from developing.

Based on the established theory of key strata in the control of mine pressure and water prevention, this study focuses on the characteristics of mining gas channel expansion in the remote overlying strata as well as its broad effect on control of the flow of pressure-relief gas. In this paper the remote mining protective layer of Xinjing Coal Mine of Yangquan has been used as a test case, where in-situ testing of mining gas channel expansion and pressure relief gas drainage of overlying strata has been carried out in order to provide theoretical support for adopting the technology of pressure relief gas drainage and designing the construction parameters.

2. Basic form and partition of the mining gas channel in the overlying strata

Mining coal seams causes the rock strata to move and leads to breakage and damage of the overlying strata, which results in the development of many mining-induced fractures in the overlying strata. Fracture development in the overlying strata can be longitudinally divided into a caving zone, a fractured zone and a bending subsidence zone [5]. The mining fractures in the overlying strata can be separated into two categories. The first of these is comprised of cross-layer breakage fractures, vertical or oblique to the rock strata, which are generated by bending subsidence of the overlying strata and shearing of upper rock strata. Some or all of the fractures cross the rock stratification, but adjacent sides of the rock strata do not generate relative displacement and maintain stratiform continuity. This kind of fracture only develops at a certain height in the overlying strata. In the second category are separation layer fractures which are mainly caused by the difference in mechanical properties between different rock strata as well as asynchronously bending subsidence of rock strata. The separation layer fractures are the sites of converging and enriching gas. The fracture network forms because the separation layer fractures and cross-layer fractures intersect. The interconnected fractures connect with the underlying goaf or the gas drainage system, and hence become the channel for movement of mining gas. Due to the effect of the pressure gradient, the gas in a coal seam can continually flow into the gas drainage system along the gas channel until the pressure gradient of gas in the coal seam reduces to zero. Only separation layer fractures exist in the inner overlying strata in the bending subsidence zone; mining fractures cannot form a fracture network, and the separation layer fractures only provide space for converging pressure-relief gas and cannot become the pathway for gas movement. Coal seams in the bending subsidence zone generate a certain degree of pressure relief, but only part of the pressure relief gas moves into the separation layer fractures and cannot therefore be drained from the coal seam. With the closure of separation layer fractures, gas is again adsorbed into the coal seam.

A gas channel, which is a penetrative region characterized by static and turbulent gas flow, is formed by visible openings or fractures with diameters greater than 10^{-1} mm [13]. Such channels determine the macroscopic plane of rupture, and part or whole of the pressure-relief gas can naturally drain along this channel. Thus, the region of cross-layer fracture channels having diameters greater than 10^{-1} mm is taken as the developing area of mining gas channel. The pressure relief gas in a coal seam cannot naturally discharge into the overlying strata above the height of this developing area of mining gas channel. Based on the results of simulation and in-situ tests, the development region of the gas channel in the overlying strata can be longitudinally divided into three zones, as shown in Fig. 1.

From bottom up, the zones of gas channel in the overlying strata are as follows:

(1) Turbulent channel zone

The turbulent channel zone lies in the caving zone in the roof of the working face where the inner overlying strata are broken. Most or part of this zone is made up of piles of broken blocks. Large fractures and separation layer fractures are the main types of gas channel in the turbulent zone. The turbulent channels are distributed randomly, their extent being related to the extraction height of the working face, rock size distribution and arrangement in the caving zone, lithology of roof strata, original stress, etc. The permeability of the turbulent channel is high. The state of gas movement is mainly turbulent, and its height of the channel is the same as the caving zone, generally 6–8 times the mining height.

(2) Transition circulation channel zone

This zone is located in the fractured zone and the lower edge of the bending subsidence zone. Overlying strata in this zone are relatively intact and still takes on a stratiform distribution. Gas channels are mainly tensile fractures. One- or two-way channels interconnect, which results in a large network of interconnected gas channels. Air permeability of the coal seam increases dramatically, and the state of gas movement is mainly nonlinear transitional flow. The height of the transition circulation channel zone is approximately 9–15 times the mining height.

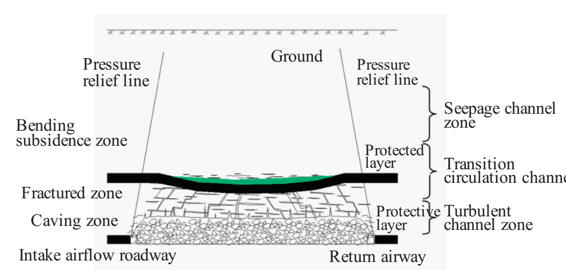

Fig. 1. Distribution of mining gas channel in overlying strata of working face.

