INTRODUCTION

In China, unconventional sources of oil and gas, such as coalbed methane, shale gas, and low-permeability oil and gas resources, possess huge mining potential. The radial horizontal well technology can develop the potential of the unconventional oil and gas reservoirs. This technology requires a high-speed jet bit to accomplish the effect of rock-breaking and drilling by forcing a high-pressure fluid through a small diameter coiled tubing and a high-pressure hose into the jet bit. The jet bit is the essential technology in this case since it not only needs to break the rock and enlarge the borehole but also provides the tractive force to the high-pressure hose. Using experimental and numerical simulation methods, Wang Ruihe studied the rock-breaking and drilling mechanisms of a swirling jet. Roland E. Shaddock proposed a type of self-propelled jet nozzle. The front of the nozzle is a spheroid, and the back of the nozzle contains a V-shaped groove with multiple backward nozzles evenly distributed along the circumference of the groove to provide forward thrust to the bit. Li and Song systematically studied the peculiarity of a dual-jet flow field and the law of rock-breaking. Buset and Carl developed a self-propelled multijet nozzle and analyzed its rock-breaking mechanism and tractive force. Hualin Liao and Gang Bi studied...
the rock-breaking and drilling features of multijet bit and established a flow field computational model. The numerical computational results of the pressure and flow rate at the inlet of the jet bit and annular space were consistent with the experimental results. Based on the multijet bit theory, Ma\textsuperscript{16} presented a pulsed cavitating multihole jet bit. The jet bit was difficult for practical application due to its complex structure of the jet bit. Zhu et al\textsuperscript{17} investigated the rock-breaking rule of the self-propelled multijet bit by laboratory experiment. Li\textsuperscript{18} analyzed the energy conversion efficiency of the multiorifice nozzle. Bi\textsuperscript{14} studied the fluid characteristics of the self-propelled swirling jet bit. However, laboratory experiments were not analyzed for the self-propelled swirling jet bit. In conclusion, most scholars who studied jet bits focused on multijet bit. Since a multijet bit breaks rock via a combination of multiple jet flows, the jetting energy is concentrated, superposed and enveloped, and it has a longer standoff, a larger borehole diameter and a deeper borehole depth. The equivalent diameter of a backward nozzle of the multijet bit must be larger than that of a forward nozzle, and the number of forward nozzles cannot be too large, as such a setup will decrease the rock-breaking efficiency under high confining pressures. However, if the number of forward nozzles is too few, it would have an adverse effect on the jet bit and the forward motion of the hose. Because the diameter of the drilled hole would be smaller, the shapes would be unconformable and the individual holes would not be connectable. Therefore, a novel type of jet bit is desired which not only provides high rock-breaking efficiency but also meets the requirements of the roundness of the borehole and a constant diameter.

Based on the theory of multijet bit, this paper developed two kinds of swirling multijet bit including self-propelled swirling jet bit and self-propelled combined swirling and round multijet bit. The rock-breaking effect for the two jet bits were analyzed and compared by laboratory rock-breaking drilling experiment. The jet bit with high rock-breaking efficiency and its structure parameters were optimized according to laboratory test. The novel jet bit can improve drilling velocity for radial horizontal drilling.

2 | DESIGN OF THE SELF-PROPELLED SWIRLING JET BIT

As shown in Figure 1, the self-propelled swirling jet bit primarily comprises the jet bit body and the impeller. The left side of the jet bit is a female joint connecting the high-pressure hose, and the impeller is installed inside of the jet bit. The front side of the jet bit is perforated with a single or multiple apertures, and there are also multiple backward nozzles on the jet bit body which produce jet flows with a direction opposite to that of the front nozzles. By enhancing the flow rate of the backward jet, the reverse thrust of backward jet will be greater than that of the forward jet. Hence, the jet bit will provide a traction force to the high-pressure hose. The jet flow will be swirled by the impeller to expand the borehole diameter, but the blind area of the jet flow will cause a lug boss in the center of the breaking surface. Hence, it is necessary to design a central hole on the impeller to effectively solve this problem. According to the presence of a central hole on the impeller, the designed jet bit can be classified as a self-propelled swirling multijet bit or a self-propelled combined swirling and round multijet bit.

