Research on structure design and flow field characteristics of the novel jet bit for radial horizontal drilling

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Abstract
The self-propelled swirling jet bit was designed to ensure the rock-breaking efficiency of radial horizontal drilling and meet the roundness of borehole diameter and borehole shape. The jet bit provides swirling jet through internal rotating impellers and increases the drilling depth by jetting through the central holes on the impeller. Based on numerical simulation method, RNG \( k-\varepsilon \) turbulence model was employed to analyze the three-dimensional flow characteristics of flow field inside and outside of the two kinds of jet bits. Moreover, the rock-breaking efficiency of the two jet bits was also compared and analyzed in accordance with the laboratory experiments. The results show that the simulated bottom-hole flow field for the two jet bits can be both divided into bottom-hole overflow area, forward jetting area, and backward jetting area. The forward jet is a jet beam which consists of a central jet and four circumferentially equispaced jets, which generates more complex overflow area at the bottom hole. The maximum jet speed and the jet impact energy of forward jetting from the combined swirling and round multijet bit are larger than that of the swirling multijet bit. The speed attenuation law of forward jet nozzle from the two kinds of jet bits is similar. They both increase slowly in the mixing zone, while increase remarkably when approach to the nozzle. Then decrease linearly in the impact zone, and decline straightly when get close to the impact area. The simulation results of flow field characteristics are in coincidence with the actual rock-drilling features. Therefore, the simulation results of flow field characteristics can provide guidance for jet bit design and structure parameter optimization for radial horizontal drilling.

KEYWORDS
combined swirling and round multiple jets, flow field characteristics, radial horizontal drilling, RNG \( k-\varepsilon \) turbulence model, swirling multiple jets

1 | INTRODUCTION
Radial horizontal drilling is an efficient approach to develop low-permeability reservoirs, coal-bed methane, and enhance oil recovery. Recently, it has become the hot topic with strategic importance and an important direction of the drilling development for oil and gas resources in the future. Drilling radial horizontal wells by water jet means to drill one or more radially distributed slim holes along the radial direction of the wellbore, giving full play to the characteristics of high-pressure water jets. This technology has unmatched effects compared with others in improving the distribution of...
reservoir pressure, enhancing oil and gas recovery, and single well output, but there are still many technical issues need to be addressed. One of the key issues to be solved is contradiction between the drilling depth by jetting and the roundness of the borehole and borehole diameter. The key technology to solve this problem is jet bit, which requires the jet bit with strong reaming capability, large effective standoff distance, and high erosion and crushing efficiency. Numerous researchers studied the multiple jetting bits. Li Gen-Sheng and Song Jian et al. gave systematic study on dual-jetting flow field characteristics and rock-breaking laws. Buset et al. and Carl developed a self-propelled multijet nozzle, and analyzed the rock-breaking mechanism of the nozzle as well as its traction effects. Li Gen-sheng and Liao Hualin et al. analyzed the rock-breaking behavior of multijet bit, and established a flow field model of the jet bit. The inlet and annulus pressure and flow rate of the jet bit from numerical simulation results are consistent with experimental results. Gang et al. analyzed the self-propelled ability of the multijet bit. From the above analysis, the multijet bit break rocks and drilling through combination of multiple jetting stream. The characteristics of jet energy distribution are concentrated and overall superimposed envelope, so it has long effective target distance, large borehole diameter, and borehole depth. The equivalent diameter of the backward nozzle needs to be bigger than that of the forward nozzle of the multijet bit. Meanwhile in condition of high confining pressure, more forward nozzles will decrease the rock-breaking efficiency, which means the number of forward nozzles should be limited. However, when the number of forward nozzles is too small, the borehole diameter after rock breaking is relatively small. The borehole is irregularly shaped and even the boreholes cannot be connected, which is against for high-pressure hoses and jet bits to advance. Hence, a new and efficient rock-breaking jet bit is highly needed to ensure rock-breaking efficiency and meet the roundness of borehole diameter and borehole shape.

