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Original Research

Research and Application of Sealed coring Technology in In-situ Coal Seam of Directional Long-boreholein Coal mine

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A B S T R A C T

To accurately obtain the gas content of in-situ coal seams in coal mines, a sealed coring technology for in-situ coal seams in coal mines is proposed. Utilizing the pressure difference generated by high-pressure water at both ends of the piston, the piston is driven to cut off the positioning pin. This in turn drives the ball valve in the coring device to rotate, cut off and seal the in-situ coal core. Performance tests were conducted on the sealing pressure of the coring device by opening the water holes on the piston and using suspension pins of different materials. This verifies the working parameters of the piston opening amount and suspension pins made of different materials, providing basic data for subsequent industrial underground tests. Finally, during the industrial test underground, it was found that the gas content in the coal seam measured by closed sampling was 1.9-2.5 times higher than that of the coal seam sampled by the hole. This verifies the successful design of the closed sampling device.

Keywords: *Directional long-borehole; In-situ coal seam; Sealed coring; Pressure difference; Cutting mechanism.*

Introduction

Coalbed methane(CBM) content is an important technical parameter to characterize the characteristics of underground coal reservoirs, and is the main basis for the development and utilization of CBM resources and comprehensive gas control (Chen et al., 2017).The coal-bed gas resources are rich in China, with up to 29.8 trillion cubic meters (Tao et al., 2019).However, due to complex geological conditions as well as difficult exploration and development technology, the main method is the underground gas drainage drilling methods (Sang et al., 2024). CBM is usually stored in coal seams or rock fractures with the characteristics of flammability and explosiveness. During the construction of underground gas drainage drilling, if the samples and the gas content parameters of in-situ coal seam cannot be accurately obtained, it is difficult to formulate effective and reasonable gas control measures, posing a serious safety hazard to coal mine production (Van et al., 2020).

Coal seam borehole sampling and testing technology is an important means to obtain original geological information such as coal seam gas content. It is the most basic technical work for underground gas disaster control and comprehensive utilization of coalbed methane (Long et al., 2022; Karacan et al., 2021). The detection parameters of coal seam gas content mainly include gas content, desorption amount and residual amount (Li et al., 2020; Szlązak et al., 2021; Akdaş et al., 2023). The desorption amount and residual amount can be accurately measured, while the gas content can only be estimated based on the initial desorption law of the coal sample taken. The estimated value is related to sampling time, and coal sample exposure time. The longer the coal sample exposure time, the more inaccurate the estimated value will be (Zhao et al., 2023; Guo et al., 2023). Therefore, how to ensure the in-situ information of coal samples is closely related to the sampling method of coal samples. There are two methods to determine the gas content of coal seam: the orifice sampling method and the coal sample tube method. Due to the prolonged exposure time of the coal seam during the process of returning to the borehole, not all coal samples are immediately drilled from the borehole. Therefore, the coal sample data obtained through this method is far from the data of the on-site coal seam. However, the coal sample tube method also has some problems, such as long exposure time of samples, ands serious deterioration of coal

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samples due to grinding and heating. Therefore, the coal sample data obtained using the orifice sampling method and coal sample tube method have serious distortion problems, which cannot meet the accurate formulation and implementation of gas control measures. To obtain accurate coal samples of underground coal seams, many researches on adopting in-situ coal seam coal samples have been conducted.

To accurately obtain deep oil and gas resources, Guo et al. (2023a, b, 2024) and Xie et al. (2021) proposed a design scheme for a new in-situ pressure-preserved coring (IPP-Coring) tool. This scheme is used to complete performance tests and on-site industrial tests to obtain stable sealed samples. In response to the current situation of shallow sampling depth and low accuracy, Li et al. (2017) proposed a long-distance fixed-point pressure sealed coal seam gas content measurement sampling technology underground. It can improve the coal sample collection rate and sampling depth, and improve the accuracy of coal sample collection to a certain extent. With the development of the resource exploration and environmental science drilling, Yu et al. (2020) proposed an in-situ core drilling method to obtain fidelity rock samples from deep rocks. To avoid distortion in the evaluation of deep oil and gas reserves, Wu et al. (2023) studied a pressure intelligent control coring device and innovatively proposed the theory and method of deep intelligent temperature pressure coupling control. To obtain high-condition preserved core samples, Yang et al. (2023) proposed a development strategy for a high toughness and high barrier sealing film based on molecular structure design and filler synergistic enhancement. To solve the problem of low core recovery rate during drilling, Wang et al. (2022a) discussed the flow field characteristics of the closed device valve core under different working conditions.