$L_1$, total length of the self-propelled swirling jet bit, mm; $D_1$, internal diameter of the self-propelled swirling jet bit, mm; $D_2$, external diameter of the self-propelled swirling jet bit, mm; $L_2$, outlet length of the central nozzle, mm; $d_{11}$, diameter of the central nozzle, mm; $d_2$, diameter of the forward circumferential nozzle, mm; $\alpha$, convergence angle of the self-propelled swirling jet bit, °; $L_3$, length of the mix chamber, mm; $d_{12}$, diameter of the mix chamber, mm; $L_4$, length of the impeller, mm; $d_3$, external diameter of the impeller, mm; $d_5$, central aperture diameter of the impeller, mm.
2.1 | Body structure design of the jet bit

The self-propelled swirling jet bit is designed based on the conventional multijet bit. Therefore, its body structure is similar to that of the conventional multijet bit. A three-dimensional body structure diagram is shown in Figure 2. The difference in the swirling jet bit is that there is a pair of steps inside the jet bit on which to place the impeller. The major structural parameters include the diameter of the forward circumferential apertures \( d_f \), the diffusion angle of the backward nozzle \( \theta_b \), the diameter of the forward central aperture \( d_1 \), the diameter of the backward nozzle \( d_b \), and the convergence angle \( \alpha \), as shown in Figure 1.

2.1.1 | Design of the aperture diameter

If the equivalent diameter of the jet bit is \( d_e \), the number of forward apertures is \( n \), and the number of backward apertures is \( m \), then

\[
d_1^2 + nd_f^2 + md_b^2 = Cd_e^2
\]

(1)

In this equation, \( C \) is a constant that is correlated to the local head loss coefficient of the bit aperture \( \xi \).

According to formula (1), if the equivalent diameter of the forward aperture is \( d_{fe} \) and the diameter of each forward circumferential aperture is equal, then

\[
(n-1)d_f^2 + d_1^2 = C_f d_{fe}^2
\]

(2)

Here, \( C_f \) is a constant which is correlated to the local head loss coefficient of the forward nozzles \( \xi \). If \( \xi_1 \), \( \xi_2 \), and \( \xi_3 \) are the local head loss coefficients of the central, forward circumferential and backward apertures, respectively, and it is assumed that \( \xi_1 = \xi_2 \) since the diffusion angle of the lateral aperture is generally less than 30°, then \( C_f \) is approximately equal to 1, and formula (2) can be modified to

\[
(n-1)d_f^2 + d_1^2 = d_{fe}^2
\]

(3)

Combining formulas (1) and (3), if the equivalent diameter of the jet bit is known, the diameters of the nozzles can be designed according to the practical requirements.

According to the previous research results, the equivalent diameter of the jet bit is closely correlated to the jet pressure, the flow rate and the flow coefficient of the jet bit:

\[
d_e = 0.69 \sqrt{\frac{Q}{\mu \sqrt{P}}}
\]

(4)

where \( d_e \) is the equivalent diameter of the jet bit, mm; \( Q \) is the flow rate, L/min; \( \mu \) is the flow coefficient of the jet bit, dimensionless; and \( P \) is the impact pressure, MPa.

The experimental results show that the flow coefficient of the multijet bit, \( \mu \), is approximately 0.75. To ensure the rock-breaking capacity during field operation, the jet pressure should be greater than 30 MPa and the pump displacement should be approximately 100 L/min. Substituting these parameters into formula (4), the equivalent diameter of the jet bit \( d_e \) can be determined to be approximately 3.5 mm. Overall, considering the rock-breaking and self-propulsion performance, the number and diameter of the apertures designed are shown in Table 1.