In this work, a novel self-propelled swirling jet bit was developed based on the multiple jets bit theory. A swirling

FIGURE 1 Structural design of self-propelled swirling jet bit. A, Self-propelled swirling multijet bit. B, Self-propelled combined swirling and round multijet bit
jet flow is modulated by the inner impeller of the jet bit, which increases the curl. Moreover, by opening holes at the center of the impeller, the depth of the jetting hole is increased, which ensures the borehole diameter not reduced when the number of the forward nozzle is limited. Thus, the new design not only improves the rock-breaking efficiency but it is also beneficial for the jet bit to drive the pressure hose moving forward. The self-propelled swirling jet bit was optimized with high rock breaching efficiency by analyzing the flow field characteristics of the designed jet bits and the velocity and pressure distribution of the jet bits through numerical simulation method. The numerical simulation results match well with the experimental results according to experimental verification method, which ensures the accuracy of design method and numerical simulation results.

2 | STRUCTURE AND WORKING PRINCIPLE OF THE SELF-PROPELLED SWIRLING JET BIT

As is shown in Figure 1, the self-propelled swirling multi-jet bit mainly consists of drill bit body and an impeller. The left side of the jet bit body is the box, which is used to connect the high-pressure hose. The impeller is mounted inside the jet bit body. The front end of the jet bit body opens one or multiple holes. Furthermore, multiple backward nozzles are designed on the jet bit body. The reversed jetting directions are opposite to forward jetting directions. By increasing the flow rate of the reversed jet, the thrust force of the reversed jet is greater than the forward jet, thereby enabling the traction force of the high-pressure hose by the jet bit. The impeller rotates the jet flow, which enlarges the borehole diameter. However, there exists a blind zone of rock breaking. A convex plate occurs in the center of the rock-breaking surface by jet breaking. Hence, a central hole at the center of the impeller is suggested to be designed, which can effectively address the above problems. According to whether there is a hole in the center of the impeller or not, the jet bit can be divided into two types: self-propelled swirling multi-jet bit and self-propelled combined swirling and round multi-jet bit.

3 | NUMERICAL SIMULATION ON FLOW FIELD OF SELF-PROPELLED SWIRLING MULTI-JET BIT

3.1 | Calculation model and boundary conditions of numerical simulation

3.1.1 | Geometric model

The geometric model is shown as Figure 3. Forward central nozzle diameter is 0.9 mm, and there are four lateral nozzles with 0.6 mm diameter around the center nozzle which form 15-degree angles between the two kinds of nozzles. Six symmetrically distributed backward nozzles form 30 degree angle with the central axis and their diameter is 0.9 mm. There are three guide vanes at the rotary section and rotary segment length is 8 mm; the outer diameter of the bit is 18 mm, and fluid inlet diameter is 12 mm. In order to better focus the rotational energy of the jet in the mixing zone, a design that both sides are relatively flat, whereas top is in a large curvature is adopted. The distance between impact bottom hole to the nozzle is 5 mm. The outer diameter of the entire flow field is 19 mm.

3.1.2 | Governing equation

The flow velocity generated by the self-propelled swirling jet bit is high and the flow is turbulent flow under normal working conditions, which is more complex than the common steady
flow. Therefore, the selection of the turbulence models and the
determination of the model parameters have a direct effect on
the accuracy of the numerical results. Ideally, the flow field
can be simulated by DNS directly. However, it cannot be real-
ized due to the complex geometric structure and limited com-
puting resources. Thus, it needs to find a turbulent viscosity
model which is well developed and suitable for the calculation
of swirling flow field. The semi-empirical double-equation
standard \( k-\varepsilon \) turbulent viscosity model is widely used due to
its simple computation format and better calculation results.
The standard \( k-\varepsilon \) turbulent viscosity model mainly applies to
the fully developed turbulent flow or flow with low rotation
velocity. The reason is that the flow is assumed as fully devel-
opled turbulent flow and the molecular viscosity is neglected in
the derivation of the standard \( k-\varepsilon \) turbulent viscosity model.
Many turbulent viscosity models are proposed based on the
basic model in order to expand the application of the \( k-\varepsilon \) tur-
bulent model, among which the RNG turbulent model and the
Realizable turbulent viscosity model apply more widely than
the other models.