In terms of coal mine soft rock coring, Zhao et al. (2023) developed the Pressure Maintaining Continuous Coring Technology (PHCCT) and equipment and achieved high coring quality. To improve the sampling rate of fragmented soft coal seams, Chu et al.(2022) studied the "mechanical+hydraulic" multi branch hole sampling drilling technology combined sampling technology with directional branch hole drilling technology. This provides a new method for sampling and gas parameter determination of fragmented soft coal seams in coal mines. To avoid the influence of cutting and friction of the drilling bit for coal core quality, Wang et al. (2022b) established a thermodynamic model of the coring drilling bit and coring tube during the coring process. They studied the main influencing factors during the coring process through numerical simulation. To accurately obtain deep coal cores in coal mines, Huang et al. (2023) developed a low disturbance pressure maintaining coring sampler for sampling tests and analysis of coalbed methane content. To determine the methane content in hard coal seams, Szlązak et al. (2021) studied the gas loss during the sampling process to estimate the consistency between the core and drill cuttings samples. To measure the gas content of coal samples, Hua et al. (2022) used different sampling methods to obtain in-situ coal seams, measured the gas content and compared and analyzed the data. To solve the problem of inaccurate estimation of coalbed methane loss, Chen et al. (2017) proposed a testing device for sealed coring of coal seam, and improved the CBM sealed coring drilling process. Based on the characteristics of conventional coring and closed coring, combined with underground directional drilling in coal mines, an in-situ coal seam closed sampling device for long directional drilling in coal seams is studied. Many performance tests and field tests are conducted to improve the in-situ coal sampling rate and sealing effect. The results can provide reliable in-situ coal seam data for gas detection in coal mines.

1. Design of coal seam closed core-taking device

1.1. Technical development ideas

Since the depth of directional drilling long hole in coal mines is deeper, generally more than 300m, the coal samples obtained by conventional coring drilling technology will be exposed to the air for a long time during coring and drilling. A large number of gas adsorbed in the coal seam will be rapidly desorbed and dissipated. As a result, the gas loss estimated by the method ("Coal Seam Gas Content Underground Direct Determination Method" or the power function method) is quite different from the actual loss. The coal seam gas content cannot be accurately measured. Therefore, according to the technical requirements for measuring coal mine gas content, an in-situ coal seam sealed sampling and testing device is developed. That is, when coring drilling, the coring drilling time and the contact time between coal samples and air are reduced as much as possible. After sampling drilling, the coal samples are quickly sealed in the core tube by using relevant mechanisms to avoid exposure to the air for escaping of gas. Then, the sealed coal sample is analyzed on site with special sampling. After recording the analytical data, the coal sample is loaded into the coal sample tank and sent to the laboratory for other data detection. Compared with conventional sampling techniques, the coal sample taken by this device can greatly reduce the exposure time of the coal sample in the air. It can preserve the original occurrence of the coal seam, greatly improve the accuracy of data testing such as the original coal seam gas content, and provide accurate coal seam data for coal mine gas control.

1. 2. Structural design and working principle of the in-situ sealed core-taking device

The in-situ sealed coring device is mainly composed of outer tube, piston, suspension pin, intermediate tube, rear inner joint, coring inner tube, rear outer joint and coring bit, as shown in Fig. 1. The device adopts a three-tube single-acting structure, wherein an outer tube is connected with a drill rod through a rear outer joint. The front end of the outer tube is provided with a coring bit that has the functions of power transmission and movement. The middle tube is a drive tube, which is connected with the rear inner joint through a suspension pin. Under the action of hydraulic pressure difference, the suspension pin can be cut off, and the piston pushes the drive tube to move forward. At the same time, the drive tube drives the gear fixedly connected with the ball valve to rotate 90 degrees through its own rack mechanism, to complete the cutting and sealing of the coal sample. The coring inner tube can accommodate and resolve the coal sample.