(3) Seepage channel zone

This zone is located in the middle of the bending subsidence zone, and overlying strata in this zone move en-mass. Only a few vertical tensile fractures remain in this zone. The channels do not completely connect and thus it is difficult for networks of gas channels to form. The air permeability increases a little, but this air permeability is greater than the air permeability of the original coal. The state of gas movement is mainly seepage. The height of this zone is about 16–25 times the mining height.

3. Expansion rule of mining gas channel in the overlying strata

Where there are many types of rock strata in the overlying strata of a working face, the rock strata that play a whole or part role in rock movement is referred to as the 'key strata'. The former is referred to as the 'main key stratum' and the latter as the 'sub-key stratum'. The key strata control the movement of the overlying strata, and also control, dynamically, the expansion of the mining gas channel. This kind of control action determines the gradual breakage of each sub-key stratum. The height of the fractured zone develops rapidly until it stops developing below the non-breakage sub-key stratum or main key stratum in the form of a separation layer fracture zone. Due to the influence of rock stiffness as well as the obstruction effect caused by weaker rock, the height of the cross-layer fracture stops developing at a certain height. Thus, the height of the mining gas channel only develops to a certain height. With the breakage of key strata, the dynamic process of expansion is controlled by the key strata. Rapid development will also appear, but the final form is not determined by the key strata but is controlled by the degree of bending of rock and the presence of weak rock. Accordingly, the key strata that control the move of overlying strata and the dynamic expansion of fractures certainly influence the flow and convergence of pressure-relief gas in the overlying strata. The key strata should be firstly determined in order to investigate the expansion of the mining gas channel in the overlying strata. According to the definition and deformation characteristics of the key strata: if the load on the $(n + 1)$th layer is less than that on the nth layer, the following expression is obtained [5]:

$$(q_{n+1})_1 < (q_n)_1 \tag{1}$$

The deformation of rock from 1 to n layers is referred to as synchronous coordination; it is easy to get a rock combination from the 1st layer to the nth layer and its lowermost layer is the key strata. Consider the load formed by the influence of the nth layer of rock strata on the first layer, which can be calculated using the following equation [6]:

$$(q_n)_1 = \frac{E_1 h_1^3(\gamma_1 h_1 + \gamma_2 h_2 + \ldots + \gamma_n h_n)}{E_1 h_1^3 + E_2 h_2^3 + \ldots + E_n h_n^3} = \frac{E_1 h_1^3 \sum_{i=1}^{n} \gamma_i h_i}{\sum_{i=1}^{n} E_i h_i^3} \tag{2}$$

where $(q_n)_1$ is the load on the key strata, considering the influence of the nth overlying stratum controlled by the key strata, MPa; E the elastic modulus of the strata, GPa; γ the volumetric strength of rock, MN/m^3; and h the thickness of strata, m.

Due to the control of the key stratum, development of height and scope of the mining gas channel in the overlying strata is controlled by the falling of hard rock. Because of certain roof conditions, the first breakage step for a key stratum consists of the product of step number l_i and "edge-long" coefficient ω [7]:

$$a_i = l_i \cdot \omega \tag{3}$$

where l_i is the falling step number of hard strata, and is only determined by its own properties (σ_t, μ, h, q) and has no relationship with the length of working face and boundary conditions; ω the "edge-long" coefficient, is determined by the geometry and shape of the goaf and boundary constraint conditions.

The step number of a key stratum under the condition of fixed support boundary is as follows:

$$l_i = \frac{h}{1-\mu^2}\sqrt{\frac{2\sigma_t}{q}} \tag{4}$$

where μ is the Poisson's ratio of rock; q the weight of rock and the load, kPa; h the thickness of rock, m; and σ_t the tensile strength of rock, MPa:

$$\omega = \sqrt{\frac{1+\lambda^4}{1+\mu\lambda^2}} \tag{5}$$

where μ is the Poisson's ratio of rock; λ the geometry coefficient of goaf, $\lambda = \frac{a_1}{b}$; a_1 the advancing distance of working face, m; and b the length of working face, m.

