INTRODUCTION

Coalbed methane (CBM) is a type of clean and efficient energy source,\(^1\) which is formed in the immature period of coalification.\(^2\) Besides, it is also an important factor causing gas disasters such as gas explosive and outburst, which pose a great threat to the safety production in coal mine.\(^3\) Thus, exploiting CBM efficiently can not only increase the clean energy supply and alleviate the shortage of gas and oil in our country, but also improve the coalmine safety production and reduce the greenhouse gas emission.\(^4\) Therefore, to enhance the CBM extraction efficiency, many scholars have proposed many coal seam
stimulation techniques, including presplit blasting, hydraulic flushing, hydraulic slotting, and hydraulic fracturing. However, issues such as bad permeability enhancement effect still exist.

To improve the rock-breaking ability of water jet, some new types of water jet techniques have been proposed. With the contact mechanics used, Wang et al. established a new mathematic model of rock stress under abrasive slurry jet impacting, and the simulation results show that rock stress concentration appears at four areas (the center, edge, axis of particle indentation, and the edge of slurry jet), where rock is apt to be broken with axial compressive failure, radial tensile failure, shear failure, and radial tensile failure, respectively. The simulation combined with the experimental procedure was conducted by Zhao et al. for optimization of the particle water jet parameters, and the results show that both the impact depth and breaking volume efficiency factor decreased with the increase in the water inlet velocity. For the appearance of a deeper and wider crater, the optimized standoff distance was ranged from 20 to 30 mm. Similar experiment conducted by Ren et al. showed that rock-breaking depth by particle jet impact increases with the increase of jet velocity and particle mixing ratio in high-pressure water jet and decreases with the increase of particle diameter. And Wang et al. also pointed out that the dimensionless rock-breaking depth would increase linearly with the initial incident velocity. Moreover, the volume of jetted hole formed by particle jet is 2-4 times that of pure water jet under the same condition. As the erosion time of particle jet increases, the volume of jetted hole formed by particle jet rock-breaking increases, but the rock-breaking efficiency decreases. When the particle jet pressure is greater than 10 MPa, the rock-breaking efficiency of particle jet increases rapidly. When the injection angle is greater than 6°, the rock-breaking efficiency decreases rapidly. Huang et al. investigated the influence of velocity of high-pressure water jet on failure patterns of sandstone, and the results showed that the broken pit and the circumferential cracks on the surface of sandstone occurred when the velocity of water jet was above about 72 m/s, and the former was produced by the shear stress of water hammer pressure, and the later was induced by the tensile component of Rayleigh wave. Many transverse cracks were produced by the radial tensile stress waves when the velocity was between 300 and 700 m/s. The major failure pattern of sandstone is the split cracks when the velocity is above 700 m/s. Nowadays, radial horizontal drilling is an efficient approach to develop the low-permeability reservoirs, and it has become an important direction of the drilling development for gas resources in the future. Studies have shown that the fracturing pressure and fracture initiation position of the horizontal wells with controllable perforation vary with perforation angle and departure angle. Moreover, the in-plane perforation can guide and control the fracture strike near the wellbore, so as to produce the initial fracture plane perpendicular to the wellbore of horizontal wells and avoid the distortion of near-wellbore fractures caused by helical perforation. In addition, many scholars have studied the rock-breaking characteristics and energy conversion efficiency of water jet produced by multi-orifice nozzle. It is found that the rock-breaking effect of water jets produced by multi-orifice nozzle increases linearly with the jet pressure, and there exist maximum rock-breaking volume and optimum standoff distance. However, due to the single rock-breaking form and low rock-breaking efficiency, it is difficult to form large size and regular holes. Based on this, scholars have proposed internal rotating nozzle, that is, the high-pressure water passes through the nozzle arranged by internal guide impellers to produce rotating water jet with axial and tangential velocity. Experiments conducted by Reinsch et al. showed that the jetted holes can intersect fractures with different angles, and the jetted holes do not follow a straight path. And the water jets from the nozzles with central orifice combined with multiple lateral orifices arranged in circumference have better hole-forming shape ability, but the diameter of formed hole is small. The erosion experiments regarding straight jet, swirling jet, and straight-swirling integrated jet showed that the straight-swirling integrated jet can eliminate the low velocity area. Moreover, both the width of jet distribution and the hole diameter are bigger than those of straight jet. However, this type of nozzle may not be suitable for engineering practice due to its complicated design of structural parameters, high requirements on materials and processing technology, and large pressure loss of jet flow.