The combined swirling and round jet flow not only in-
cludes straight jet, but also the high intensity of rotating jet,
which is much more complex than the average steady flow.
Therefore, the RNG \( k-\varepsilon \) turbulence model is used to an-
yze the jet flow structure. This model has a similar form to the
standard \( k-\varepsilon \) model equations, except that an \( R \) term is added
to the \( \varepsilon \) transfer equation, making the model for rotational
flow simulation with high accuracy.\(^{16,17}\) Three-dimensional
turbulent flow control equations in cylindrical coordinates
can be written as:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \phi}{\partial r} \right) + \frac{1}{\gamma} \frac{\partial}{\partial \theta} \left( \gamma \frac{\partial \phi}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \frac{\partial \phi}{\partial z} \right) + S = \sum_s \Phi_s \tag{1}
\]

where \( \phi \) is the dependent variable, such as \( u, v, w, \rho, k, \) and \( \varepsilon; \)
\( S_\phi \) is the source term of equation.

Take no account of buoyancy for incompressible fluid.

The time average transfer equations for turbulent kinetic en-
ergy \( k \) and dissipation rate \( \varepsilon \) in RNG \( k-\varepsilon \) model are written,
respectively, as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_k \mu_k \frac{\partial k}{\partial x_i} \right) + \mu_k \left( \frac{\partial u_j}{\partial x_j} \right)^2 - \rho \varepsilon \tag{2}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_\varepsilon \mu_\varepsilon \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \frac{\varepsilon}{k} \mu_k \left( \frac{\partial u_j}{\partial x_j} \right)^2 - C_2 \rho \frac{\varepsilon^2}{k} - R \tag{3}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_\varepsilon \mu_\varepsilon \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \frac{\varepsilon}{k} \mu_k \left( \frac{\partial u_j}{\partial x_j} \right)^2 - C_2 \rho \frac{\varepsilon^2}{k} - R \tag{4}
\]

where \( R \) is the difference between the RNG \( k-\varepsilon \) model and
the standard \( k-\varepsilon \) model. The existence of \( R \) enables the RNG
\( k-\varepsilon \) model to simulate flow with great strain and large flow
line curvature more accurately.

### 3.1.3| Discretization

In this study, the finite volume method was employed for
governing equation discretization of swirling turbulent
flow. Hybrid format was adopted in the discretization
of convection and diffusion terms in each governing
equation. A negative slope linear is implemented on the
source term. TDMA (tridiagonal matrix algorithm) line-
by-line scanning relaxation iteration method was used
for the solutions to the discretized equation of vari-
ables. The SIMPLE algorithm was employed to itera-
tive solution of the coupled continuous and momentum
equations.

The finite volume method for the discretization of differen-
tial equations reflects the geometric flexibility of the fi-
nite element method, the accuracy of characteristic line
method and the efficiency and conservation of finite differ-
ence method. After using the finite volume method for in-
tegrating the equation along the control volume, following
equations were computed:

\[
\int \frac{\partial \phi}{\partial t} dV + \int \phi U \cdot ndA - \int \Gamma_\phi \nabla \cdot ndA = \int S_\phi dA = \sum S \tag{5}
\]

where \( dV \) is control volume; \( dA \) the surface area of the micro-
elements on control volume; and \( n \) is the external normal
direction of the control volume surface.

### 3.1.4| Mesh generation

Binning mesh method was taken to separate the impeller portion
from the main jet bit body. From Figure 4, the grids are subtly
divided in the region where flow field changes drastically such
as the interior region and outlet of the jet bit. These areas can
express flow characteristics of self-propelled swirling jet. There
is a grid quality inspection tool in the Gambit mesh generation
software. This tool estimates the grid quality by the grid distor-
tion factor. Generally, the grid quality is well if the distortion
factor is below the value of 0.8. In this model, by combining
the tetrahedral mesh and the hexahedral mesh, local mesh refi-
nement approach was adopted to ensure the accuracy of the

**FIGURE 4** Mesh of calculation field
simulation results. The grid quality was qualified by the verification of the grid quality inspection tool.

