Research on gas leakage mechanism and detection technology of coal mine gas drainage

Quanbin Ba\textsuperscript{1,2*}

\textsuperscript{1} National Key Laboratory of Gas Disaster Detection, Prevention and Emergency Control, Chongqing, 400037, China
\textsuperscript{2} China Coal Technology Engineering Group Chongqing Research Institute, Chongqing, 400037, China
*Corresponding author’s e-mail: quanbin.ba@foxmail.com

Abstract. Aiming at the low concentration of gas in the percolation borehole, the paper analyzes the mechanism of gas leakage in the sealing hole of the pumping hole based on the multi-physics coupling theory based on the distribution of the surrounding rock stress field of the mining borehole and the roadway. The drilling hole sealing detection device and the determination method are used to detect gas concentration at different depths in the borehole in the normal extraction state, and analyze the variation law of the gas drainage concentration along the hole depth distribution to achieve fast and accurate judgment of the leak position and sealing test of the pumping hole. The test proves that the method and the device can effectively detect the leaking position and sealing effect of the extraction drilling hole, and can provide a simple and rapid detection method and science for the improvement of the sealing process, the adjustment of the sealing depth and the fine management of the coal mine site.

1. Introduction
Coal seam gas drainage is one of the main technical measures to prevent coal mine gas disasters. It has been widely used in high gas mines, and has multiple meanings of safety, environmental protection and energy conservation\cite{1}. According to statistics\cite{2,3}, the concentration of gas drainage in coal seams is generally low. About 65\% of the mining face is less than 30\%, which is difficult to use effectively. As the depth of coal mining continues to increase, this problem is even more severe.

The existing field experience and theoretical calculation methods are still difficult to adapt to the coal seam roadway under different conditions. Simple, convenient and practical methods of investigation, as well as effective supervision and management methods. In view of this, this paper analyzes the leakage mechanism of the extraction drilling hole from the extraction hole and the surrounding rock stress field distribution of the coal mine gas drainage hole, and puts forward the sealing test of the drilling sealing section. The judgment method provides a scientific basis for adjusting the sealing parameters and improving the sealing process materials at the coal mine site to improve the extraction effect.

2. Leakage mechanism and type division of drainage holes

2.1. Mechanism of leakage of drainage holes

2.1.1. Drilling axial fracture gap distribution.
Roadway excavation destroys the stress balance state of the original coal and rock layers, so that the stress in the coal body is redistributed, inducing inevitable damage and plastic damage to the surrounding rock mass; when the concentrated stress value reaches the strength limit of the coal body, the part of the coal body first undergoes yield deformation, and the concentrated stress is transferred to the deep part of the coal body. The stress of the surrounding rock of the roadway is analyzed. As shown in Figure 1, there are four areas from the outside to the inside: the fracture zone, the plastic zone, the elastic zone and the original stress zone, in which the gas leakage of the sealing hole is affected.

2.1.2. Drilling radial crack leakage zone distribution.
Drilling radial fracture leakage belt distribution gas drainage drilling can be regarded as a miniature circular roadway, so it can be analyzed according to the mechanical model of the surrounding rock stress field of the roadway, also due to stress release, transfer and strong unloading load. Deformation, forming a certain range of pressure relief areas, the strength of the coal body is reduced, a large number of cracks are generated in the coal body, the permeability is improved, and the crushing zone, the plastic zone, the elastic zone and the original stress zone are sequentially formed along the radial direction of the borehole. The crack around the hole develops and is affected by the dynamic change of the mining. After the crack communicates, a leaking channel is gradually formed. The stress distribution around the borehole is shown in Figure 2.

2.1.3. Multi-stress field coupling.
During the drilling construction process, when the drilling hole is drilled into the crushing zone, the stress is lower than the original stress of the coal body, the crack communication is good, and the fracture of the drilling section is most developed; when drilling the hole into the plastic zone, around the drilling hole the plastic deformation zone is generated, in which the hole wall is prone to unstable deformation, and the radial fracture of the borehole penetrates with the fracture of the plastic zone; when the borehole is drilled into the elastic zone, the stress of the coal body gradually increases, does not reach the strength.
limit, and is in the stage of elastic deformation. Under the action of confining pressure, some of the original cracks in the coal body are compacted by extrusion, and some new radial fractures are generated.