2.1.2 | Design of the diffusion angle of backward nozzles

The backward nozzles provide a tractive force to the jet bit by the reverse thrust effect, and the horizontal component of this reverse thrust will be greater if the angle between the axis of the nozzle and the axis of the bit \( (\theta_b) \) is smaller. Considering that the backward nozzles also have an auxiliary hole-enlarging function, if the diffusion angle, \( \theta_b \), is too small, this function will not be effectively achieved. In addition, the lower the angle is, the greater the local head loss will be, and the flow rate, the outlet jet velocity and the reverse thrust will be lower as well. Therefore, the diffusion angle, \( \theta_b \), generally ranges from 20° to 30°.

2.1.3 | Other parameters

According to the diverter structural size of the radial horizontal well and the result of the ground test, the length of the multijet bit \( l \) should be 8-10 times \( d_e \), where \( d_e \) represents the equivalent diameter of the jet bit.

The process of drilling radial horizontal wells is firstly using a milling bit to open a window on the casing, then putting the jet bit with the high-pressure hose into the drilled hole, and drill a small diameter horizontal wellbore. Therefore, the external diameter of...
the jet bit should be smaller than that of the milling bit. According to previous experimental results, the external diameter of the jet bit should meet the following requirement to ensure that the jet bit can successfully pass through the casing window:

\[ D_j \leq D_m - 4, \]

where \( D_j \) represents the external diameter of the jet bit, mm; \( D_m \) represents the external diameter of the milling bit, mm. The convergence angle \( \alpha \) is equals to 45-120°; the forward/lateral diffusion angle \( \theta_f \) is equal 10-30°; the number of forward apertures is generally 6-7; and the number of backward apertures is generally 5-6.

### 2.2 Design of the impeller structure

The impeller is the critical component of the self-propelled swirling jet bit. The impeller is close to the wall of the jet bit body and the rear end of the impeller is fixed to the step. The fluid with high velocity ejected from the high pressure hose changes its flow trajectory when flow through the guide impeller and the fluid trace is spiral. The design of the impeller directly influences the performance of the swirling jet flow and rock-breaking capacity. As shown in Figure 3, the impeller changes the jet flow trace by rotating its blades, causing the trace to take on a helical form. Under a high rotational speed, the jet flow could maintain a strong curl even if it escapes from the impeller due to the strong centrifugal force. Because of the three-dimensional velocity of the jet bit, the swirling jet flow takes on a unique conical shape. When a central hole is opened on the impeller, the fluid passing through the central hole will form a straight jet, while the fluid passing through the slot part will become a swirling jet. A combined swirling and round jet flow will ultimately be formed when the two jets meet in the mix chamber.

As shown in Figure 4, the primary structural parameters of the impeller are the number of blades, \( n \); the length, \( L_4 \); the outlet angle, \( \beta \); the external diameter, \( d_3 \); the thickness of the blade, \( t \); the diameter of the wheel, \( d_4 \); and the diameter of the central hole, \( d_5 \). After considering the size of the self-propelled swirling jet bit and the consequent manufacturing difficulty of producing perfectly round rock-breaking holes, a three-channel impeller was chosen as the experimental device in this design.

Based on the flow structure and the rock-breaking experimental performance of the dual jet and swirling jet,\(^{10,19,20}\) in this design, the length of the impeller \( L_4 = (2-4)d_{fe} \); the length of the mix chamber \( L_3 = (2-4)d_{fe} \); and the convergence angle \( \alpha = 45-120^\circ \), where \( d_{fe} \) is the forward aperture equivalent diameter of the jet bit, mm. These parameters were optimized by rock-breaking experiments.

### 3 EXPERIMENTAL APPARATUS AND METHOD OF STRUCTURE OPTIMIZATION OF THE JET BIT

#### 3.1 Experimental apparatus

The experimental apparatus is primarily composed of a high-pressure pump, a pipeline system, a pressure monitoring system and a jet rock-breaking system.