During coring drilling, the coring device is sent to the bottom of the hole. When it touches the coal wall, the coring device is slowly drilled with a small bit pressure and a small pump volume. When the coring is 3-5 m, the drilling is suspended, and the bit pressure is increased. The connecting pin between the outer bit and the inner bit for coring is cut off, and then the coring drilling is carried out. Under the action of the coal core, the inner bit and the coal core are pushed into the inner tube for coring. After the sampling is completed, the pump pressure is increased. The pressure difference between the two ends of the piston is also increased. The suspension pin between the middle tube and the rear inner joint is cut off. The middle tube moves rightward under the action of the piston, and drives the gear rack mechanism to act. In this way, the ball valve cuts off the coal core and seals the coal core in the coring inner tube, and the coal sample drilling is completed.

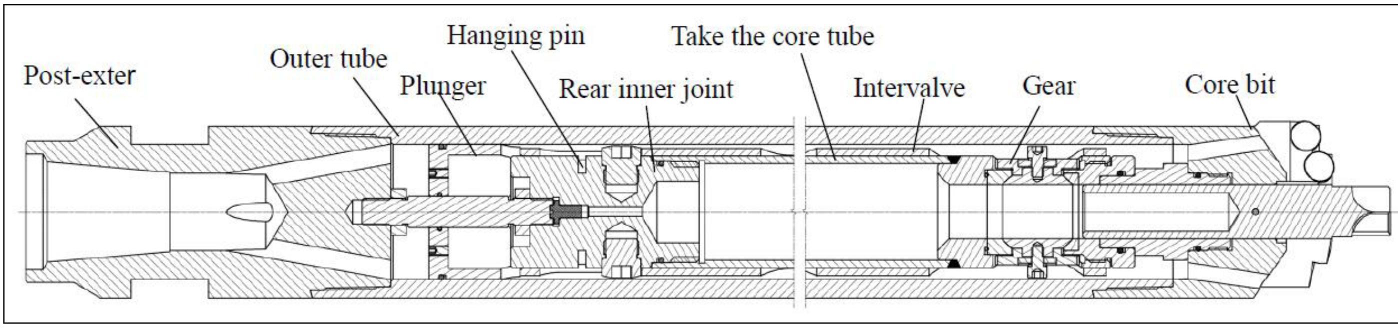


Figure 1. Structural design of the in-situ sealed core device

1.3. Calculation of the cutting force of the suspension pin

The drive pipe and the rear inner connector are fixed by the suspension pin (as shown in Fig. 2). As the pressure difference between the piston sides gradually increases, the allowable shear stress of the suspension pin is exceeded. According to the assembly structure, the shear force of the suspension pin under the differential pressure of both sides of the piston is as follows:

$$F = 2A \bullet \tau \quad (1)$$

where, F is the actual shear force of the piston on the suspension pin, N; A is the shear area of the suspension pin, m^2, as shown in Fig.2, and τ is the shear stress on the suspension pin, MPa.

To ensure that the piston thrust can cut the suspension pin, the actual shear force should be greater than the allowable shear stress of the material τ. That is, the actual shear force of the hanging pin in the upper type should be greater than the maximum shear stress that the material can withstand under the allowable shear stress state, namely:

$$F \geq 2A \bullet [\tau] \quad (2)$$

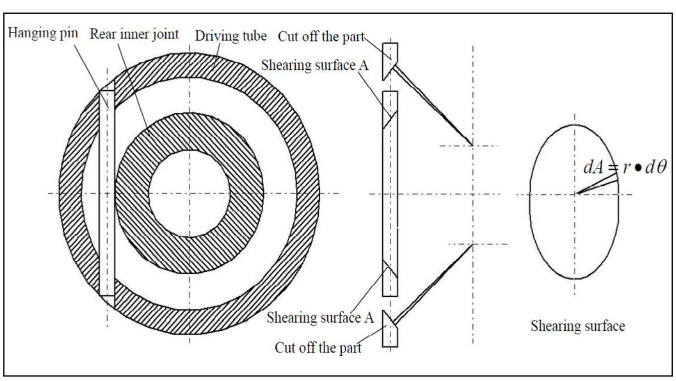


Figure 2. Assembly structure and force analysis of the hanging pin

1.4. Calculation of the pressure difference between both ends of the piston

According to the fluid dynamic knowledge, the flow rate and pressure difference characteristics at both ends of the piston are as follows (Ding, 2022):