2.2. Drilling and leaking type
According to the mechanism of leakage of the drilling hole\[^{9,10}\], according to the position of the air leakage space, the type of leakage of the drilling hole is divided into the following two types.

![Figure 3. Coal mine gas drainage drilling type](image)

**2.2.1. Coal seam geological structure or borehole.**
The geological structure of the coal seam is complex, and faults, holes, fissures, etc. are common. At the same time, the cross-arranged boreholes are collided with each other or the adjacent boreholes pass through the development fissures, which causes the deep borehole sections to leak through each other. At present, there is no good solution for deep borehole penetration and leakage. Only by detecting the geological structure in advance, optimizing the drilling design scheme, and improving the drilling construction accuracy and trajectory measurement.

**2.2.2. Drilling and sealing hole sealing leak.**
The sealing quality of the drilling and sealing section is poor, mainly affected by factors such as sealing technology, sealing material and sealing operation. The strength of the extraction pipe is not enough or the sealing of the joint and the sealing material is poor, resulting in damage to the extraction pipe or Air leaks at the connection. In terms of sealing technology, after the development of yellow mud, cement mortar, polyurethane, etc., the sealing effect has also been greatly improved. However, there is still a closed space and shrinkage phenomenon that cannot effectively block the suction pipe and the hole wall. Therefore, it is still necessary to continue to investigate the material and material sealing property of the sealing material.

Due to the unreasonable depth of the drilling and drilling hole, under the continuous action of high pumping and negative pressure, it is not enough to resist the effect of the negative pressure migration affected zone, and may eventually lead to air leakage. "Prevention of coal and gas outburst"\[^{11}\], gas drainage through the hole sealing hole section shall not be less than 5m, the bedding hole sealing section shall not be less than 8m. The geological conditions of each coal mine and the mechanical properties of coal and rock vary greatly. The existing empirical theory is still difficult to meet the needs of the site under different conditions.

3. Drilling gas leakage detecting device and method

**3.1. Detection principle and method of discrimination**
According to the above analysis of the air leakage position and the cause of the air leakage, it is known that under the condition of negative pressure pumping, the leakage position of the borehole and the influencing factors of the air leakage are very complicated. In the shorter area, the change of the negative pressure is usually not obvious\[^{12}\]. The amount of gas emission provided by the borehole is a relatively constant value per unit time. When the drilling hole leaks, under the action of suction negative pressure, the air that is poured into the gas drainage hole will cause the gas drainage concentration to be greatly
reduced, that is, the gas concentration in the borehole will be abruptly changed. Therefore, it is scientifically feasible to use the gas concentration difference to determine the gas leakage state between the two points, and then to analyze the cause of gas leakage and the gas leakage intensity. The position and judgment basis are shown in Table 1.

Table 1. Gas extraction drilling leak detection and discrimination method

| Serial number | Air leak        | Discrimination basis         | Leakage cause              |
|---------------|----------------|-------------------------------|----------------------------|
| 1             | Drainage pipe  | \(C_0 < C_1\)                  | Damaged pipe or interface leak |
| 2             | Sealing seal section | \(C_1 < C_2 < C_3\)         | Drilling and drilling hole sealing effect is poor |
| 3             | Sealing depth   | \(C_2 < C_3 < C_4\)          | Insufficient sealing depth |
| 4             | Deep coal seam | \(C_3 < C_4 < 100\%\)        | There may be leaks in the deep |

3.1.1. Detection device
The detecting device integrates a pressure sensing head, a methane concentration sensing head, a micro vacuum pump, a collecting and draining device, etc., and uses a micro vacuum pump to suck gas of different depths in the hole into the gas sample detecting chamber, and obtains and displays the gas concentration by the gas concentration sensor. Finally, it can quickly and accurately determine the parameters such as pumping negative pressure and methane concentration in different depths of coal seam gas drainage boreholes in the extraction state, so as to master the gas distribution in the pumping borehole.

3.1.2. Air intake unit.
The gas take-off component mainly comprises a gas take-up head, a gas take-up rod and a tail end three-way three parts. The front end of the air intake head is a hemispherical closed structure, which is convenient for the detection tube to penetrate into the hole. A large number of air intake holes are opened in the middle direction of the middle section to avoid the suction of cinder to block the detection pipeline; the gas extraction rod is a light stainless steel rod, adopting 1.5m. The root is fast-inserted at both ends, and a metal protective cover is arranged on the outer surface of the interface. When used, a certain number of gas-receiving rods are connected, and the gas is collected inside the drill hole to collect the gas; the three-way device is used for the pumping tube. The measuring rod and the sampling pipe network are connected to make the measurement in a normal state of extraction.