### TABLE 1 Aperture diameter design of the jet bit

| Number of forward apertures | Diameter of the central aperture, mm | Diameter of the circumferential aperture, mm | Number of backward apertures | Diameter of the backward apertures, mm |
|-----------------------------|--------------------------------------|-------------------------------------------|-------------------------------|---------------------------------------|
| 1                           | 1.50                                 | 0.00                                      | 6                             | 0.90                                  |
| 1 + 3                       | 0.90                                 | 0.70                                      | 6                             | 0.90                                  |
| 1 + 4                       | 0.90                                 | 0.60                                      | 6                             | 0.90                                  |
| 1 + 5                       | 0.80                                 | 0.60                                      | 6                             | 0.90                                  |

**FIGURE 3** Three-dimensional diagram of the impeller. A, Impeller without a central hole. B, Impeller with a central hole
1. High-pressure pump: The high-pressure plunger pump has a 60 MPa rated pressure, a 100 L/min rated flow rate and a 120 kW rated power diesel engine.

2. High-pressure hose: A high-pressure hose is used as the experimental pipeline system. The total length is 10 m, with a 14.2 mm external diameter and a 9.5 mm internal diameter, and the maximum compressive strength is 40 MPa.

3. Jet rock-breaking system: The confining pressure tank jet rock-breaking system is mainly composed of a confining pressure tank and a core holder. The structural diagram is shown in Figure 5.

4. Jet bit: The jet rock-breaking experiment is divided into two parts. The first part attempts to find the rock-breaking and drilling law of different self-propelled swirling jet bits with the same equivalent diameter. The equivalent diameter is 3.5 mm, the diameter of each individual aperture on the jet bit is as shown in Table 1, and the lateral aperture diffusion angle is 15°. The rest of the parameters are as shown in Table 2.

In addition, in this article, a “1 + 4” noncentral hole swirling jet bit denotes that the swirling jet bit has five apertures, where one is a central aperture and the other four surround the center evenly, and there is no central hole on the impeller; the other bits are named in a similar manner. In this experiment, 1-aperture noncentral hole, 1-aperture central hole, 1 + 3 noncentral hole, 1 + 3 central hole, 1 + 4 noncentral hole, 1 + 4 central hole, 1 + 5 noncentral hole, and 1 + 5 central hole swirling jet bits were used to conduct the rock-breaking experiment, as shown in Figure 6.

The second part of the experiment is the structural optimization of the selected jet bit from the first part of the experiment, with the ultimate goal of selecting the jet bit with the optimal rock-breaking capacity that is applicable in radial horizontal well technology. The parameters of the second part of the experiment are shown in Table 3.

5. Experimental rock sample. Cement concrete is used as the experimental rock sample, and the average uniaxial compressive rock strength is approximately 50 MPa.

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### Table 2: Structural parameters of the self-propelled swirling jet bit

| Structural parameter                          | Value |
|----------------------------------------------|-------|
| Total length $L_1$ (mm)                      | 30    |
| External diameter $D_2$ (mm)                 | 18    |
| Internal diameter $D_1$ (mm)                 | 12    |
| Length of the central nozzle $L_2$ (mm)      | 3     |
| Convergence angle $\alpha$ (°)               | 75    |
| Length of the mix chamber $L_3$ (mm)         | 6     |
| Diameter of the mix chamber $d_3$ (mm)       | 11    |
| Number of blades $n$                         | 3     |
| Length of the impeller $L_4$ (mm)            | 8     |
| External diameter of the impeller $d_1$ (mm) | 12    |
| Outlet angle of the impeller $\gamma$ (°)    | 45    |
| Diameter of the wheel $d_4$ (mm)             | 4     |
| Thickness of the impeller $t$ (mm)           | 1     |
| Diameter of the impeller’s central hole $d_5$ (mm) | 2     |
3.2 | Experimental method

The equipment described above was used to study the rock-breaking and drilling law of the self-propelled swirling jet bit under normal pressure conditions according to the following method:

1. Use different self-propelled swirling jet bits to study the rock-breaking and drilling performance changing with the erosion time;
2. Adjust the inlet pressure of the jet bits by a pressure regulator to study the rock-breaking and drilling characteristics of jet bits with different structures changing with the jet pressure;
3. Keep the hydraulic parameters and the structural parameters, including the length of impeller, the length of mix chamber and convergence angle of the jet bit constant. Study the influence of central aperture diameter of the impeller on the rock-breaking effect of the jet bit.
4. Keep the hydraulic parameters and the structural parameters, including central aperture diameter of the impeller, the length of mix chamber and convergence angle of the jet bit constant. Study the influence of the length of impeller on the rock-breaking effect of the jet bit.
5. Keep the hydraulic parameters and the structural parameters, including central aperture diameter of the impeller, the length of impeller and convergence angle of the jet bit constant. Study the influence of the length of mix chamber on the rock-breaking effect of the jet bit.
6. Keep the hydraulic parameters and the structural parameters, including central aperture diameter of the impeller, the length of impeller and the length of mix chamber constant. Study the influence of convergence angle of the jet bit on the rock-breaking effect of the jet bit.

