WEP Warwick Evans Publishing

International Journal of Mechanical and Electrical Engineering

ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online)
Volume 8, Number 8, Year 2026
DOI: https://doi.org/10.62051/ijmee.v8n8.03

Development and Application of a Pressure-Controlled Exhaust and Drainage Device for Anti-Jet Drilling in Cross-Layer Boreholes

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ABSTRACT

To address the requirements of positive-pressure gas extraction and gas-liquid-solid three-phase separation during anti-jet drilling, a pressure-controlled exhaust and drainage device integrated with anti-jet drilling tools was developed. The device uses a safety valve as the core component for pressure-controlled exhaust and a mechanical automatic drainage system based on a lightweight float to achieve water drainage and slag discharge. Based on pressure vessel design theory, the main tank adopts a cylindrical shell with a diameter of 300 mm, a height of 400 mm, and a volume of 28.26 L, satisfying the requirement of less than 30 L volume to be exempt from special equipment supervision. The tank has a wall thickness of 6 mm and is made of 304 stainless steel. Gas-liquid two-phase flow simulation shows that stable gas-liquid stratification can form inside the tank. Under an internal pressure of 1 MPa, the maximum equivalent stress is 143.45 MPa, which is below the allowable stress of the material, indicating reliable structural strength. The calculation formula for drainage time was derived, and drainage performance can be controlled by adjusting the drainage liquid level height and the drainage hole area. Industrial tests were conducted in the 3907 middle bottom extraction roadway of Zhongmacun Mine. Among 24 cross-layer boreholes, the 12 boreholes using the developed drilling tools had an orifice gas concentration of 0.04%–0.12% with no jetting incidents, while the 12 boreholes using conventional drilling tools had a gas concentration of 0.08%–0.33% with 5 jetting incidents. The results show that the developed device has a reasonable structure and reliable pressure-bearing capacity, and can significantly reduce the risk of borehole jetting and improve extraction safety.

KEYWORDS

Anti-jet Drilling; Positive-pressure Extraction; Pressure-controlled Exhaust and Drainage Device; Gas-liquid Two-phase Flow; Numerical Simulation.

1. INTRODUCTION

Gas is the main disaster factor restricting safe and efficient coal mining. During drilling, coal seam gas continuously desorbs and escapes, causing gas pressure accumulation in the borehole. If not discharged timely and smoothly, it can easily induce borehole jetting dynamic phenomena, leading to excessive gas concentration at the working face and threatening underground safety production [1]. Therefore, drilling equipment and its supporting extraction devices must simultaneously achieve efficient gas discharge and effective cleaning of borehole media.

Traditional gas extraction mainly relies on negative-pressure suction at the borehole orifice, where a suction pump creates negative pressure to passively extract gas [2]. This process has obvious drawbacks: roadway air, borehole water, and coal dust are easily mixed in during extraction, resulting

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in low gas concentration and impure composition, reducing the value of resource utilization. It also easily causes slag and water accumulation in pipelines, obstructing ventilation [3]. Meanwhile, negative pressure suppresses the discharge of coal-water mixtures from the borehole, easily leading to coal slag accumulation and blockage of the slag discharge channel, which causes faults such as borehole blockage and drill sticking.

Anti-jet drilling is a new drilling technology whose core technical requirement is positive-pressure gas extraction, meaning that the original coal seam pressure is used to create a positive-pressure exhaust environment for active and continuous gas discharge, reducing the mechanism of gas outburst risk [4]. Therefore, developing a dedicated pressure-controlled exhaust and drainage device matching the anti-jet drilling tools to achieve effective separation of gas, water, and coal slag, while improving extracted gas purity, has important engineering value [5].

Taking the anti-jet drilling process as the background, this paper completes the structural design, numerical simulation, and optimization of the pressure-controlled exhaust and drainage device, and verifies the feasibility of the scheme through prototype pressure-bearing tests.