To investigate the characteristics of flow field of water jets form different nozzles, scholars have conducted a lot of numerical simulations. Lei and Dai studied the outflow field of nozzle using SIMPLEC algorithm, and the results illustrated the influence of water hole arrangement on flow field. Simulation conducted by Song et al. indicates that the bottom hole central temperature and pressure are higher than the two sides under multiple hydrothermal jets conditions, which are similar to the flow pattern with a single jet. Moreover, the distribution of axial velocity has three peaks at cross sections, and the axial velocity of centerline is the highest. There is a negative relationship between the maximum radial velocity and the ratio between axial distance and nozzle diameter. Liao et al. pointed that the jet by the new designed nozzle has both features of round straight jet and swirling jet, which can form larger hole diameter than conical round jet nozzle and deeper depth than swirling jet nozzle. The axial velocity of jet formed by the designed nozzle has no potential core compared with round jet and higher speed to a certain depth of drilling with no protrusion from hole bottom compared with swirling jet.

Based on the previous research, a novel self-rotatory multinozzle drilling bit was proposed in this paper. First, the simulation tests were conducted to study the effects of...
inclination angle of forward nozzles and standoff distance. Then, the effects of the nozzle arrangement, jet pressure, standoff distance, and hole-forming performances of the bit were studied through the laboratory tests. This paper aims at studying the rock-breaking mechanism and effect of water jets generated by self-rotatory multinozzle drilling bit.

2 WORKING PRINCIPLE OF SELF-ROTATORY MULTINOZZLE DRILLING BIT

2.1 Geometrical structure of self-rotatory multinozzle drilling bit

The main function of the self-rotatory multinozzle drilling bit is to generate rotating water jets to achieve rock-breaking and self-propelled effects, so the rotating body is the core component of the self-rotatory drilling bit, as shown in Figure 1. The rotating body is connected to the drilling body through a rotating shaft, and the nozzle is sealed by a special sealing rotator. Several forward nozzles and backward nozzles are arranged with different inclination angles and radial angles on the arc surface of the front end of the rotating body. The water flows in from the water inlet and is ejected from the nozzles after being pressurized, generating high-pressure water jets with different directions. Forward nozzle jets provide the rotate torque for the rotation of the rotatory body, which make the multiple jets impact the rock in a circular trajectory to form a borehole. Backward nozzle jets generate a self-propelled force for the bit to push the high-pressure hose forward. The jets can also break the rock further, enlarge the borehole, and discharge the rock debris. When the superposition of the rotational torque is greater than the friction of the rotatory body, the rotatory body begins to rotate. The forward nozzle jets mainly crush the rock, and the backward nozzle jets mainly provide the self-rotating force and self-propelled slag discharge. The water jets from the multinozzle have certain velocity in different directions, combined with the self-rotation of the drilling bit, which can generate impacting and shear breaking effect on the surface of the rock.