3.1.5 Boundary conditions

Entry boundary
The sheer velocity in the entry $v_{in}$ is 8 m/s. Assuming that the sheer velocity of the inlet boundary is uniformly continuous, so that the parameters $k$ and $\varepsilon$ can be expressed by the following formulas:

$$k_{in} = 0.03v_{in}^2$$  \hspace{1cm} (6)

$$\varepsilon_{in} = C_\mu k_{in}^{1.5} / l_{in}$$  \hspace{1cm} (7)

where $L_{in}$ denotes length of entry mixed section.

Exit boundary
The determined pressure is 2.0 MPa.

Wall boundary conditions
Using no-slip solid wall boundary condition in the calculation of the wall boundary. According to the single wall function to determine the first near wall center point parameter of control volume, in other words, supposing the near wall dimensionless velocity distribution obeys logarithmic distribution:

$$U_{+p} = \frac{1}{k} \ln (E y_{+p})$$  \hspace{1cm} (8)

$$y_{+p} = C_\mu^{1/4} k_p^{1/2} y_p / \nu$$  \hspace{1cm} (9)

$$\mu_{i} = y_{+p} \frac{\mu}{\ln (E y_{+p}) / k}$$  \hspace{1cm} (10)

where $k$ is Karman constant, $k = 0.4$; $E$ is the surface roughness, and for the hydraulic smooth wall, $E = 9.0$; $\nu$ and $\mu$ are kinematic viscosity and dynamic viscosity coefficients. In order to ensure the validity of the logarithm distribution law, the value range of $y_{+p}$ is as follows:

$$11.5 \sim 30.0 \leq y_{+p} \leq 200 \sim 400$$

The turbulent kinetic energy close to the wall is still calculated by $k$ equation and the boundary condition is as follows:

$$\left( \frac{\partial k}{\partial \varepsilon} \right) W = 0$$  \hspace{1cm} (11)

$$\varepsilon_p = \frac{C_\mu^{3/4} k_p^{3/2}}{k y_{+p}}$$  \hspace{1cm} (12)

Wall dissipation rate equals to zero.

3.2 Numerical simulation results and analysis

3.2.1 Flow field characteristics of self-propelled swirling multijet bit

Figure 5 is the central axis cross-sectional velocity field structure of the self-propelled swirling multijet bit. High-pressure fluid flows through the rotary segment and mixing zone, breaks the rocks by running through the forward central nozzle and four circumferentially equispaced lateral nozzles, and generates a self-propelled force from passing through the backward nozzles in front of the mixing zone. The flow field characteristics become more complex due to the rotation and multiple jets.
3.2.2 The velocity distribution and development of forward jet

Figure 6 shows the forward jet of the self-propelled swirling multijet bit consists of rotating jet ejected from each jet nozzle. The central nozzle jet velocity is slightly larger than the speed of circumferential jet nozzles. The reason, on the one hand, is that the direction in the center of flow velocity field is the same with the central axis direction due to the rotation characteristics of the mixing zone, but the fluid particles around the flow field show strong rotation characteristics, therefore, there are velocity components in three directions, reducing the magnitude of the axial velocity. On the other hand, there is an angle between circumferential nozzle axis and the drill bit central axis, and its cross-sectional area is smaller which weakened the intensity of the jet. The combined effects of multiple jets strengthen the jet impact range, and make it easier to form a larger impact area as a result of the rotating characteristics of the jet.