Therefore, the distance of working face advance, which corresponds to the first falling step of key strata in the overlying strata can be calculated by the model, as shown in Fig. 2:

$$L = 2H_i \tan\alpha + a_i \tag{6}$$

where L is the advance distance of the working face that corresponds with the key strata first falling, m; H_i the vertical distance from key strata to mining coal seam, m; a_i the step of a key stratum first break, m; and α the mining pressure-relief angle of rock in the roof.

With the advance of a working face, mining gas channels in the overlying strata gradually expand, and their expansion stops at the lower first key stratum due to the control of the key strata. With continuing advance of the working face, mining gas channels can continuously expand and then stop at the upper key stratum, when the first key stratum of overlying strata reaches the first falling step and the key stratum breaks. In the above process, the distance of working face advance which corresponds with development of mining gas channels in the overlying strata can be calculated using Eq. (6), and the coal seam below the key stratum steps into the period of pressure relief and breakage. Thus, the design of the working method for a coal seam and the drainage time limit for a mining pressure relief gas project can be determined.

4. Mining gas channel expansion in the overlying strata influencing on the flow of pressure-relief gas

The expansion of mining gas channels in the overlying strata is controlled by rock movement, and the macroscopic flow of pressure-relief gas is controlled by the expansion of mining gas channels. This research is to study further the expansion height and scope of mining gas channels in the overlying strata, which change with the advance distance of working face, and its influence on the flow of pressure-relief gas. When mining the lower protective

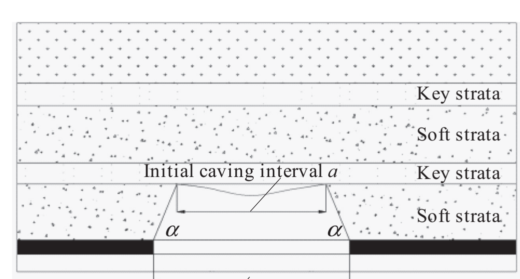

Fig. 2. Model for the step of key strata firstly falling and its corresponding advancing distance of working face.

layer, remote in-situ testing is carried out to investigate the expansion of mining gas channels in the overlying strata and the effect on pressure relief gas drainage.

4.1. Background of in-situ test

The predominant coal seams mined at Xinjing Coal Mine in the Yangquan Group are 3# and 15# coal seams. There is a high risk of coal and gas outburst in 3# coal seam-gas pressure in this coal seam reaching 1.3 MPa. The gas content of the seam is 17.28–18.17 m^3/t, and the hardness coefficient of the coal seam is low (0.5–0.66). The coefficient of air permeability (1.48×10^{-2} m^2/(MPa^2 d)) is also low. Gas drainage of 3# coal seam is difficult prior to the start of mining operations, and this has resulted in many coal and gas outburst-related accidents which seriously hampers the safe exploitation of the 3# coal seam.

According to the regulations for controlling coal and gas outbursts, the gas control of 3# coal seam should give priority to technology for mining the protective layer and pressure relief gas drainage. There exist several coal seams in the roof and floor of 3# coal seam, but none of them has any productive value. Only 15# coal seam, with an average distance of 125 m from the 3# coal seam, is stable and recoverable without the risk of coal and gas outbursts. Consequently, 15# coal seam can be considered as the lower protective layer, as shown in Fig. 3. According to the classification of the protective layer, the interlayer space between 3# and 15# coal seam is 125 m, which can be considered as mining the remote protective layer [12].

In-situ testing is carried out in the 80,201 working face of 15# coal seam in Xinjing Coal Mine. The 80,201 working face of 15# coal seam in Lubei region is treated as the first working face when mining the lower protective layer. The surroundings of the working face is the actual coal body, with an average depth of 505 m. The strike is 430 m, and the tendency is 200 m. The average dip angle of coal seam is 6°, and the average thickness is 6.14 m. The method of longwall fully mechanized coal mining is used in this test, and the full height of the coal seam is mined using the full caving method to control the roof. According to the corresponding relations of the working face of the coal seam, the 7315 working face of the upper 3# coal seam is the working face of the protected layer. The average mining depth of this working face is 380 m.