2.2 The hole-forming process of self-rotatory multinozzle drilling bit

The hole-forming process of the self-rotatory multinozzle drilling bit can be expressed as shown in Figure 2. At the same spray distance, the first nozzle jet impacts the rock first. Due to the rotation of the drilling bit, a circle groove is formed on the rock surface (Figure 2A). With the self-propelling of the drilling bit, the second circle groove is formed by the second water jet (Figure 2B). With the continuous propel-ling of the drilling bit, when the distance from the third nozzle to the rock surface reduced to the effective rock-breaking distance of the third jet, the third circle groove is formed around the previous two formed grooves (Figure 2C). Thus, a “threaded” annular groove would be formed on the rock surface. This process would be repeated until the drilling work is completed. Finally, a borehole with certain radius would be formed (Figure 2C,D). Generally, the first and second nozzles have small inclination angles, and the third nozzle has a larger inclination angle. Thus, the first and second nozzle jets mainly act on hole forming, and the third nozzle jet can effectively form the lateral broken pits.

3 NUMERICAL SIMULATION OF WATER JETS GENERATED BY SELF-ROTATORY MULTINOZZLE DRILLING BIT

To study the effects of inclination angle of the forward nozzles and the standoff distance, the ANSYS FLUENT was used to simulate the variation and distribution characteristics of the flow field of water jets.

3.1 Physical model

The physical model of the self-rotatory multinozzle drilling bit under submerged conditions was established as shown in Figure 3. The model consists of a cylindrical computational area with diameter of 20 mm and height of 30 mm and the self-rotatory multinozzle drilling bit. The diameter of the internal flow channel is 3.5 mm. Three forward nozzles and two backward nozzles are arranged. The diameters of each forward nozzle and each backward nozzle are 0.5 mm and 0.8 mm, respectively. The axial angles of the first, second, and third nozzles are 20°, 30°, and 60°, respectively. Moreover, the axial and radial angles of the backward nozzle are 40° and 14°, respectively. The definition of axial and radial angles can be seen in literature. The boundary of the internal flow channel of the drilling bit is selected as the pressure inlet, and the boundary between the inside of the computational domain and the outside of the drilling bit is set as the pressure outlet, and the lateral and the other end surface are chosen as the wall surface.

3.2 Control equation

To investigate the flow field of the water impinging jet, ANSYS FLUENT was employed. For high-pressure water jet flow field, the RNG k-ε turbulence model was used in this
The governing equations for the standard k-ε turbulence model are as follows:

**Mass balance equation**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \tag{1}
\]

where \( \rho \) is density of fluid; \( t \) is time; \( u, v, \) and \( w \) are the components of velocity in the \( x, y, \) and \( z \) directions, respectively.

**Momentum conservation**

\[
\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho U) = \text{div}(\eta \text{grad} u) + S_u - \frac{\partial p}{\partial x} \tag{2}
\]

\[
\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho Uv) = \text{div}(\eta \text{grad} v) + S_v - \frac{\partial p}{\partial y} \tag{3}
\]

\[
\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho Uw) = \text{div}(\eta \text{grad} w) + S_w - \frac{\partial p}{\partial z} \tag{4}
\]

where \( \text{div} \) and \( \text{grad} \) are vector symbols, that is,

\[
\text{div}(a) = \frac{\partial a_x}{\partial x} + \frac{\partial a_y}{\partial y} + \frac{\partial a_z}{\partial z} \tag{5}
\]

\[
\text{grad} u = \left( \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z} \right) \tag{6}
\]

And \( S_u, S_v, \) and \( S_w \) are generalized source terms in momentum conservation equation, that is,

\[
S_u = F_x + s_x \tag{7}
\]

\[
s_x = \frac{\partial}{\partial x} \left( \frac{\eta}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\eta}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\eta}{\partial z} \right) + \frac{\partial}{\partial x} (\lambda \text{div} U) \tag{8}
\]

where \( p \) is the pressure on the fluid micro-element; \( U \) is the velocity vector; \( \eta \) is the dynamic viscosity; \( F_x \) is the volumetric forces on the micro-element; and \( \lambda \) is the second viscosity.
Energy balance

\[
\frac{\partial (\rho T)}{\partial t} + \text{div} (\rho \mathbf{U} T) = \text{div} \left( \frac{k}{C_p} \text{grad} T + S_T \right) \tag{9}
\]

where \(C_p\) is the specific heat capacity; \(T\) is the temperature; \(k\) is the heat transfer coefficient of the fluid; and \(S_T\) is the viscous dissipation term.