Figure 7 shows the distribution at the center axis of the center nozzle and the circumferential nozzle of self-propelled swirling multijet bit, where the 0.0035 m is the bottom hole, 0.0025 m is the mixed zone starting interface, and 0.0032 m is the nozzle exit. As can be seen from the figure, the center nozzle and circumferential nozzle mainly show similar velocity increasing or decreasing characteristics. In the mixing zone the speed increases slowly and exhibits a linear characteristic, while the velocity rapidly rising to the highest point within a short distance in front of the nozzle. The maximum velocity of central jet reaches 235 m/s, the maximum speed of circumferential forward jet is slightly smaller, and the jet speed slightly attenuated inside the nozzle. After outflow from the nozzle, jet velocity can be basically divided into two areas. In the area far from the bottom hole, the jet velocity drops linearly and velocity attenuation is relatively slow. In the area near the bottom of the well, jet velocity declines sharply and rapidly attenuates to zero. Compared with the central nozzle, the position of circumferential nozzles is relatively closer to the mixing zone, hence, the position of velocity rising advances, and the velocity attenuation is faster after ejects from the nozzle. That is because the angle between the circumferential nozzle and the central axis leads to a longer jet length.
Figure 8 show the dimensionless center and circumferential jet axis velocity curve. Central jet velocity attenuation law is identical to the typical law of single round jet velocity attenuation with restriction of solid wall under submerged conditions. From the figure, central jet velocity decreases slowly, and before reaching the bottom, speed rapidly attenuates to 0 m/s due to the limitation of the bottom hole. The circumferential jet law is similar to the center jet, but the circumferential jet velocity declines faster than the center jet. Affected by the bottom-hole overflow, the center jet and circumferential jet both occurs velocity attenuation slowdown region near the impact area. In front of the impact flow field, the jet velocity attenuation shows a linear trend. In the middle or back of the flow field, the jet velocity shows acceleration attenuation behavior. When close to the bottom, the velocity drops sharply to zero. The figure shows that the attenuation trend of circumferential jet velocity goes faster, so the jet capability of the center nozzles is better than the circumferential nozzles.

3.2.3 | The velocity distribution and development of backward jet

Figure 9 is the jet velocity contour plot of backward nozzle. Backward nozzle forms an 30° angle with drill bit central axis. Part of the fluid enter backward nozzle from inside the jet bit and sprays into the annulus, forming a backward jet. From Figure 8, a low-pressure area generated when the fluid flows through the backward nozzle due to the larger turning flow angle combined with the fluid inertia, the maximum nozzle jet velocity is approximately 250 m/s and the speed is not symmetrically distributed along the axis. After flowing through the nozzle, jet velocity rapidly attenuates to 100 m/s and impact the bottom hole with an certain angle, which generates a strong shear stress in the wall, making it more conducive to breaking rocks, and with the effect of depressurization and reaming.

The large steering speed of backward nozzle results in large loss of kinetic energy and big local drag coefficient. Optimizing backward nozzle length, angle, and shape help reduce energy losses, increase the backward jet velocity, thereby improving its self-feeding and reaming capacity.

3.2.4 | Bottom-hole flow field analysis

Velocity distribution

Figure 10 shows the bottom-hole velocity profile of the self-propelled swirling multijet bit. It is the plane velocity distribution with 1 mm from the bottom hole in the limitation of the bottom-hole wall surface. The jet of circumferential lateral nozzles forms an annular high-speed impact area. In the middle of the lateral nozzles, as the velocity superposition of the center nozzle and lateral nozzles, there occurs a velocity concentrated area, showing four cone-shaped high-speed areas. A low velocity zone exists between the central nozzle and the circumferential lateral nozzles, so the velocity distribution of whole cross-section exhibits a high-low-high and finally diffusion attenuation performance.

Figure 11 shows the combined velocity and component velocity curves with 1 mm from the bottom hole along the radial direction. From the figure, the combined velocity and component velocity basically exhibits two peaks, one is flowing through the central nozzle while the other one is flowing through the circumferential lateral nozzles. Y-velocity, namely, the velocity along the central axis of the jet bit, is in dominant position, followed by the speed along the radial direction. Z-velocity is close to zero. The change

FIGURE 10  Bottom-hole velocity distribution of self-propelled swirling multijet bit
in velocity curves above is in accordance with velocity contours at the bottom hole. The second velocity peak is the annular velocity increasing area from the circumferential lateral nozzles.

Pressure distribution
Figure 12 shows the bottom-hole pressure contours. From the figure, the static pressure is concentrated in the nozzle jetting area and reduced from the middle to the surrounding area. The static pressure in central nozzle is greater than that of the circumferential lateral nozzles. Its value is around 18 MPa.

The dynamic pressure contour shows that the dynamic pressure appears double ring-shaped distribution. Since the mixing function of the central nozzle and the lateral nozzles, there forms two annular dynamic pressure increasing region around the central nozzle and outside the lateral nozzles. The corresponding dynamic pressure of the nozzle is the minimum pressure and spread outward.