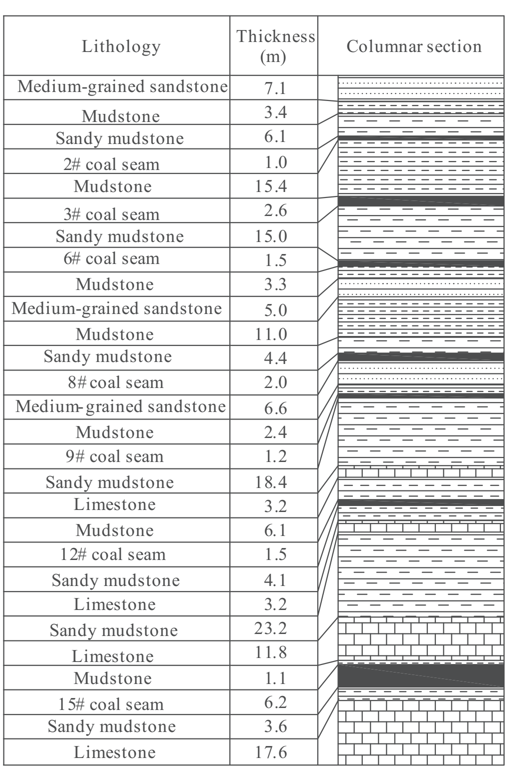

Fig. 3. Coal comprehensive columnar section of 80201 working face in Xinjing Coal Mine.

4.2. Expansion rule of mining gas channel

According to the comprehensive local columnar section of 80,201, the main physical and mechanical parameters of 80201 working face are shown in Table 1. Eqs. (1) and (2) are used to determine the key stratum of the overlying strata of 15# coal seam.

There are four sub-key strata above 80,201 working face of 15# coal seam within 150 m. The thickness of the sandy mudstone is respectively 23.2, 18.4 and 15 m, and the thickness of the mudstone key stratum is 15.4 m. The key stratum, which is controlled by gas-containing coal rock strata in the overlying strata of 15# coal seam, is the key stratum with arenaceous rock that is about 12.9 m from 15# coal seam. This key stratum controls the movement of 12# coal seam and K_3, K_4 limestone. This coal rock stratum is the main source of gas emission for the adjacent layers of 15# coal seam. The upper key stratum is the key stratum with sandy mudstone which is about 54.2 m from the 15# coal seam, and also controls the movement of the upper 6#, 8# and 9# coal seams. The key stratum, which is above the upper key stratum, is the key stratum with sandy mudstone which is 110 m from 15# coal seam, and controls the movement of the upper 3# coal seam. This stratum controls the expansion of mining gas channels of the protective layer. The top layer is the key stratum with mudstone which is 127.6 m from 15# coal seam. This key stratum controls the movement of roof rock of 3# coal seam.

According to the physical and mechanical parameters for the key strata of the overlying strata (Table 2) and the design parameters of the protective layer's working face, the dominating height of gas channels of the key stratum and the corresponding advance distance of the working face can be calculated by Eqs. (1) and (2).

From Table 2, it is clear that the expansion of mining gas channels in the overlying strata for the 80,201 working face is controlled by the key strata and shows the following characteristics.

When the working face has advanced to 55.33 m, the mining gas channel expands to 12.9 m below the first sub key stratum. When the working face has advanced to 96.76 m, the mining gas channel below the first sub key stratum has fully developed and the initial caving step of the upper sub key stratum is established. Also, the second sub key stratum breaks, and the mining gas channel expands to 110 m below the third sub key stratum. When the working face has advanced to 178.25 m, the mining gas channel below the third sub key stratum is fully developed at the moment the initial caving step of upper sub key stratum is reached. At the

Table 1
Deciding the key stratum discrimination of overlying strata in 80201 working face of Xinjing Coal Mine.

Number	Lithology	Elastic modulus (GPa)	Volume force (MN/m^3)	Poisson's ratio	Tensile strength (MPa)
1	Coal seam	4.10	0.0139	0.38	2
2	Sandy mudstone	19.60	0.0251	0.28	5
3	Mudstone	18.60	0.0246	0.24	4
4	Medium-grained sandstone	35.90	0.0267	0.22	7
5	Limestone	33.20	0.0271	0.21	6

Table 2
Dominating heights of gas channels of key strata and the corresponding face advance distance (m).