2. ENGINEERING OVERVIEW

2.1. Cooperation Mode and Principle Between the Pressure-Controlled Exhaust and Drainage Device and Anti-Jet Drilling Tools

The self-developed pressure-controlled exhaust and drainage device can form an integrated operation system with anti-jet drilling tools. High-pressure gas in the borehole is guided by the anti-jet device into the annular channel of the drill rod, sequentially passes through the drill rod and drill tail water swivel, and finally converges into this device [6]. Under positive-pressure control, the device connects high-purity gas to the negative-pressure extraction pipeline and discharges the separated water and coal slag, achieving safe and efficient gas discharge and improved extraction purity.

To achieve the anti-jet function, the internal space of the drill rod is divided into an independent central channel and an annular channel. The central channel is used for gas discharge, while water is conveyed through the annular channel. Using the central channel for gas discharge can avoid the risk of gas discharge failure caused by blockage of the borehole annular gap, ensuring stable and unobstructed gas discharge. The annular channel for water conveyance can continuously flush the coal body and discharge coal-rock particles from the borehole, and also provides cooling for the drill bit and drill rod body, improving the underground working conditions of the drilling tools.

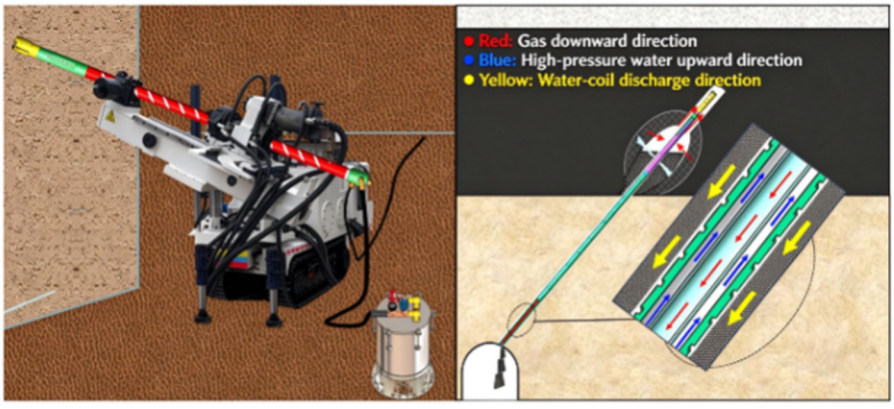

Fig 1. Integrated anti-jet system and anti-jet principle diagram

2.2. Design Requirements and Key Design Points of the Pressure-Controlled Exhaust and Drainage Device

Considering the characteristics of the anti-jet drilling process and supporting drilling tools, the device needs to satisfy two functional requirements.

(1) Adjustable positive-pressure exhaust: Different mines have different gas occurrence pressures and emission volumes. The device must be able to adjust the opening of the pressure control valve to maintain a set positive-pressure range internally. Exhaust opens only when the pressure reaches a preset value, achieving directional and controllable gas discharge, and connects to the downstream negative-pressure extraction pipeline to solve the working condition matching problem between positive-pressure exhaust and negative-pressure gathering and transportation.

(2) Integrated drainage and slag discharge: The incoming medium is mainly high-pressure gas, accompanied by a small amount of water and coal slag. The device must simultaneously achieve gas-liquid-solid three-phase separation, preventing water vapor and coal slag from entering the extraction pipeline and avoiding pipeline blockage and equipment corrosion.

To ensure the rationality of the overall design and working condition adaptability, it is necessary to comprehensively consider the device's dimensional constraints, the complex underground coal mine working environment, and the matching degree between structure and working principle, and carry out refined selection and verification of the key design points of the device's core structure.

(1) The pressure-controlled exhaust scheme must be highly adaptable, structurally simple, reliable in performance, and not occupy excessive space.

(2) The drainage scheme adopts a mechanical automatic drainage form, which can meet underground explosion-proof operation requirements by relying solely on pure mechanical structures for automatic drainage, while also saving labor.