4 | NUMERICAL SIMULATION ON FLOW FIELD OF SELF-PROPELLED COMBINED SWIRLING AND ROUND MULTIJET BIT

4.1 | Numerical calculation model and boundary conditions

Figure 13 shows the calculating model, and most of the parameters are the same as that of the self-propelled swirling multijet bit except for a diameter of 2 mm hole opened in the central of the impeller. In order to better focus the rotational energy of the jet in the mixing zone, a design that both sides are relatively flat whereas top is in a large curvature is adopted. The distance between impact bottom hole to the nozzle is 5 mm. The outer diameter of the entire flow field is 19 mm.

The RNG k–ε turbulence model is adopted in calculation, with the same boundary conditions as the self-propelled swirling multijet bit. Binning mesh method is taken for grid division as shown in Figure 14.

4.2 | Results and analysis of numerical simulation

4.2.1 | Flow field characteristics of self-propelled combined swirling and round multijet bit

Figure 15 shows the central axis cross-sectional velocity field structure of self-propelled combined swirling and round multijet bit. Part of the fluids firstly enters the backward nozzle, and then flows through the rotary segment and mixing zone, and jetting from the nozzle. With central hole on the swirling jet bit can not only reduces energy loss but combined swirling and round jet also can compensate the inadequate rock-breaking energy in the center of the swirling jet flow field.

4.2.2 | The velocity distribution and development of forward jet

From Figure 16, compared the forward jet of self-propelled combined swirling and round multijet bit with self-propelled
swirling multijet bit, the maximum jet velocity and the impact energy of jetting is larger. And the jets still consist of each round jet from the nozzle. The jetting energy of the circumferential nozzles is less than the central nozzle.
Figure 17 shows the velocity distribution at the center axis of the center forward nozzle and the circumferential forward nozzle of self-propelled combined swirling and round multijet bit, where the 0.0035 m is the bottom hole, 0.0025 m is the mixed zone starting interface, and 0.0032 m is the nozzle exit. The figure shows that the trend of forward nozzle velocity attenuation curves is similar to swirling multijet bit. It increases slowly in the mixing zone, and rises rapidly in proximity to the nozzle, then declines linearly in the impact zone, and falling sharply when close to the impact plane area. The position of the lateral nozzles is at the front and the nozzle cross-sectional area is smaller, therefore, the curve rising earlier and the maximum velocity of the lateral nozzle are less than the central nozzle.

Figure 18 show the dimensionless center and circumferential jet velocity curves along the nozzle axis. The velocity attenuation law is similar to that of the swirling multijet bit. However, the obvious velocity attenuation area of the central forward nozzle is after the 2.6 times of standoff distance, while the jet velocity of swirling multijet bit attenuates obviously after 2.0 times of standoff distance. Thus, the presence of the center hole in the impeller increases jet impact strength. The velocity attenuation of lateral nozzles of the two kinds of jet bits is exactly similar. It begins to decrease at 3.0 times of standoff distance, which shows little effect of the impeller center hole on the lateral nozzles.

4.2.3 The velocity distribution and development of backward jet

Figure 19 shows the jet velocity contour plot of backward nozzle. Backward nozzle forms an 30° angle with drill bit central axis. Part of the fluid enter backward nozzle from inside the jet bit and sprays into the annulus, forming a backward jet. Arranging the backward nozzles in the front of the rotary section reduces the backward jetting energy loss. The jetting characteristics of combined swirling and round multijet bit are the same as the swirling multijet bit.

4.2.4 Bottom-hole flow field analysis

Velocity distribution

Figure 20 shows the bottom-hole velocity distribution of self-propelled combined swirling and round multijet bit. The plane velocity distribution with 1 mm from the bottom hole is complex in the limitation of the bottom-hole wall surface. The whole rules of plane velocity distribution are the same as the swirling multijet bit, but the impact velocity of combined swirling and round multijet bit flow field is bigger. And when the jet velocity of the two kinds of jet bits is the same, the combined swirling and round multijet bit has a larger impact area. The erosion edge of yellow area looks more uniformly. Thus, the combined swirling and round multijet bit has a better rock-breaking effect.

