The experimental study on the coal rock breaking efficiency of the self-rotating multi-orifice nozzle applied in URRS technique

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Abstract. China has abundant coalbed methane (CBM) reserves, but the production of single well is rather low. The Ultra-short Radius Radial System (URRS) technique can drill multiple radial branch holes with hydraulic jetting to effectuvely improve the production of single well. The high-pressure jet nozzle plays an important role in URRS technique and the structure of nozzle directly affects the efficiency of radial drilling. This paper adopts the experimental study on breaking coal rock efficiency of the self-rotating multi-orifice nozzle with different structures. The uniaxial compressive strength, tensile strength and shear strength of experimental rock samples were tested and calculated. Using natural coal and briquette rock, number of experiments under submerged conditions were carried out. The effects of nozzle pressure, jetting distance, jetting time and jetting direction on rock breaking effect were studied. The experimental results show that natural coal rock has strong anisotropy and demonstrate the coal rock breaking efficiency of the self-rotating multi-orifice nozzle. The key findings are expected to provide theoretical and technical support for development of CBM reserves by using the URRS technique.

1. Introduction
China has abundant CBM resources, and the low rank coalbed methane resources account for about one-third of the total resources (Wang et al., 2019). However, caused by its low permeability, the production of single well by conventional development method is relatively low (Yang et al., 2019; Ren et al., 2014). The low average single well production has become main bottleneck in the development of China's coalbed methane industry, which has seriously affected the economic benefits of coalbed methane development (Zhu et al., 2019). In the 1980s, the Ultra-short Radius Radial System (URRS) technique was first proposed and developed (Dickinson et al., 1989). URRS can drill multiple radial branches with hydraulic jetting to effectuvely improve the production of single well (Marbun et al., 2011). High pressure jet nozzle is an important device for rock breaking in URRS technology (Cinelli et al., 2013). The nozzle structure will directly affect the rock breaking efficiency of URRS drilling. The multi hole high pressure jet nozzle is mainly used in URRS technique (Bin et al., 2016). The multi hole high pressure nozzle can form multiple jets through its own holes but it is difficult to ensure easy drilling in stratum with strong anisotropy. In this paper, the rock breaking effect of self-rotating multi-orifice nozzle in coal rock was studied by experimental method. The uniaxial compressive strength, tensile strength and shear strength of experimental rock samples were tested and
calculated. Using natural coal and briquette rock, number of experiments under submerged conditions were carried out. The effects of nozzle pressure, jetting distance, jetting time and jetting direction on rock breaking effect were studied. The results of this paper demonstrate the coal rock breaking efficiency of the self-rotating multi-orifice nozzle, providing theoretical and technical support for the development of CBM reserves by using the URRS technique.

2. Structure Design of self-rotating multi-orifice nozzle

The self-rotating multi-orifice nozzle consists of nozzle head, rotating shaft, cylindrical cavity, outlet housing and inlet housing, as shown in Figure 1. High pressure fluid enters the nozzle body from high pressure pipeline through inlet housing; Part of high pressure fluid flows through cylindrical cavity from the middle of the rotating shaft to nozzle head; By draining a small amount of high-pressure fluid into the narrow gap between the rotating shaft and the outlet housing, a "fluid bearing" support can be provided for the rotating shaft, which not only reduces the friction between the rotating shaft and the outlet housing, but also realizes the high pressure fluid crevice seal.

![Figure 1. Structure of self-rotating multi-orifice nozzle](image)

This paper focuses on the structure design of nozzle head. The diameter and number of nozzle holes affect the velocity of jetting. On the other hand, the angle and position of jetting holes mainly affect the rock breaking range of the nozzle.