3. MAIN TANK SIZE SIMULATION AND STRENGTH VERIFICATION

3.1. Main Tank Size Simulation

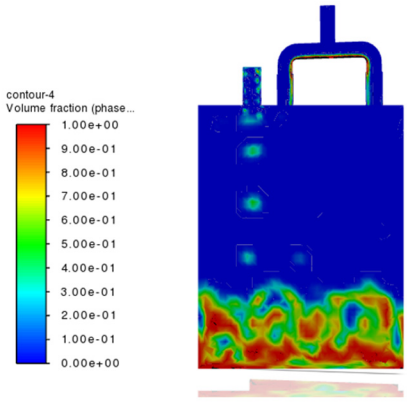

Fig 2. Simulation contour of internal flow field in the main tank

According to national special equipment safety supervision standards for pressure vessels, equipment with a maximum working pressure of no less than 0.1 MPa and a volume of no less than 30 L is subject to supervision. The main tank of this device bears gas impact loads, and the internal pressure can exceed 0.1 MPa under certain working conditions. To exempt the device from special equipment supervision, the design volume must be less than 30 L. Under the volume constraint, it is necessary to maximize the effective volume and reasonably match parameters such as diameter and height.

Considering the pressure vessel design scheme, volume constraints, and machining difficulty, a preliminary size scheme was developed using a cylindrical shell as the main tank. The tank has a diameter of 300 mm, a height of 400 mm, and a volume of 28.26 L. A three-dimensional model was established, meshed using Fluent Meshing with adaptive tetrahedral grids and local refinement of key areas such as the inlet and pipelines, and simulated with boundary conditions matching actual working conditions. The results are shown in Fig. 2. The model can form stable gas-liquid stratification at the bottom of the tank, verifying that this tank size can ensure stable internal flow field during actual operation and guarantee the airtightness of the device [7].

3.2. Main Tank Strength Verification

The main tank wall thickness is selected as 6 mm, and 304 stainless steel is used as the material for strength verification. This material has excellent corrosion resistance, high-temperature resistance, and machinability. During normal operation, the tank bears an internal pressure not exceeding 0.5 MPa. To reserve a safety margin, an internal pressure load of 1 MPa was applied to the inner wall for strength simulation. The simulation results are shown in Fig. 3. Most areas of the tank have low stress levels, with sidewall stress generally in the range of 12.145–36.019 MPa, and stress distribution is uniform along the cylinder body. The maximum equivalent stress is 143.45 MPa, concentrated at the center of the bottom head and the connection between the lower end cover and the cylinder body. Referring to the typical 0.2% yield strength (Rp0.2) of ASTM A240 annealed 304 stainless steel of approximately 290 MPa, the allowable stress is greater than the maximum equivalent stress of the tank. This indicates that with a wall thickness of 6 mm, the main tank has sufficient structural strength and will not undergo plastic deformation or damage.

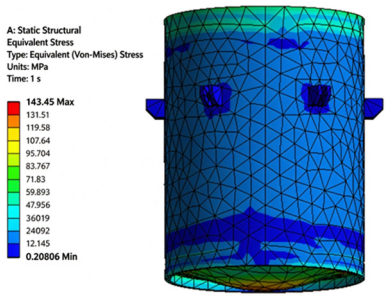

Fig 3. Simulation contour of equivalent stress in the main tank

4. ANALYSIS AND CALCULATION OF THE DRAINAGE SCHEME

4.1. Drainage Scheme Analysis

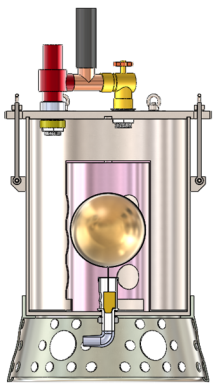

Fig 4. Component diagram of the pressure-controlled exhaust and drainage device

The drainage scheme is designed as shown in Fig. 4, with a lightweight float as the core of the automatic drainage scheme. The split combined structure of a lightweight float, connecting rope, and independent sealing plug has adaptive adjustment capability and stronger posture adaptability. It can effectively avoid drainage jamming caused by equipment installation tilt or working condition disturbances, greatly improving the operation stability and reliability of the device under complex underground working conditions.