4. Field test and effect analysis

4.1. Coal mine overview and drilling conditions
A mine design well field has a production capacity of 1.2Mt/a. According to the coal seam outburst danger assessment results, the gas pressure is 0.6–2.0MPa, the coal seam gas content is 8.32–11.25m³/t, and the coal seam permeability coefficient is 0.029–0.594m²/(MPa·d), for coal and gas outburst mines.
The field test is carried out in a working lane of the mine. According to the amount of cuttings and the gas desorption of the cuttings, the range of confining stress concentration on both sides of the roadway is 6~10m. The test arrangement consisted of 8 sets of comparative drilling holes. The drilling conditions and sealing parameters were arranged as shown in Table 2. The comparison test was carried out by using polyurethane with cement mortar and bag sealer combined with inorganic sealing material sealing process. The slurry pressure is 1.5MPa, which can achieve the sealing effect of pressure grouting to verify the sealing effect of different sealing process materials; the sealing depth is set to 8m, 10m, 12m and 14m respectively, and the test sealing hole is reasonable sealing depth, testing parameters The arrangement is shown in Table 3.

Table 2. Drilling conditions and sealing parameter settings

| Serial number | Sealing process                  | Aperture /mm | Hole depth /m | Inclination /° | Sealing depth /m |
|---------------|---------------------------------|--------------|---------------|----------------|-----------------|
| 1             | Polyurethane + cement mortar    | 113          | 100           | 0              | 8               |
|               |                                  |              |               | +1             | 10              |
|               |                                  |              |               | +1             | 12              |
|               |                                  |              |               | +2             | 14              |
|               |                                  |              |               | +2             | 8               |
| 2             | Pocket sealer + inorganic material | 113         | 100           | 0              | 12              |
|               |                                  |              |               | +1             | 14              |

Table 3. Test hole leakage detection parameter arrangement

| Sealing depth /m | Detection position from the orifice distance /m | C₀ % | C₁ % | C₂ % | C₃ % | C₄ % |
|-----------------|-----------------------------------------------|------|------|------|------|------|
| 8               | 0.5, 7, 9, 11, 13, 15, 17, 25                 |      |      |      |      |      |
| 10              | 0.5, 7, 9, 11, 13, 15, 17, 25                 |      |      |      |      |      |
| 12              | 0.5, 7, 9, 11, 13, 15, 17, 25                 |      |      |      |      |      |
| 14              | 0.5, 7, 9, 11, 13, 15, 17, 25                 |      |      |      |      |      |

4.2. On-site inspection data and effect analysis

4.2.1. Field test data.

Table 4. Test hole leakage detection parameter arrangement

| Sealing process                  | Negative pressure /kPa | Negative pressure /kPa | Negative pressure /kPa | Negative pressure /kPa | Negative pressure /kPa |
|---------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Polyurethane + cement mortar    | 7/(19.5), 2/(18.7), 39/(20.4), 45/(18.3), 19/(20) | 7/(19.5), 16/(18.6), 40/(20.3), 45/(18.1), 21/(19.9) | 8/(19.1), 32/(18.2), 45/(18.1), 52/(18.5), 35/(19.5) | 24/(18.7), 77/(18.0), 59/(18.4), 74/(19.5), 74/(19.9) | 83/(18.5), 78/(17.6), 57/(18.1), 88/(19.2), 75/(18.8) |
| Pocket sealer + inorganic material | 32/(18.8), 39/(19.4), 69/(20.6) | 32/(18.6), 60/(19.4), 69/(20.5) | 56/(18.5), 65/(19.2), 72/(20.1) | 78/(18.2), 74/(19.0), 75/(19.9) | 80/(18.9), 75/(19.8), 85/(19.5) |

The test borehole is pumped with a negative pressure of about 20 kPa. Immediately after the completion of the plugging, the network is pumped. After driling for 15 days, the test is carried out. The test data are shown in Table 4. From the perspective of the negative pressure change of extraction, the variation
range is small. It is verified that the detection of the leak detection by the negative pressure detection is not obvious, but the normal extraction state is ensured in the borehole.