3.3 | Meshing and boundary conditions

Model meshing quality is a key factor affecting the convergence of control equations. The model adopts unstructured mesh, and several nozzles are distributed with different angles on the drilling bit. And the nozzle is meshed densely. In the meshing process, the models of rotating body and the static flooding area are processed separately, and an interface is set between the two areas, so that the rotating body can rotate around the central axis during the simulation. The mesh number is 2 146 595, and the number of mesh nodes is 419 908. In addition, the corresponding boundary parameters are set as follows:

- **Inlet boundary:** The inlet pressure is set as 40 MPa;
- **Outlet boundary:** The outlet pressure is set to the atmospheric pressure of 0.1 MPa;
- **Wall condition:** No slip wall boundary.

3.4 | Simulation results and analysis

Figure 4 shows the velocity distribution of forward nozzle jets of the self-rotatory drilling bit. From the cloud diagram, the actual jet flow from the forward nozzles can be indicated. When conducting the rock-breaking test, the first and second nozzle jets are mainly responsible for hole forming, and the third nozzle jet can effectively form lateral broken pits. With the increase of the inclination angle of nozzles, the attachment phenomenon of the jet in the hole is more serious, and the energy loss is larger. Moreover, the larger the inclination angle of nozzle is, the larger the tangential velocity of jet is, and the smaller the axial velocity of jet is, which is unfavorable for hole forming but beneficial to hole enlarging. The definition of radial and tangential velocity can be seen in literature.\(^{19}\) Thus, it is necessary to optimize the inclination angle of nozzle to improve the rock-breaking effect of the water jet.

3.4.1 | Influence of the inclination angle on velocity distribution of water jet

In some complex physical problems, it is difficult to conduct effective quantitative analysis due to that there exist so many variables. Thus, the dimensionless coefficient, which incorporates many parameters with similar physical properties, is introduced to investigate the physical phenomenon. In this section, the dimensionless standoff distance represents the ratio of the actual standoff distance to the diameter of nozzle. To investigate the influence of the inclination angle on velocity distribution of water jet, the axial and tangential velocity variation data of single jet are extracted from the simulation results, as shown in Figure 5. Obviously, the larger the inclination angle of the nozzle is, the smaller the axial velocity of the jet is and the larger the tangential velocity of jet is. Moreover, when dimensionless standoff distance increases from 0 to 2, both the axial and tangential jet velocities
decrease rapidly. After that, the jet velocity decreases slowly, which is favorable for rock breaking in this stage. In addition, the axial velocity of jet is greater than its tangential velocity in the range of inclination angle from 15° to 45°, and the rock-breaking effect is mainly dominated by compacting effect of the water jet. When the inclination angle increases from 45° to 60°, the tangential velocity of jet is greater than its axial velocity, and the shear-tension effect of jet plays an important role for the rock-breaking effect.

3.4.2 Influence of the standoff distance on velocity distribution of water jet

Figure 6 shows the distributions of jet velocity with different standoff distances, and Figure 7 shows the variation of maximum jet velocity with different standoff distances. It can be seen that the jet velocity with different standoff distances has similar distribution characteristics. That is, first nozzle jet velocity is the largest, followed by the second and third nozzle jet velocities. This is because the distance from the three nozzles to standoff wall increases in turn. With the standoff distance increasing from 0.5 mm to 4.0 mm, the jet velocity gradually decreases. Moreover, the velocity of first and second nozzle jets decrease slowly with the standoff distance increasing from 0.5 mm to 1.0 mm and decrease sharply with the standoff distance increasing from 1.0 mm to 4.0 mm, while the third nozzle jet velocity decrease sharply with the standoff distance increasing from 0.5 mm to 2 mm and decrease slowly with the standoff distance increasing from 2.0 mm to 4.0 mm.