3.3 | Evaluation of the rock-breaking effect

The evaluation indexes of rock-breaking efficiency by water jet technology mainly include borehole depth, borehole diameter and rock-breaking volume. The following is the measuring method of the evaluation indexes.

1. Measurement of borehole depth and borehole diameter

   The measuring tool is a vernier caliper with precision of 0.02 mm. Take the three deepest places of the craters on the rock for measurement when measuring the borehole depth. The borehole depth is measured twice and takes the average value. When measuring the borehole diameter, two maximum and minimum diameters passing through the center of the borehole are measured. And take the average value as the effective value of the borehole diameter.

2. Measurement of the rock-breaking volume

   i. Measure the weight of the rock sample, \( M_1 \), using the electronic scales (see Figure 3.10) with precision of 0.1 g.
   ii. Fill the craters on the rock using the uniform texture fine sand, ensuring all the interstices are filled with fine sand. The superfluous sand is swept by hairbrush to keep the sand level with the rock surface.
   iii. Measure the weight of the rock sample, \( M_2 \), after sand filling by the electronic scales.
   iv. Calculate the weight of sand filled in the rock sample, \( M = M_2 - M_1 \). Divide \( M \) by the density of fine sand and the rock-breaking volume can be computed.
   v. Each rock sample is measured twice and takes the average value to reduce measurement error.

4 | EXPERIMENTAL RESULTS AND ANALYSIS

4.1 | Analysis of jet bit optimization

By conducting rock-breaking experiments using 8 different swirling jet bits (1-aperture noncentral hole, 1-aperture
central hole, 1 + 3 noncentral hole, 1 + 3 central hole, 1 + 4 noncentral hole, 1 + 4 central hole, 1 + 5 noncentral hole, and 1 + 5 central hole), the rock-breaking efficiency can be optimized.

The erosion time directly influences the feed speed of the pipeline during the radial horizontal drilling. Normally, the hydraulic jet rock-breaking improves with increasing erosion time, as well as increases in the borehole diameter, depth, and rock-breaking volume. However, the situation changes with the length of time and for the different types of jet bits. Under normal pressure conditions, if the inlet jet pressure is 30 MPa and the standoff distance is 12 mm, the curves of the rock-breaking volume changes with erosion time for the 8 different jet bits are as shown in Figure 7.

As shown in Figure 7, with increasing erosion time, the rock-breaking volume first increased considerably and then became steady. More accurately, this volume increases rapidly in the first 2 minutes, begins to stabilize during the 3rd minute, and increases only slightly in the 4th minute. Therefore, 3 minutes is set as the erosion time in the subsequent jet rock-breaking experiments. The comparison of rock-breaking efficiency of the two designed swirling multijet bits is shown in Figure 8 when the inlet jet flow pressure is 30 MPa, the standoff distance is 12 mm, and the erosion time is 3 min under no confining pressure conditions.

According to the analysis above, under the experimental conditions (a standoff distance of 12 mm and a jet pressure of 20-35 MPa), when the jet pressures are the same, the rock-breaking performance of the jet bit with a central hole on the impeller is higher than that of the noncentral hole jet bit, and the rock-breaking efficiency of the self-propelled combined swirling and round jet bit increases first and then decreases due to the interference effect of the forward diffusion angle on the combined swirling and round jet flow.