4.2.2. Analysis of leaks at the detection point.

When sealing polyurethane and cement mortar, C2~C3 and C3~C4 are leaking sections when the sealing depth is 8m; when sealing depth is 10m, C0~C1 and C1~C2 are leaking sections; sealing depth is 12m; when C1~C2 is a leaking section; when the sealing depth is 14m, there may be a leak point in the deep part of the borehole.

When the sealing hole depth is 8m, C1~C2 and C2~C3 are leaking sections; when sealing depth is 10m, C1~C2 and C2~C3 are leaking sections; When the sealing depth is 12m, the sealing effect is better; when the sealing depth is 14m, the sealing effect is better.

Therefore, when the sealing depth is 8-10m, the insufficient sealing depth is the main cause of air leakage; when the sealing depth is 12-14m, the sealing property of the sealing material is the main factor affecting the sealing performance of the drilling hole. At the same time, there is a possibility that the drilling hole is damaged and there is a leak point in the deep hole.

| Table 5. Discrimination of air leakage at the position of the measuring point in the borehole |
| Sealing process | Sealing depth/m | C0~C1/% | C1~C2/% | C2~C3/% | C3~C4/% | Air leak determination |
|-----------------|----------------|---------|---------|---------|---------|------------------------|
| Polyurethane + cement mortar | 8 | 0 | 1 | 16 | 59 | Sealing depth and deep hole |
| | 10 | 14 | 16 | 45 | 1 | The pump tube is leaking and the sealing depth is insufficient |
| | 12 | 1 | 40 | 4 | 4 | Sealing section |
| | 14 | 0 | 7 | 7 | -2 | There may be a leak point in the deep part of the seal |
| Pocket sealer + inorganic material | 8 | 2 | 14 | 39 | 5 | Sealing depth and deep hole |
| | 10 | 0 | 24 | 22 | 2 | Insufficient sealing depth |
| | 12 | 1 | 5 | 9 | 1 | Better sealing effect |
| | 14 | 0 | 3 | 6 | 7 | Better sealing effect |

4.2.3. Comparative test effect analysis.

From the difference of sealing process and materials, the sealing effect of bag sealer and inorganic sealing material is obviously better than that of polyurethane and cement mortar. The position of each corresponding measuring point in the sealing section is increased by 1.5~2.71 times, mainly due to polyurethane. The bonding strength with the coal body is low, and it is impossible to achieve high pressure grouting sealing, that is, the sealing material can not effectively block the crack around the drilling hole. Therefore, from the perspective of the drainage effect, the capsule sealing device should be popularized and applied. And the "two plugs and one injection" of the inorganic sealing material is pressed and sealed.

From the comparison of the sealing depth data, there are multiple gas extraction concentration abrupt points in the borehole depth range of 8~10m, that is, the gas leakage point; when the sealing depth is 12m, the ratio is increased when the sealing depth is 8m or 10m. 150%~471% and 87.5%~215%, the gas concentration inside the borehole shows a linear growth trend, which proves that the plugging depth needs to be larger than the crushing zone, the plastic zone and the elastic zone, reaching the original rock stress zone and effectively blocking. The cracks are penetrated around the borehole to minimize the leakage range; the sealing depth of 14m is 13% and 15% higher than the sealing depth of 12m, and the sealing depth is 12m, and the sealing depth is not large when the sealing depth is 14m, and the sealing is small. The material and sealing difficulty are greatly improved. Therefore, in terms of economic sealing, the sealing depth of the test site should be about 12m.
5. Conclusion
(1) The mechanism of the air leakage in the sealing hole of the extraction hole is analyzed. According to the principle of air leakage detection, the method of checking and judging the leakage of the drilling hole is proposed. By measuring the negative pressure and gas concentration at different depths in the pumping hole under normal extraction conditions, the gas concentration is analyzed. According to the variation law of the distribution of the hole depth, the gas distribution in the extraction hole is obtained, and the sealing quality and the leak position of the extraction hole are determined.

(2) According to the on-site comparison test and investigation, the test hole drilling depth range from 0 to 10m, and the reasonable sealing depth is about 12m. At the same time, the "two plugs and one note" pressure grouting effect is better, and it is recommended to strengthen the application. Through the application practice, the gas leakage detection method of the gas drainage hole can effectively judge the sealing effect of the sealing hole of the extraction drilling hole and detect the air leakage position, adjust the sealing parameter and improve the sealing method for the coal mine site, and improve the gas drainage.

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