4 ROCK-BREAKING EFFECT

4.1 Test equipment and procedures

Laboratory experiments using self-developed drilling simulation system (Figure 8) were conducted to study the effects of the structural parameters, hydraulic parameters, and
jet parameters on the rock-breaking and hole-forming effects, and then optimized spatial orifices layout of nozzle. The test equipment mainly consists of water tank, plunger pump, pressure regulator, and test platform. A high-pressure plunger pump is used as a power source at a rated pressure of 100 MPa and a certified capacity of 100 L/min.

To ensure the homogeneity, sandstone was selected to make specimen. The large rock block was cored to obtain the standard cores measuring 50 mm in diameter and 100 mm in length. The related physical and mechanical parameters are listed in Table 1. And 30 rock specimens are used to study the effect of different parameters on the rock-breaking effect of multinozzle drilling bit.

The indicators including the depth, diameter, and volume of jetted hole are selected to evaluate the rock-breaking effect. The jetted hole depth and diameter are measured by vernier caliper. And the hole volume is measured using fine-sand-filling method. That is, fill the hole with fine sand and then take out the fine sand to measure the volume of its natural accumulation, which can be regarded as the volume of the jetted hole. The main experimental procedures are as follows:

1. Install the nozzle and fix the specimen at a target distance.
2. Connect high-pressure hose, plunger pump, and water tank. To ensure safety, test and check whether there is any leakage in the pipeline of the whole test system. If there is any leakage, cut off the power and turn off the water supply system immediately.
3. Open the water supply control switch and the power supply control switch and then fire the plunger pump.
4. Use the pressure regulator to adjust the jet pressure to predetermined pressure for rock-breaking experiments. After each test, record the jet pressure, standoff distance, and measure the depth, diameter, and volume of jetted hole.
5. After the rock-breaking experiment, adjust the pump pressure to zero and shut down the power supply and

TABLE 1 Physical and mechanical properties of the sandstone samples

| Parameters                  | Bulk density (g/cm³) | Tensile strength (MPa) | Uniaxial compressive strength (MPa) | Elastic modulus (GPa) |
|-----------------------------|----------------------|------------------------|-------------------------------------|----------------------|
| Value                       | 2.711                | 4.48                   | 40                                  | 6.5                  |

FIGURE 7 The variation of maximum jet velocity with different standoff distances

FIGURE 8 High-pressure water jet rock-breaking experimental system
water supply system. Then, take out the specimen and label it.

6. New rock-breaking tests just need to repeat steps (1)-(5).

4.2 Determination of the nozzle number

4.2.1 Effect of the nozzle number on the flow coefficient of drilling bit

There is a certain relationship between the equivalent diameter and the flow coefficient of nozzles of drilling bit. Thus, the equivalent diameter of the drilling bit can be obtained according to the Equation (10).

\[
d_e = \sqrt{\sum_{i=1}^{n} d_i^2}
\]

where \(d_e\) is the equivalent diameter of nozzles, and \(d_i\) is the equivalent diameter of \(i\)th nozzle. When the equivalent diameter of drilling bit is constant, the more nozzles, the smaller the diameter of each nozzle. In this paper, the diameters of each forward nozzle and each backward nozzle are 0.5 mm and 1 mm, respectively. The flow coefficient reflects the flow rate of the jet as it flows through the nozzle. Figure 9 shows the variation of the flow coefficient with different number of forward nozzles. As the nozzle number increases, the flow coefficient increases first and then decreases. When the number of forward nozzles is 2, the flow coefficient is maximum, 0.577; when the nozzle number is increased to 4, the flow coefficient is minimum, 0.530. Therefore, in terms of the flow coefficient, two forward nozzles may be the best choice. However, there may be other factors affecting the actual rock-breaking effect of the drilling bit, so the further analysis is needed.