Figure 9 shows the effect of the jet pressure on the rock-breaking volume of four different jet bits under normal pressure conditions when the erosion time is 3 minutes and the standoff distance is 12 mm. From Figure 9, when the pressure increases to a certain value, and the relationship is linear. When the jet pressure is constant, as the number of apertures increases, the breaking volume increases first and then decreases. This is because when the number of apertures increases, the jetting area increases and thereby the volume increases. However, if the number keeps increasing, the interference of the forward diffusion angle with the combined swirling and round jet flow will be stronger, which diminishes the jet strength and decreases the rock-breaking efficiency, so the rock-breaking volume decreases.

According to Figures 7 and 8, the presence of the central hole on the impeller affects the rock-breaking effect significantly. When the other structures of the jet bit are the same, the rock-breaking efficiency of the impeller with a central hole is higher than that of the impeller with a noncentral hole. Compared to the noncentral hole jet bit, the energy of the straight jet flow of the jet bit with the central hole is more powerful, while the swirling jet flow is weaker, which enlarges the borehole depth but reduces the borehole diameter. However, the decrease in diameter is minor compared to the increase in depth, so the total rock-breaking volume is increased. When the number of forward apertures is small, the influence will be minor. When the number increases, the rock-breaking efficiency will increase drastically. However, if the number increases further, the efficiency will decrease due to the interference effect of the forward diffusion angle on the combined swirling and round jet flow.

**FIGURE 7** Changes in rock-breaking volume with erosion time.
decreases with the increase in the number of forward apertures. This is because with the increase in the number of apertures, the jetting area increases and thereby the volume increases. However, if the number keeps increasing, the interference effect of the forward diffusion angle with the combined swirling and round jet flow becomes stronger, which diminishes the jet strength. The rock-breaking efficiency decreases when the decrease degree of borehole depth is larger than the increase degree of borehole diameter. Therefore, the 1 + 4 combined swirling and round jet bit is the optimal structure for a high-efficiency rock-breaking jet bit.

4.2 Optimization of structural parameters and result analysis

The structural parameters of the designed jet bit are shown in Table 3. Rock-breaking experiments were conducted with different jet bits from group 1 to group 4 to optimize the structural parameters of the jet bit.

4.2.1 Diameter optimization of the central hole on the impeller

Four jet bits from group 1 were selected for experimentation. Figure 10 show the influence of the central hole diameter of the impeller on the rock-breaking efficiency. With the increase in the central hole diameter, the borehole diameter decreases, while the borehole depth increases. The reason is that the fluid is separated into two parts by the impeller, and the fluid which passes through the central hole forms a straight jet flow, while the fluid which passes through the slot part becomes a swirling jet flow. When the central hole diameter increases, the flow rate that passes through the center hole will increase as well, which will intensify the straight jet flow energy to form a straight-based and swirling-supplemental combined swirling and round jet flow. Since the borehole diameter of the straight jet flow is minor but the borehole is deep, with the increase in the central hole diameter, the straight jet is intensified and the borehole diameter decreases, while the borehole depth increases.

As shown in Figure 10, the rock-breaking volume increases with the increase in the central hole diameter. This is because the straight jet flow is intensified by the increase in the central hole diameter, which deepens the borehole but minimizes the diameter due to the weakening of the swirling jet flow. When the decrease in the diameter is minor and the increase in the depth is large, the rock-breaking volume is enlarged.

In conclusion, when the central hole diameter of the impeller is 2 mm, the combined swirling and round jet flow can meet the requirements of both the borehole diameter and depth. Therefore, a 2 mm central hole diameter was optimal under the experimental conditions.

4.2.2 Optimization of the length of the impeller

Four jet bits from group 2 were selected for experimentation. Figure 11 show the influence of the impeller length on
The rock-breaking and drilling efficiency. With an increase in the impeller length, the borehole diameter is nearly constant. That is because the bore diameter is correlated with the diffusion angle of the combined swirling and round jet flow, and the length of the impeller section does not affect the structure of the jet flow field.

As shown in Figure 11, with the increase in the impeller length, the rock-breaking volume and borehole depth increase initially and subsequently decrease. This phenomenon is observed because the swirling effect will be enhanced gradually when the length of the impeller section becomes longer, which will subsequently deepen the borehole. However, if the length of the impeller section increases continuously, the fluid frictional loss will be greater, so the borehole depth will decrease due to the energy loss.