2.1. The diameter and number of the nozzle holes design

By calculating the velocity of jet flow to the rock surface, the influence of nozzle diameter and number on jet velocity is studied. In the process of calculation, the experimental fluid is considered as pure water and Newtonian fluid. The velocity and density are expressed as the continuous and differentiable function of space coordinates and placing time. The jet velocity at the nozzle hole can be calculated by using the continuity equation as shown in formula (1).

$$\frac{dP}{dt} + \rho \text{div} u = 0 \tag{1}$$

There will be velocity loss of jet fluid from nozzle head holes to rock surface. For the axial velocity of submerged jet section, the empirical formula of submerged jet velocity attenuation law obtained by Prandel mixing length theory is used to calculate. The ratio of jet axial velocity $u$ to core velocity $u_m$ has a certain relationship with dimensionless radial distance, as shown in formula (2).

$$\frac{u}{u_m} = (1 - \eta^{1.5})^2 \tag{2}$$

Where: $u=$jet velocity, m/s; $u_m=$axial velocity of jet, m/s; $\eta=$dimensionless radial distance ($\eta = y/R$); $y=$radial distance, m; $R=$jet radius, m.

For any section of turbulent jet, the momentum conservation passing through each section in unit time is equal to that at the nozzle outlet, so there are formula (3):
Where, \( \rho \) = fluid density, kg/m\(^3\); \( A \) = sectional area, m\(^2\); \( u_m \) = jet velocity, m/s; \( u_0 \) = nozzle outlet jet velocity, m/s; \( R_o \) = nozzle diameter, m.

According to formulas (2) and (3), the attenuation law of jet axial velocity is obtained:

\[
\frac{u_m}{u_0} = \begin{cases}
1, & s \leq s_0 \\
\frac{10.96R_o}{4R_o + s}, & s > s_0
\end{cases}
\]

Where: \( u_m \) = jet velocity, m/s; \( u_0 \) = nozzle outlet jet velocity, m/s; \( s \) = axial distance of jet, m; \( R_o \) = nozzle hole diameter, m; \( s_o \) = core segment length \( s_o = 1.74h_o = 6.96R_o \).

### 2.2. The angle of nozzle holes design

As shown in Figure 2, the rock breaking holes on nozzle head can be divided into three types (central hole, rock breaking hole and enlargement hole) according to their functions. Central holes are located on the central axis of the nozzle with a certain inclination angle to deepen the rock breaking depth. The inclination angle of rock breaking holes is tangent to the concentric circle of the nozzle, which provides power for the rotating of nozzle while breaking rock. Enlargement holes assist to break rock and increase the area of rock breaking. Through the pilot test applied in red sandstone, it is found that the three types of rock breaking holes have different rock breaking areas. The red sandstone rock breaking area can be divided into four areas: A - jet unbroken area; B - breaking zone of central hole; C – rock breaking zone; D - enlargement rock breaking zone.

![Figure 2. Structure of self-rotating multi-orifice nozzle](image)

### Table 1. The design of nozzle hole

| No. | Nozzle number | Hole inclination /° | Hole distance/mm |
|-----|---------------|---------------------|------------------|
| 1   | 8-2           | 8                   | 2                |
| 2   | 8-3           | 8                   | 3                |
| 3   | 10-2          | 10                  | 2                |
| 4   | 10-2.5        | 10                  | 2.5              |
| 5   | 10-3          | 10                  | 3                |

The central hole angle of nozzle is mainly adjusted to eliminate the uncracked area of jet, ensuring efficient rock breaking and easy drilling. The rock breaking and enlargement hole angles are adjusted...
to connect the areas B, C and D. Five types of self-rotating multi-orifice nozzles with different structures are designed by changing angle of jetting hole (8°, 10°) and jetting hole distance (2mm, 2.5mm, 3mm). The parameter design is shown in Table 1.

3. Mechanical properties of experimental rock samples

30 pieces φ100mm × 100 mm briquette rock samples and 8 pieces natural coal samples wrapped with cement were prepared. Briquette rock samples were used to study the rock breaking effect under different nozzle pressure and jetting distance. Natural coal rock samples were used to study the rock breaking effect under different jetting angles to bedding. The natural coal samples used in experiment were all collected from a coal mine in Qinghebei District, Fuxin City, Liaoning Province. The same batch of coal rocks had similar lithology and the size met the experimental requirements. The cutting method of natural rock sample is shown in Figure 3. The manufacturing process is shown in Figure 4.