Inferior key strata	Lithology	Step of initial fracture	Height to 15# seam roof	Height of controlled gas channel	Advancing distance of corresponding face of key strata relief[a]	Advancing distance of corresponding face of fully developed gas channel[b]
4	Mudstone	29.21	127.6	160.0	178.25	
3	Sandy mudstone	31.27	110.0	127.6	138.19	178.25
2	Sandy mudstone	40.06	54.2	110.0	96.76	138.19
1	Sandy mudstone	41.43	12.9	54.2	55.33	96.76

[a] 65° is used as the relief angle of strata in calculation [14].
[b] The corresponding advancing distance of working face, before upper key strata fractured, the key strata height and scope of development of gas channel zone reach the full development.

same time, the third sub key stratum breaks, and the mining gas channel expands to 12.7 m below the fourth sub key stratum. At this point, 3# coal seam enters the gas seepage channel zone, and the pressure-relief gas in the coal seam can be captured by the gas drainage system along the gas channel.

The developing height of the final mining gas channel for a fully mechanized working face can be obtained using the empirical equations of limiting altitude of the fracture zone:

$$H = K\left(\frac{100M}{1.2M + 2.0} + 8.9\right) \tag{7}$$

$$H = K\left(30\sqrt{M} + 10\right) \tag{8}$$

In Eqs. (7) and (8), H is the final height of the developing mining gas channel, m; M the mining height of the coal seam, m; and K the influence coefficient of height of the fractured zone around the mechanized working face, corresponding to the mining method used: stratification mining or mechanized mining, and K is 1.5 for hard rock.

In the case of the 80,201 working face of Xinjing Mine, substituting the mining height 6.5 m of 15# coal seam into Eq. (7) the value of H, 112.8 m is obtained. From Eq. (8), we obtain a value of H of 129.7 m. Using the maximum value of H, it is easy to demonstrate that the final height to which the mining gas channel develops is 129.7 m. This value is in line with the results of other research [14,15].

Therefore, the development of the mining gas channel in overlying strata is controlled by three sub key strata, respectively controlling the development of gas channels within 54.2, 110, and 127.6 m of the 15# coal seam roof. In addition, corresponding gas channels in the 80,201 working face will also occur at three locations. In particular, the breakage of the sandy mudstone sub key stratum, which is 12.9 m distant from 15# coal seam roof results in maximal gas drainage. However, the upper 3# protected layer which is 125 m distant from 15# coal seam remains at the upper edge of the fracture zone. A separation layer develops, but does not form a gas channel. The air permeability increases, while the distance to the mining layer is far away. Pressure-relief gas cannot discharge itself but needs help to improve the effect of pressure-relief gas drainage in the protective layer. Gas drainage eliminates the problem of coal and gas outburst in the protected layer.

4.3. Expansion of mining gas channel in the gas channel and its influence on pressure-relief gas drainage

The overlying strata of 80,201 working face include the following coal seams: 12#, 11#, 9#, 8#, 6#, 5#, 3# and 2# in addition to the limestones of K_3 and K_4. In order to effectively control the pressure-relief gas flow which affects the mining environment and improve the effect of pressure-relief gas drainage of 3# coal seam, 11# coal seam, which is 50–60 m distant from 15# coal seam, incorporates a high level drainage tunnel driven on strike. A floor gas drainage tunnel is formed in 5# coal seam which is 15 m distant from the floor of 3# coal seam. From the analysis of the key strata controlling the expansion of mining gas channels as well as the project practice, we can determine that 15# and 3# coal seams respectively lie in the mining gas channel zone in the overlying strata and the gas transition circulation channel zone [14]. The strike high drainage tunnel of the 80,201 working face is located above the first sub key stratum, and its effect on gas drainage is controlled by the second sub key stratum with a thickness 18.4 m.

The concentration, pumping and drainage volumes of gas for each gas control project in the process of mining 80,201 working face vary with advance of the working face, as can be seen from Fig. 4a–c. As noted in Fig. 4a–c, the gas emission rule of the 80,201 working face of 15# coal seam displays the following three-stage characteristics:

(1) When the working face advances to 15 m, the falling of direct roof causes the overlying strata to generate many gas channels which connect the K_2 limestone with the mining space, and imports the dissociative gas in the caving zone into the mining space. This results in the first peak value of gas emission in the working face.

(2) When the working face advances to 40 m, gas concentration in the high level suction roadway of 11# coal seam begins to increase. When the mining working face advances to 46 m, the high level suction roadway begins to play a role and gas concentration quickly increases (see Fig. 4a). Gas pumping and drainage volume reaches 27.07 m^3/min (see Fig. 4b) and can be seen as the second peak value of gas emission in the working face. When the working face advances to 67.3 m, the gas concentration in high level suction roadway appears as the first peak and is 60% of that value. Under this condition, the pumping and drainage volume of gas reaches 46.2 m^3/min and appears as the third peak value of absolute gas emission volume in the corresponding working face, with a value of 53.88 m^3/min.