$$Q \equiv K \bullet A_0 \bullet \Delta p^m \quad (3)$$

where, K is the coefficient of throttling, decided by the shape of the throttle orifice, and fluid properties. $K = d^2 / (32v \bullet L)$, where d and L are the diameter and length of the throttle orifice, respectively. v is the dynamic viscosity of the fluid; A_0 is the flow area of the throttle hole, mm^2; Δp is the pressure difference between the two ends of the piston, MPa.

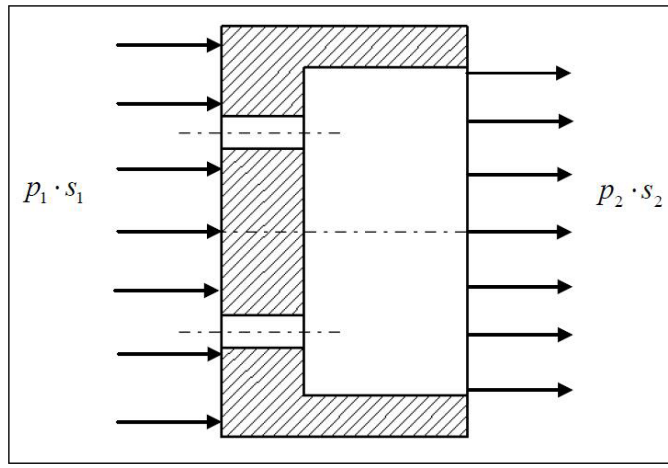


Figure 3. Flow and pressure difference characteristics on both sides of the piston

Through calculating the pressure difference and flow characteristics on both sides of the piston, the thrust force of the fluid on the piston can be calculated as $F = p_1 s_1 - p_2 s_2$ (s_1 and s_2 represent the area on both side of the piston, respectively). From the force analysis of the suspension pin, we have $F = F \geq 2A \bullet [\tau]$. Thus, the relationship between the flow rate and the shape and quantity of the piston throttle mouth can be obtained.

1.5. Calculation of the core cut force

When the pressure difference on the piston is large enough, the suspension pin is cut off and the high pressure water pushes the piston to the right. At the same time, the end surface on the right side of the piston acts on the left side of the drive pipe. The gear rack on the drive pipe pushes the gear fixed on the cut-off valve core to rotate. When the driving force is sufficient, the core is cut and sealed.

According to the engagement of the gear and the drive pipe, the tangential force and torque on the gear are as follows:

$$F_t = F' / 2 = p_1 s_1 - p_2 s_2 \quad (4)$$

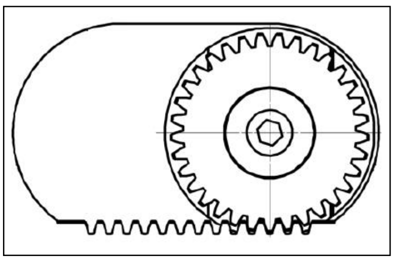
$$T_c = F_t \cdot \frac{d}{2} \quad (5)$$

where, F_t is the tangential force of the gear, which is equal to the thrust of the piston on the drive pipe. Due to the double teeth, the tangential force is half of the force on the driving pipe; T_c is the rotation torque of the gear, acting on the indexing circle; d is the diameter of the gear indexing circle, mm.