![Figure 3. Schematic diagram of natural coal rock sample](image-url)

In the laboratory of rock mechanics of China University of Petroleum (Beijing), natural rock samples with different bedding directions and briquette rock samples were coring. Three groups of 15 uniaxial compressive tests and three groups of 9 tensile strength tests were carried out. The average values of results are summarized in Table 2.

The shear strength of rock can be calculated by 3-axis test. The calculation method is to test more than three groups of 3-axis compressive strength under different confining pressures for the same rock sample, with uniaxial compressive strength (which can be regarded as 0 confining pressure), four groups of Mohr's stress circle can be drawn. The angle of the x-axis is the internal friction angle φ, the intercept on the y-axis represents the cohesive force C. Mohr's stress circles of coal rock samples in vertical to bedding/parallel to bedding and briquette rock samples are drawn in this study. Mohr's stress circles of coal rock samples in vertical to bedding are shown in Figure 5.
Table 2. The rock mechanics of experimental rock samples

| Types of rock samples | Uniaxial compressive strength (MPa) | Tensile strength (MPa) | Shear strength (MPa) | Internal friction angle φ(°) | Cohesive force C(MPa) |
|-----------------------|-------------------------------------|------------------------|----------------------|-----------------------------|----------------------|
| Briquette coal        | 15.610                              | 1.03                   | 6.874                | 35.375                      | 4.635                |
| Natural coal sample   |                                     |                        |                      |                             |                      |
| Parallel bedding      | 10.914                              | 0.83                   | 4.238                | 31.790                      | 3.324                |
| Vertical bedding      | 30.802                              | 1.49                   | 11.504               | 41.672                      | 7.285                |

Figure 5. Mohr's stress circles of coal rock samples in vertical to bedding

4. Experiment on coal and rock breaking by self-rotating multi-orifice jet nozzle

Under the condition of no confining pressure submergence, with briquette rock samples, using five types of self-rotating multi-orifice nozzles designed in Part 2 and two types of multi-orifice nozzles as the contrast, the coal rock breaking experiment was carried out by changing the nozzle pressure, injection distance and jetting direction.

4.1 Research of rock breaking effect with different nozzle pressure

Figure 6. The change of hole-diameter with different nozzle pressure

Figure 7. The change of rock breaking volume with different nozzle pressure
The rock breaking effect of nozzles with different nozzle pressure was studied in submerged condition without confining pressure, jetting time and jetting distance remained unchanged. According to the rock breaking experiment results, the rock breaking characteristic charts of different nozzle structures under different nozzle pressure are drawn as Figure 6 and Figure 7. The charts represent the minimum hole diameter and rock breaking volume of seven types of nozzles under different nozzle pressure.

From experimental results, the following conclusions can be obtained:

1. With the increase of pump pressure and hydraulic energy, the rock breaking effect of different types of jet nozzles increases in varying degrees; However, when the nozzle pressure is above 30 MPa, the rock breaking effect will not increase obviously with the increase of pump pressure;

2. In terms of breaking rock diameter and volume, the rock breaking effect of self-rotating multi-orifice nozzle is better than that of multi hole nozzle. Under the nozzle pressure of 18 MPa, the breaking hole diameter and volume of R10-3 are 40.22 mm and 20.7 mm$^3$, which are 1.56 and 1.58 times of M16-5 (25.45 mm and 13.3 mm$^3$).

4.2 Research of rock breaking effect with different jetting distance

![Figure 8. The change of hole-diameter with the jetting distance](image)

![Figure 9. The change of rock breaking volume with the jetting distance](image)

Under the experimental conditions of injection time=1 min and nozzle pressure=18 MPa, the influence of jetting distance on rock breaking effect was studied. The self-rotating multi-orifice jet nozzle R10-3 and multi hole jet nozzle M16-5 with good rock breaking effect were selected in this comparison. Figure 8 described the change of rock breaking hole diameter with different jetting distance; Figure 9 described the change of rock breaking volume with different jetting distance.