4.2.2 Influence of nozzle distributions on the rock-breaking effect

To achieve the self-rotating function of the drilling bit, the nozzle must be distributed on the drilling bit at a certain inclination angle. Meanwhile, to ensure the stability of the rotating body in the process of rock breaking, two or more nozzles must be needed to achieve the mechanical balance of drill bit under the reaction force of different nozzle jets. From Section 4.2.1, when the nozzle number exceeds two, the flow coefficient of drilling bit decreases with the increase of the nozzle number. Therefore, the drilling bits with two and three forward nozzles were selected to compare their rock-breaking effect. Figure 10A,B shows the layouts of two and three forward nozzles on the drilling bit.

When two forward nozzles are arranged on the drilling bit (Figure 10A) and the inclination angle of the first forward nozzle near the center axis of the drilling bit is ranged from 10° to 30°, the water jet from first nozzle is mainly used for hole forming. While the inclination angle of the second forward nozzle is ranged from 30° to 45°, the water jet from the second nozzle is used for hole enlarging. When three forward nozzles are arranged on the drilling bit (Figure 10B) and the inclination angle of the first forward nozzle is ranged from 0° to 25°, the inclination angle of the second forward nozzle is ranged from 25° to 45°, the third forward nozzle is ranged from 45° to 60°, and the first and second forward nozzle jets are mainly used for hole forming, while the third nozzle jet is used for lateral broken pits. Thus, there will not exist blind zone during rock-breaking process.

Figure 11 shows the rock-breaking effect of the drilling bits with two and three forward nozzles. From Figure 11A, when the inclination angles of the first and second forward nozzles are separately set as 15° and 30°, the diameter of jetted hole is only 11.0 mm; while inclination angles of first and second forward nozzles are separately set as 20° and 60°, the diameter of jetted hole is 19.0 mm. This is due to that the interaction of the two jets can be eliminated with the appropriate increase of the inclination angles of forward nozzles, and the effective impact area by the jets on the rock would increase. From Figure 11B, when the inclination angles of first, second, and third forward nozzles are separately set as 10°, 30°, and 45°, the diameter of jetted hole is 19.0 mm; when the inclination angles of the first, second, and third forward nozzles are separately set as 20°, 30°, and 50°, the diameter of jetted hole is 24.0 mm; when the inclination angles of the first, second, and third forward nozzles are separately set as 20°, 30°, and 60°, the diameter of jetted hole is 29.0 mm. Thus, from the perspective of jetted hole diameter, it can be
concluded that the drilling bit with three forward nozzles has larger rock-breaking zone.

4.3 | Results and analysis

4.3.1 | Effect of the inclination angles of the forward nozzles on rock-breaking effect

Figure 12 shows the rock-breaking results by water jet with different inclination angles of forward nozzles. Obviously, with different inclination angles of forward nozzles, the indicators including the depth, diameter, and volume of jetted holes change significantly. When the inclination angle of forward nozzle was small, the axial velocity of forward nozzle jets was large, and the tangential velocity is small. Thus, the forward nozzle jets mainly act on hole forming. With the increase of inclination angle, the axial velocity of forward nozzle jets was small, and the tangential velocity was large. Therefore, the forward nozzle jets mainly form lateral broken pits eliminate the rock-breaking blind zone. From Figure 13, the hole depth decreases, while the hole diameter increases with the inclination angle. The hole volume increases with the inclination angle increasing from 15° to 30° and decreases with the inclination angle increasing from 30° to 60°.

4.3.2 | Effect of the radial angles of the forward nozzles on rock-breaking effect

The self-rotation of drill bit is achieved by the radial arrangement of forward nozzles. And the radial angle of the nozzle affects the rotation of the rotary body. Figure 14 illustrates the variation of rock-breaking indicators with different radial angles of forward nozzles. When the radial angle increases from 10° to 30°, the hole diameter increases slightly, but the hole depth and volume decreases significantly. Thus, on the premise of guaranteeing the need rotation torque of nozzle, reduce the radial angle to control the rotation speed of nozzle and also to improve the rock-breaking effect.