After the 80,201 working face in the protective layer advances to 40 m, pressure relief appears in the underlying coal and rock mass of the high level suction roadway, and a number of mining gas channels form, which causes the adjacent layer to gradually emit gas into the mining working face. With further development of the mining gas channel, the high level suction roadway and mining space of the working face become connected. Due to the negative pressure in the high level suction roadway, pressure-relief gas

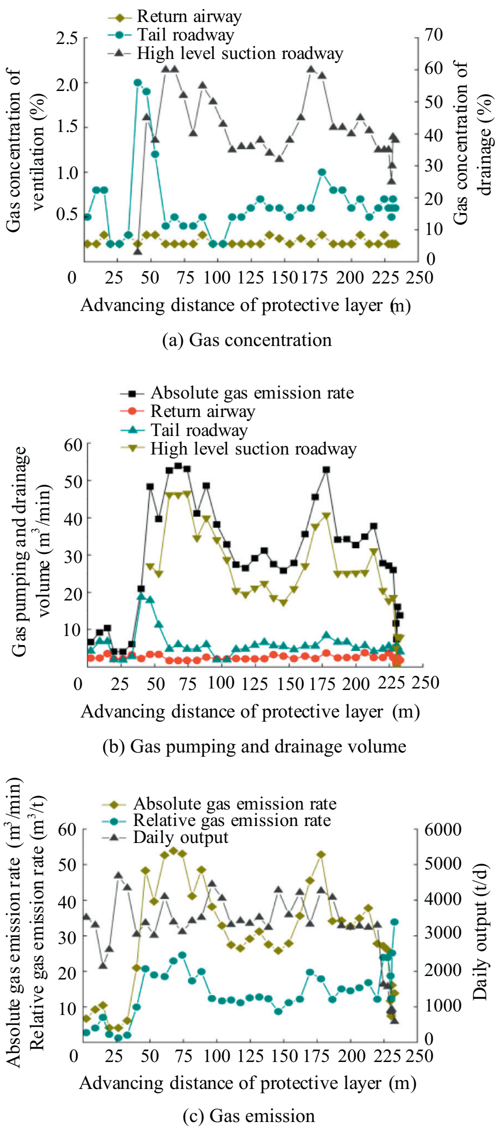

Fig. 4. Gas concentrations and emission volume of 80201working face changing with advancing distance of this working face.

in adjacent layers of the mining working face are intercepted and imported into the high level suction roadway. The gas pumping and drainage volumes of other gas control projects begin to decrease. With continued advance of the working face, the first sub key stratum reaches the initial step and then decreases, which results in pressure relief in an even larger zone of the overlying strata. Gas, which was present in gas reservoirs in the K_3 and K_4 limestones, and in 12# and 11# coal seams surges up into the mining space along the mining gas channel. This causes a gradual increase in the volume of gas emission and explains the appearance of the third peak value.

(3) When the working face advances to 96.4 m, the volume of gas emission of 80,201 working face begins to decrease, while the volume of gas emission in the floor suction roadway of 7312 working face, which is 110 m distant from the roof of 15# coal seam, reaches a peak value of 21.05 m^3/min. At this moment, gas concentration is 87%, as shown in Fig. 5. When the 80,201 working face advances to 138.6 m, the volume of gas emission in the floor suction roadway of 7315 working face stops decreasing and begins to increase. With further advance of the working face, up to 170 m, the volume of gas emission for the floor suction roadway of 7315 working face suddenly increases and exceeds 20 m^3/min.