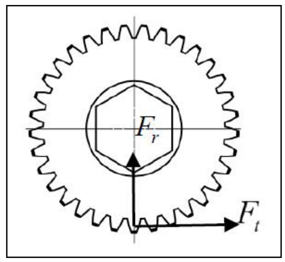
The gear is connected to the ball valve through a hexagonal connection, as shown in Fig. 4. Therefore, the shear torque of the ball valve subjected to the coal core should be equal to the rotating torque on the gear:

$$T_c = F_{shear} \cdot d_1 \tag{6}$$

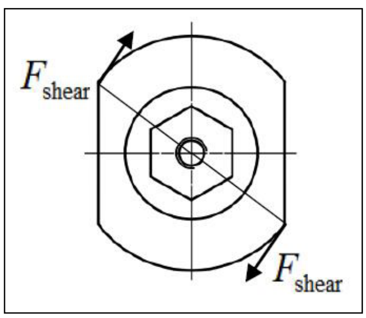
where, F_{shear} is the ball valve is subjected to a shear force derived from the coal core, N; d_1 is ball valve diameter, mm.



a) Figure of the gear and rack engagement



b) gear



c) ball valve

Figure 4. Force analysis of the gear and the ball valve

2. Testing of closed coring devices

2.1. Performance test

The device was tested on an FMC mud pump to test the closing pressure of the closed core device ball valve and the number of upward pressure holes on the piston. The rated working pressure of the FMC mud pump is 10.3 MPa, and the flow rate is 80-284 L/min. The schematic diagram of the test connection and the pressure regulation performance test are shown in Fig. 5 and Fig. 6, respectively.

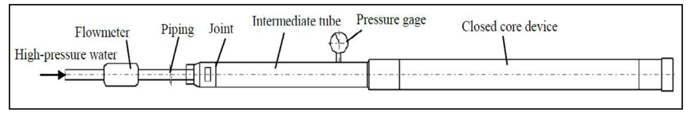


Figure 5. Schematic diagram of performance test connection for closed core device

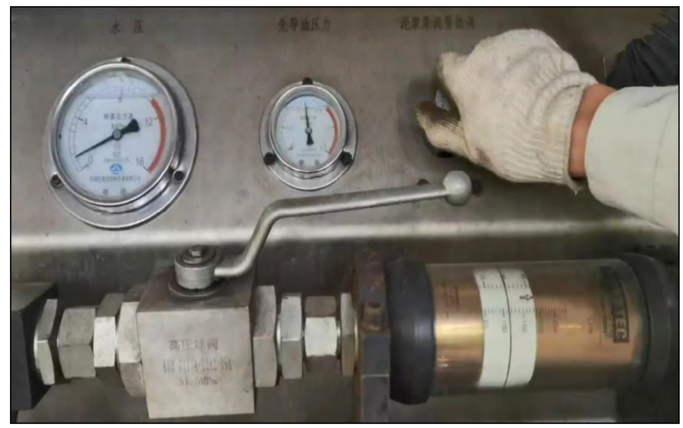


Figure 6. Pressure performance test diagram

During the test, 6061 aluminum alloy rod and 35 steel rod were used as cutting pins. The coal core was replaced by carrot, cucumber and cement block respectively. The pressure regulating holes on the piston were tested according to the number of 2, 3 and 4 openings respectively. During the test, the pump volume is slowly adjusted to slowly increase the pump pressure. When the pressure gauge has a large swing arc and the suspension pin shear sound is heard in the closed corer, the test is stopped. The test of carrot and cucumber as coal core is shown in Table 1, and the situation after the “coal core” is cut off is shown in Fig.7.

Table 1 Performance test of the sealed core device

Serial number	Number of the piston regulator openings	Pump pressure /MPa	Pump volume /L/min	Material of the suspension pin	Whether the hanging pin and the “coal core” are cut off	Conclosed condition of the ball valve
1	2	1.5	100	6061	yes	obturation
		4	150	35	yes	obturation
2	3	2.5	150	6061	yes	obturation
		6.0	200	35	yes	obturation
3	4	4	200	6061	yes	obturation
		8.5	280	35	yes	obturation

Note: In the cement block test, due to its high hardness, the pump volume and pump pressure increased appropriately, in which the pump pressure increased by 1MPa compared with the carrot and cucumber. However, due to the damage of the front and rear gaskets after the shear test, it was stopped only after two tests.