4.3.3 | Effect of jet pressure on rock-breaking effect

Figure 15 shows the variation of the specific hole parameters with different jet pressures. With the jet pressure increasing from 25 MPa to 45 MPa, the hole diameter increases while the hole depth decreases, but the hole volume increases first and then decreases. This is due to that the external swirling jet has certain axial and tangential velocities, which can break...
the rock by means of compressive stress and shear stress of water jet. With the increase of jet pressure, under the function of reverse thrust of backward nozzles, the rotation speed of nozzle increases, resulting in the increase of tangential velocity and rapid decreases of the axial velocity. Thus, 40 MPa may be the optimal jet pressure for this experiment.

**FIGURE 11** Rock-breaking effect by the drilling bit with different forward nozzles. (A) Rock-breaking effect by the drilling bit with two forward nozzles. (B) Rock-breaking effect by the drilling bit with three forward nozzles.
4.3.4 Effect of standoff distance on rock-breaking effect

From Figure 16, with the increase of the standoff distance, all the hole parameters including hole depth, hole diameter, and hole volume first increase and then decrease. And four is the critical value of the dimensionless standoff distance. It is noted that the dimensionless standoff distance represents the ratio of actual standoff distance to the diameter of forward nozzle. When the standoff distance is small, the jet cannot fully develop and the jet back flow is serious, reducing the rock-breaking effect. Therefore, with the dimensionless standoff distance increasing from 2 to 4, all the rock-breaking indicators including the depth, diameter, and volume of jetted hole increase. However, with the dimensionless standoff distance exceeding four, the jet pressure decreases significantly, reducing the rock-breaking ability of jet. It can be concluded that the optimal standoff distance is four times of the diameter of forward nozzle.
In this paper, a type of self-rotatory multinozzle drilling bit was introduced to form jetted hole borehole efficiently. The rock-breaking mechanism under multinozzle jets impact of the self-rotatory bit was investigated. Moreover, the effects of the nozzle arrangement, jet pressure, standoff distance, and hole-forming performances of the bit were studied. The following conclusions could be obtained:

1. From analysis of the rock-breaking process of self-rotatory multinozzle drilling bit, for the drilling bit with three forward nozzles, the first and second nozzle jets mainly act on hole forming, and the third nozzle jet can effectively form lateral broken pits and eliminate the rock-breaking blind zone.

2. From numerical simulation test, the larger the inclination angle of the forward nozzle is, the smaller the axial velocity of the nozzle jet is and the larger the tangential velocity of the nozzle jet is. When the inclination angle of forward nozzle is ranging from 0° to 45°, the axial velocity of nozzle jet is greater than its tangential velocity, and the rock-breaking effect is mainly dominated by jet impacting effect. When the inclination angle of forward nozzle increases from 45° to 60°, the tangential velocity of nozzle jet is greater than its axial velocity, and the shear stress played an important role for the rock-breaking effect. Moreover, there exist an optimal standoff distance of multinozzle drilling bit for rock breaking.

3. From laboratory experiments, the drilling bit with three forward nozzles has larger rock-breaking zone in terms of jetted hole diameter. Moreover, the depth of jetted hole decreased, while the hole diameter increased with the inclination angle of forward nozzle. The hole volume increased with the inclination angle of nozzle increasing from 15° to 30° and decreases with the inclination angle increasing from 30° to 60°. When the radial angle increases from 10° to 30°, the hole diameter increased slightly, but the hole depth and volume decreased significantly. With the jet pressure increasing from 25 MPa to 45 MPa, the hole diameter increased while the hole depth decreases, but the hole volume increased first and then decreased. With the increase of standoff distance, all the hole parameters including hole depth, hole diameter, and hole volume first increased and then decreased. Moreover, four is the critical value of the dimensionless target distance.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the
manuscript that is enclosed. Meanwhile, the founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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