4.2. Drainage Rate Calculation

Drainage rate is a key indicator for evaluating drainage performance. When the buoyancy of the float reaches a threshold, it lifts and the drainage port opens for water discharge. During drainage, the internal tank pressure decreases, and the pressure on the sealing plug decreases. As the water level drops, the buoyancy of the float also decreases synchronously, but the decay rate of buoyancy is lower than the decay rate of sealing force caused by pressure reduction. The time difference of dynamic equilibrium between the two constitutes the effective drainage period, during which the drainage volume should be maximized. The drainage rate per unit time determines the drainage volume, and the drainage rate is calculated accordingly to provide a basis for drainage performance evaluation. The drainage time calculation formula is:

$$t = \frac{2A\sqrt{H}}{C_d A_l \sqrt{2g}}$$

where C_d is the discharge coefficient, taken as 0.65; A is the cross-sectional area of the main tank, in m²; A_l is the drainage hole area, in m²; H is the drainage liquid level height, in m; g is the gravitational acceleration, taken as 9.8 m/s².

It can be seen from the formula that to ensure a reasonable drainage time, the drainage liquid level height and the drainage hole area can be adjusted.

5. INDUSTRIAL FIELD TEST

To verify the actual effectiveness of the pressure-controlled exhaust and drainage device and anti-jet drilling tools for high outburst coal seams, industrial tests were conducted in the 3907 middle bottom extraction roadway of Zhongmacun Mine. A total of 24 cross-layer boreholes were completed. Among them, 12 boreholes in Group 1 used the drilling tools developed in this paper, while 12 boreholes in Group 2 used conventional drilling tools. Table 1 records the orifice gas concentration and jetting phenomena of the 24 boreholes.

Table 1. Orifice gas concentration and jetting phenomena of the two groups of boreholes

Borehole No. (Group 1)	Orifice Gas Concentration	Jetting Occurred	Borehole No. (Group 2)	Orifice Gas Concentration	Jetting Occurred
1-1	0.08%	No	2-1	0.1%	No
1-2	0.09%	No	2-2	0.24%	Yes
1-3	0.1%	No	2-3	0.11%	No
1-4	0.05%	No	2-4	0.33%	Yes
1-5	0.07%	No	2-5	0.22%	Yes
1-6	0.12%	No	2-6	0.08%	No
1-7	0.06%	No	2-7	0.12%	No
1-8	0.06%	No	2-8	0.28%	Yes
1-9	0.08%	No	2-9	0.18%	No
1-10	0.11%	No	2-10	0.13%	No
1-11	0.07%	No	2-11	0.25%	Yes
1-12	0.04%	No	2-12	0.09%	No

6. CONCLUSION

Aiming at the process requirements of positive-pressure extraction in anti-jet drilling, this paper completed the structural design, numerical simulation, and field industrial verification of the pressure-controlled exhaust and drainage device. The main conclusions are as follows:

(1) The pressure-controlled exhaust and drainage device and anti-jet drilling tools form an integrated operation system, adopting a dual-channel structure with central channel for exhaust and annular channel for water supply. The device uses a safety valve as the core for pressure-controlled exhaust and a mechanical automatic drainage system based on a lightweight float, adapting to underground high-gas, high-dust explosion-proof working conditions, and achieving gas-liquid-solid three-phase separation and high-purity gas discharge.

(2) Based on pressure vessel design theory, the main tank adopts a cylindrical shell (diameter 300 mm, height 400 mm, volume 28.26 L) with uniform stress and no stress concentration, and satisfies the requirement of less than 30 L volume to be exempt from special equipment supervision.

(3) Gas-liquid two-phase flow simulation shows that stable gas-liquid stratification can form inside the tank with this size, and the internal flow field is stable, ensuring the airtightness of the device. Under 1 MPa internal pressure verification, the maximum equivalent stress is 143.45 MPa, which is below the allowable stress of 304 stainless steel, indicating safe and reliable structural strength.

(4) The drainage scheme adopts a float-type split mechanical automatic drainage design. The drainage time calculation formula was derived, and drainage performance can be controlled by adjusting the drainage liquid level height and the drainage hole area.

(5) Industrial tests in the 3907 middle bottom extraction roadway of Zhongmacun Mine show that none of the 12 boreholes using the developed drilling tools experienced jetting, with an orifice gas concentration of 0.04%–0.12%, while 5 out of the 12 boreholes using conventional tools experienced jetting, with a gas concentration of 0.08%–0.33%, verifying the effectiveness of the device in reducing jetting risk and improving extraction safety.

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