Figure 7. The cutting-off "coal core"

From the test, as the regulating holes increase, the pump pressure and pump volume required for the suspension pin and the "coal core" are gradually increased, and the ball valve can be well closed and sealed. When the suspension pin is made of 6061 aluminum alloy, the pump pressure and pump volume when it is cut off are only about 40% of the 35 steel. It shows that the sealed core sampling is feasible, and it will be sent to the underground for industrial test.

2.2. Industrial testing

1) The general situation of the test mine

The designed annual production capacity of Zhaogu No. 2 Mine of Henan Coking Coal Group is 1.8 million tons; the construction period is 45.3 months, and the service life is 55.5 years. The mine geological reserves are 339 million tons, and the designed recoverable reserves are 140 million tons.

The main coal seam is No. 1 coal seam of Permian, whose inclination Angle is generally 2°-6°.Its average thickness is 6.16m, belonging to a nearly horizontal and stable thick coal seam. The coal quality is high quality anthracite with medium ash, low sulfur, high calorific value, high ash melting point and high yield of lump coal, and the calorific value can reach 30.03 MJ/ kg. The construction of the mine was officially started on January 9, 2007, and completed and put into operation on April 23, 2011. After full operation, the annual sales revenue is 1.6 billion yuan, and the profit and tax are 600 million yuan.

2) Main test equipment

In this test, the deep hole fixed point sealing core device is used to close the coal seam of different depths of underground coal seam, and the gas content is measured. The closed core drilling equipment is ZYD6000-type directional drill and NB-300 mud pump of Xi'an Research Institute of China Coal Science and Industry Group. The drill pipe adopts Φ73 groove spiral drill rod of Xi'an Research Institute.

3) Analysis of the test results

The gas content of coal samples is determined according to GB/T23250-2009 "Underground Direct Determination Method of Gas Content in Coal Mines". A total of 9 test holes in the test were carried out, and coal samples were connected to the holes using a coal sample tank for comparative measurement of the same gas parameters. The test results are shown in Table 2.

Table 2 Comparison of CBM gas content for different core-extraction methods

Hole number	Sampling method	Sampling depth/m	Shear pressure of Cut-off pin(ball valve closing pressure) /MPa	Mud pump flow/L/min	The CBM gas content/(m^3/t)		Hanging pin material
					The amount of the hole	obturation	
1#	Closed core	80	6	190	2.33	5.85	35
2#	Closed core	130	6	190	2.85	6.23	35
3#	Closed core	180	6.2	200	3.04	6.30	35
4#	Closed core	230	6.2	200	3.15	6.50	35
5#	Closed core	280	6.4	220	3.42	6.80	35
6#	Closed core	330	6.5	220	3.78	7.35	35
7#	Closed core	380	6.5	230	3.75	7.45	35
8#	Closed core	430	6.8	230	3.93	7.86	35
9#	Closed core	480	7	240	4.20	8.01	35

According to Table 2, at the same depth, the CBM content measured by the sealed core sampling method is 1.9-2.5 times that of the CBM content measured by coal sampling of orifice. It shows that the closed core device can meet the sealed sampling of in situ coal seam, and effectively avoiding the escape of sampling gas from coal connecting orifice. The main reason for the low CBM content measured by coal seam sampling of orifice is that the coal samples are already exposed to the air when the coal seam returns to the orifice from the bottom of the hole. However, the sealed coring is only exposed to air for a short time, and the CBM escapes less, which can measure the true content of in-situ coal seam gas more accurately.

3. Conclusion

From the experimental process of the closed core device, it can be concluded that:

1) The developed "three tube single action" sealed coring device can effectively drill coal samples from the original coal seams of the mine. This provides an effective guarantee for coal mines to obtain data on the gas content of the in-situ coal seams.

2) The developed pressure differential piston sampling structure can improve the utilization rate of mud pump pressure and effectively increased the success rate of in-situ coal core extraction in underground coal seams.

3) A 20 day industrial underground test was conducted using a sealed coring device at Zhaogu No. 2 Mine of Henan Coking Coal Group. The test results showed that the gas content of coal samples obtained by the sealed coring method was increased by 90% to 150% compared to the gas content obtained by coal sampling of orifice.

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