According to figure 8 and figure 9, the experiment results of rock breaking effect with jetting distance can be concluded as follows:

1. With the increase of jetting distance, the rock breaking effect first increases and then decreases. There are optimal jetting distance for the diameter and volume of rock breaking.

2. The experiment results show that the optimal jetting distance of self-rotating multi-orifice nozzle is 8 mm, which is 6 to 7 times of nozzle equivalent diameter, the optimal jetting distance of multi hole nozzle is 6 mm, which is 5 times of nozzle equivalent diameter.

4.3 Research of rock breaking effect with different jetting time

Jetting time is one of the factors that affect the rock breaking effect of jet nozzle in URRS. The actual drilling requires that the jet nozzle can achieve good rock breaking effect in a short time, so as to achieve better ROP. In order to study the influence of jetting time on rock breaking effect, the nozzle pressure and jetting distance remained unchanged, the experiment results are shown in Figure 10 and Figure 11. According to the rock breaking effect in Figure 10 and Figure 11, the following conclusions can be drawn:
With increase of jetting time, the effect of rock breaking increases, but the increasing is not obvious. It shows that under the experimental conditions, the rock breaking effect of the nozzle is nearly perfect, and the long-term hydraulic energy supply will not further improve the rock breaking effect.

Under the pressure of 18MPa, two types of nozzles can rapidly break the rock in 10 seconds, the rock breaking effect can reach a better state in 30 seconds.

4.4 Research of rock breaking effect with different jetting direction

8 groups of experimental research of rock breaking effect with different jetting direction were tested, each group was tested three times, the experiment rock breaking hole depth was taken as the average value. Figure 12 shows the influence of different jetting angles on the rock breaking hole depth, the following conclusions can be obtained:

(1) With the increase of hydraulic energy supply and pump pressure, the depth of rock breaking hole increases significantly. The smaller the angle between jetting direction and coal bedding, the deeper the rock breaking hole is;
(2) Although a larger hole depth can be obtained when the nozzle pressure of 24MPa nozzle is parallel to the coal bedding, the rock main body destruction occurs, the rock breaking hole width is between 10 ~ 20mm.

5. Conclusion
In this paper, the rock breaking effect of self-rotating multi-orifice nozzle in coal rock is studied by experimental method. The following major conclusions can be obtained:
(1) The anisotropy of natural coal and rock is strong, the strength varies greatly in different directions. Under the experimental conditions, the uniaxial compressive strength of vertical and parallel bedding is 30.8mpa and 10.9mpa respectively, the tensile strength of vertical and parallel bedding is 1.5MPa and 0.8MPa respectively, the shear strength of vertical and parallel bedding is 11.5MPa and 4.2mpa respectively;
(2) The rock breaking effect of self-rotating multi-orifice jet nozzle is better than that of multi-orifice jet nozzle. Under the same experimental conditions, the rock breaking volume and hole diameter of the self-rotating multi-orifice nozzle are 1.5 ~ 2.0 times of those of the multi hole nozzle;
(3) Under the experimental conditions, the rock breaking pressure of self-rotating multi-orifice nozzle and multi hole jet nozzle in briquette is 6.0 ~ 10.0 MPa; In the range of 10.0 ~ 26.5MPa, the volume and depth of rock breaking increase with the increase of pressure; In the range of 26.5 ~ 32.5 MPa, the rock breaking effect of self-rotating multi-orifice nozzle is close;
(4) Under the experimental conditions, the optimal distance of the self-rotating multi-orifice jet is 6 ~ 7 times of the equivalent diameter of the nozzle, the optimal distance of the multi hole jet is 5 times of the equivalent diameter of the nozzle; When the injection time is 30s, the self-rotating multi-orifice nozzle can complete the rock breaking process, the rock breaking effect does not increase significantly with the increase of injection time.

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