Figure 21 shows the combined velocity and component velocity curves which are 1 mm from the bottom hole along the radial direction. The change in jet velocity for two kinds of jet bits which are 1 mm from the bottom hole along the radial direction. The change in jet velocity for two kinds of jet bits is nearly the same, but compared with swirling
multijet bit, jet velocity along the central axis of combined swirling and round multijet bit is bigger, while its radial velocity and tangential velocity are relatively smaller, both showing the same laws of velocity increase or decrease.

Pressure distribution
Figure 22 shows the bottom-hole pressure contours. From the figure, the static pressure is concentrated at the nozzle jetting area and reduced from the middle to the surrounding area. The static pressure in central nozzle is greater than that of the circumferential lateral nozzles. Its value is around 20 MPa, which is a little bigger than the swirling multijet bit.

From the dynamic pressure contour, the bottom-hole dynamic pressure of the combined swirling and round multijet bit flow field is more uniformly compared with the swirling multijet bit. And the high-pressure region connects to form a complete larger annular area.

5 | EXPERIMENTAL VERIFICATION

The experiment is used to study the rock-breaking behavior of the self-propelled swirling jet bit under normal pressure conditions. The experimental apparatus is primarily composed of a high-pressure pump, a pipeline system, a pressure monitoring system, and a jet rock-breaking system. The rock-breaking experiments were conducted by 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) to study the rock-breaking performance changing with the erosion time.

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 8 different jet bits are shown in Figure 23. According to Figure 23, 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 one with a noncentral hole. The experimental results show good agreement with the numerical simulation results, which indicates that it is reliable to analyze the flow field characteristics of the designed jet bit by numerical simulation method in this work.

6 | CONCLUSIONS

To optimize the jet bit with high rock-breaking efficiency, this work analyzed the flow field characteristics of the self-propelled swirling multijet bit and the self-propelled combined swirling and round multijet bit by numerical simulation method and method validation were carried out by laboratory
experiments. Some meaningful conclusions are drawn as follows:

1. It is indicates that the flow field characteristics and the rock-breaking performance of the self-propelled combined swirling and round multijet bit are better than that of the self-propelled swirling multijet bit through analysis of the flow field characteristics and the rock-breaking experiments.

2. The forward jet of the two designed jet bits both consist of swirling jet ejected from each central jet nozzle, and the central nozzle jet width is larger than that of circumferential lateral nozzles. The forward jet velocity attenuation rule of the two jet bits is similar. The maximum jet velocity and jet impact energy of the self-propelled combined swirling and round multijet bit are larger compared with the forward jet of the self-propelled swirling multijet bit.

3. The backward jet of the two designed jet bits both consist of round straight jet ejected from each backward jet nozzle. The jetting law of the two jet bits is basically the same. The maximum jet velocity inside the nozzle is around 250 m/s, and the velocity distribution is not symmetrical along the axis. After flowing through the jet nozzle, the jet velocity rapidly attenuates to 100 m/s and impact the bottom hole with a certain angle, which generates a strong shear stress in the wall. The backward jet improves the reaming capacity and provides self-propelled force by the reverse thrust, making it easier to break rocks.

4. The dynamic pressure distribution of the two designed jet bits both show double ring-shaped distribution. Since the mixing function of the central and the lateral nozzles, there form two annular dynamic pressure increasing regions around the central nozzle and outside the lateral nozzles. However, the bottom-hole dynamic pressure distribution of the self-propelled combined swirling and round multijet bit is more uniformly compared with the self-propelled swirling multijet bit. And the high-pressure region connects to form a complete annular area, which has a larger high-pressure area and a slower attenuation rate.

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NOMENCLATURE:

\[ d_1 \]  diameter of the central nozzle, mm
\[ d_2 \]  diameter of the blended chamber, mm
\[ d_3 \]  external diameter of the impeller, mm
\[ d_4 \]  diameter of the wheel, mm
\[ d_5 \]  central aperture diameter of the impeller, mm
\[ d_f \]  diameter of the forward circumferential nozzle, 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
\[ L_1 \]  total length of the self-propelled swirling jet bit, mm
\[ L_2 \]  outlet length of the central nozzle, mm
\[ L_3 \]  length of the blended chamber, mm
\[ L_4 \]  length of the impeller, mm
\[ t \]  thickness of the blade, mm
\[ \gamma \]  outlet angle of the impeller, °

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