The three characteristics mentioned above are controlled by the expansion of the mining gas channel. With the advance of a working face, the gas channel in the overlying strata continuously expands upwards. When the 80,201 working face in the protective layer has advanced to 61 m, the underlying coal in the floor suction roadway of 7315 working face begins to experience relief of pressure, and the gas in the upper and lower adjacent coal seams enters the high level suction roadway. The gas concentration suddenly increases to 30%, and the volume of gas drainage reaches 5.7 m^3/min. When the 80,201 working face advances to 96.4 m, the second sub key stratum falls, and the mining gas channel expands to a distance of 110 m from the roof of 15# coal seam. The pressure-relief gas of 9#, 8#, and 6 # coal seams, between the first and the second sub key strata, flows into the high level suction roadway of 80,201 working face and the floor suction roadway of 7315 working face along the mining gas channel. Because the high level suction roadway of 80,201 working face is close to the mining space, the pressure gradient of this roadway has less influence in comparison to the floor suction roadway of 7315 working face. Therefore, the pressure-relief gas in 9#, 8#, and 6# coal seams enters the 7315 floor suction roadway along the mining gas channel, and consequently this reduces the flow of pressure-relief gas from adjacent coal seams into the mining space. When the working face advances to 138.6 m, the falling of the third sub key stratum results in pressure relief in the 3# coal seam, and tightly compresses the mining gas channel in underlying coal rock, which in turn causes a reduction in gas flow from lower adjacent layer to the floor suction roadway of 7315 working face. Thus, the volume of gas emission in the floor suction roadway of 7315 working face only increases a little. When the working face advances to 170 m, the fourth key stratum falls and the mining gas channel expands to the roof of 3# coal seam. Pressure-relief gas in 2# coal seam flows into the floor suction roadway of 7315 working face, which causes the peak value of gas emission to appear again, as noted in Fig. 5.

In the whole process of gas emission in the floor suction roadway for 7315 working face, the gas concentration is always in excess of 40% with a maximum concentration of 90%. The volume of gas emission is over 10 m^3/min, and the maximum volume of gas emission reaches 21 m^3/min. This demonstrates that mining of 15# coal seam greatly influences the 3# coal seam; the mining gas channel develops rapidly and the air permeability of 3# coal seam and adjacent coal seams increase significantly, which shows that the influence on gas emission is beneficial. This verifies that 3# coal seam is located at the edge of the fractured zone of 15# coal seam and is in the mining transitional gas channel.

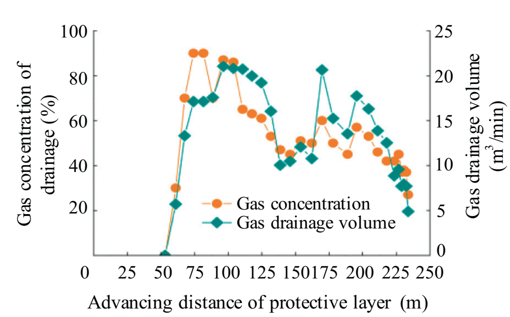

Fig. 5. Concentration and volume of gas emission for 7315 floor suction roadway changing with advancing distance of 80201 working face.

From the analysis above, the key strata control the dynamic expansion of the mining gas channel, and also control the dynamic emission and flow of pressure-relief gas in overlying strata. Accordingly, drainage of mining pressure relief gas is closely connected with the movement of key strata in the overlying strata which influences the expansion of gas channels and the flow of gas. Because of this, efficient drainage and control of pressure-relief gas can be achieved.

5. Conclusion

(1) As a result of breakage and fracture development in overlying strata, the region in which the diameter of passageways for cross-layer fracture is greater than 10^{-1} mm is defined as the developing area of the mining gas channel. Based on the state of flow of gas in this region, the development of the gas channel in overlying strata is longitudinally divided into three zones which are, from the bottom up: a gas turbulent channel zone, a gas transition circulation channel zone and a gas seepage channel zone.

(2) Based on the key strata discrimination theory of controlling the overlying strata, the current paper describes research into the expansion of the mining gas channel, which is controlled by the key strata, and demonstrates, using a calculation method, that the step-type expansion of the mining gas channel is dependent on the advance distance of the working face. In this study, the rule that the mining gas channel in the overlying strata expands with the advance of a mining working face, is also confirmed. Combining the physical and mechanical parameters of the overlying strata with the design parameters of the mining working face produces the space-time rule that the gas channel in the overlying strata expands with advance distance of the mining working face. This can be used to provide a theoretical guide for the location of engineering construction for pressure relief gas drainage and an estimate of the time limit of effective gas drainage.

(3) Based on geological conditions in the Xinjing Mine of Yangquan, in-situ testing is carried out to study the characteristics of mining gas channel expansion and pressure relief gas drainage in a remote mining protective layer. These tests confirm the evolution rule of mining gas channel development in the overlying strata of a working face and its influence on the nature of gas flow. This study also confirms, using inversion, that the step-type expansion of the mining gas channel corresponds with the advance distance of the working face, and verifies the accuracy and feasibility of the theoretical calculation method proposed in this study. This also provides theoretical support for the selection of the technology of pressure relief gas drainage and the design of the construction parameters.

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