In general, the impeller length has little influence on the borehole diameter, but there exists an optimal length to obtain the largest rock-breaking volume and borehole depth, and 10 mm is optimal under the experimental conditions.

4.2.3 | Optimization of the mix chamber length

Figure 12 shows the impact of the mix chamber length on the rock-breaking performance. With an increase in the mix chamber length, the borehole diameter first increases and then decreases. That is because when the mix chamber is short, the interference between the straight and swirling jet is intense when the combined swirling and round jet flow passes through the contraction section of the mix chamber, and the energy loss is greater. Therefore, the mixing degree of the straight and swirling jets will be intensified, which will attenuate the energy of the swirling jet, and then, the borehole diameter will be decreased.

In addition, the borehole depth decreases with the increase in the mix chamber length. This finding is observed because the swirling jet and straight jet cannot fully mix when the chamber is short, and the attenuation of the straight jet energy is minor. The swirling jet cannot fully evolve, and the rock-breaking effect primarily depends on the straight jet, so the borehole is deeper. When the chamber becomes longer, the swirling jet is fully evolved and fully mixed with the straight jet; thus, the straight jet fades, and the borehole depth decreases. When the length of the mix chamber increases further, since the swirling jet fades in the mix chamber quickly and the straight jet fades more slowly, the decrease of the borehole depth slows down and its value becomes relatively steady.

As shown in Figure 12, the rock-breaking volume increases first and later decreases with the increase in the mix chamber length. According to the change of the rock-breaking volume, borehole depth and diameter with the mix chamber length, when the length of the mix chamber is 8 mm, the performance is optimal to meet the requirements of both the borehole diameter and depth.

4.2.4 | Optimization of the convergence angle of the jet bit

Four jet bits from group 4 were selected for experimentation to analyze the influence of the convergence angle on the rock-breaking and drilling efficiency. As shown in Figure 13, when the convergence angle is small, the interference between the straight and swirling jet is intense when the combined swirling and round jet flow passes through the contraction section of the mix chamber, and the energy loss is greater. Therefore, the rock-breaking performance is not ideal. If the angle becomes larger, though, the interference becomes minor, and the rock-breaking performance improves. When the angle
increases further, the swirling jet flow diffuses heavily, and the speed and energy loss increase. Hence, the rock-breaking performance deteriorates. The optimal range of the convergence angle is between 65° and 80° according to Figure 13.

5 | CONCLUSIONS

1. For the jet bits with different structural parameters, the borehole diameter, borehole depth, and rock-breaking volume increases when the erosion time and jet pressure becomes larger. When the jet pressure is low, the increase of rock-breaking volume is small. The rock-breaking volume increases significantly and linearly when the jet pressure increases to a certain value. The jet pressure is designed greater than 30 MPa to ensure the required borehole depth in drilling.

2. The rock-breaking performance of the self-propelled combined swirling and round multijet bit is better than that of the self-propelled swirling multijet bit under the same experimental conditions. The rock-breaking effect of the self-propelled combined swirling and round multijet bit with 1 + 4 holes is optimal.

3. The central hole diameter and length of the impeller are two essential parameters influencing the rock-breaking capacity of the combined swirling and round multijet bit. Results indicate that the borehole depth of the jet bit increases with the increase of central hole diameter of the impeller. The borehole diameter decreases when the central hole diameter increases. The rock-breaking volume and borehole depth first increase and then decrease with an increase in the impeller length, while the borehole diameter is almost constant. Under the experimental conditions, the optimal central hole diameter and impeller length are 2 and 10 mm, respectively.

4. The mix chamber length of the combined swirling and round multijet bit is the key element that influences rock-breaking efficiency. With the increase of the mix chamber length, the borehole depth first decreases and then tends to remain steady, while the borehole diameter tends to first increase and then decrease. Under the experimental conditions, the optimal length of the mix chamber is 8 mm, and the optimal value of the jet bit convergence angle ranges from 65° to 80°.

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