INTRODUCTION

It is known to us that the gas disaster has been one of the most serious accidents in China’s coal mine, seriously threatening the safe production and the miners’ life safety. With the gradual exhaustion of shallow coal reservoir, China’s coal mines have entered the deep mining stage, and the coal and gas outburst disasters have become more
and more serious.\textsuperscript{1,2} At present, the fundamental method preventing coal mine gas disasters is to drill boreholes down or cross the seam to extract gas to reduce the gas content.\textsuperscript{3,4} However, the drainage radius is small because of the low permeability of coal seam.\textsuperscript{5} Thus, the density of drainage boreholes needed would be large and the construction period is also long. Recently, the experts and scholars at home and abroad have proposed a variety of measures to eliminate the outburst risk and enhance the gas extraction efficiency, mainly including destress blasting, hydraulic flushing, water injection, hydraulic fracturing, and water jet.\textsuperscript{6-12} Theoretically, destress blasting can form a cavity with a larger surface area at the bottom of borehole and a larger number of cracks along the borehole because of its powerful fracturing ability. But it is easy to induce outburst if the charge does not meet the field requirements.\textsuperscript{13} Generally, the hydraulic flushing technique can achieve good stimulation effect in soft coal seams with high gas content.\textsuperscript{14} However, due to the large diameter of the boreholes, there exist some unexpected disadvantages such as collapse, clamping, and complicated construction operations. The hydraulic fracturing technology is mainly applied for hard and brittle coal seams, and its fracturing effect has not been satisfactory in soft coal seams.\textsuperscript{15,16} Besides, it causes great waste of water resources because of its large water consumption. The water jet is an emerging technology developed in the past two decades, which has a wide application.\textsuperscript{17,18} It was first used in petroleum engineering field to increase the oil production in lean well. Nowadays, it has been widely used in modern mineral exploration, geothermal resource development, nuclear waste storage, and other fields. In recent years, this technology is attracting more and more attention in coal seam production. It can effectively solve the potential safety hazards such as hard roof, rock burst, coal, and gas outburst.\textsuperscript{19-22} The technical principle of water jet is to use pump to convert the water with high static pressure (SP) into highly concentrated water jet flow with high kinetic energy through the nozzle, which can be used to cut, crush, and clean the material. When crushing rock or coal mass, a complicated stress field would be formed. In addition to compressive stress, a shear stress field is formed near the boundary of water jet and impinging zone, and a tensile stress field is formed at a certain depth directly below the impinging zone, as shown in Figure 1.\textsuperscript{23} Normally, the tensile and shear strength of coal are 1/8 to 1/12 and 1/10 to 1/30 of the compressive strength, respectively.\textsuperscript{24} Therefore, although the compressive stress generated by the water jet cannot cause damage to the coal or rock mass, a large amount of tensile and shear fractures would be formed in coal or rock mass due to its lower tensile and shear strength. Then, the fractures would develop and expand rapidly under the action of the water wedge effect, leading to the ultimate fragmentation of coal mass. In underground field application, the water jet is used to cut the coal body on both sides along the boreholes. A series of flat slots with a certain width would be formed under the action of water jet cutting, as shown in Figure 2. The formation of the slots can release the internal stress of the coal seam, which provides favorable conditions for gas desorption and flow. On the other hand, a large amount of tensile and shear fractures would be formed around the slots due to the unbalanced movement of coal body caused by the geo-stress, the gravity stress of the coal body above the slots, the swelling deformation of the coal body below the slots etc, which further increases the stress released range.

Coal is a double heterogeneous and anisotropic porous medium composed of pores and fractures, of which the pores are the main places for gas adsorption and accumulation, while the fractures are the main channels for free gas migration.\textsuperscript{25} Therefore, the development and distribution characteristics of pores and fractures in coal reservoirs directly determine the gas state in coal seam and further influence the gas drainage effect. After being slotted, partial effective volume stress of coal body around the borehole is released and the geo-stress is redistributed, causing the continuous expansion of original fractures and the formation of new fractures.\textsuperscript{26} Thus, the effective drainage radius of a single borehole would be fully improved. What's more
important, a stress relief the coal body between boreholes can be achieved, which enlarges the effective gas drainage radius, changing the fast attenuation of gas drainage in the past. In addition, with the advancement of the working surface, the coal body around the slots is generally subjected to the mining effect, resulting in the continuous expansion of the fractures around the slots and the increase in the fracture density. As a result, the gas drainage efficiency is significantly improved, greatly shortening the gas drainage period. On the other hand, as the main channels for gas flow in coal seam, the fractures are connected to the drainage roadways through boreholes. Thus, a large amount of gas in coal seam around the fractures would desorb and be extracted under the action of pressure and concentration gradient, greatly reducing the gas internal energy and further eliminating the outburst risk.

Recently, based on the technical principle of water jet, scholars have developed many improved jet techniques, such as abrasive water jet, abrasive gas jet, and pulse water jet gas jet. As the key and terminal component of water jet technique, the nozzle would influence the formation of water jet. Thus, it is necessary to investigate the effect of the configuration and geometrical parameters of nozzle on the flow field of water jet, which is of significance to improve the cutting ability of water jet and nozzle design.

The present work is aimed to optimize a water jet nozzle system through numerical simulation using Fluent software. The effects of the configuration and geometrical parameters of nozzle on the real flow field of water jet impinging wall were discussed based on the numerical results. Additionally, the improved nozzle designed based on the numerical simulation was used in the field test to verify its cutting effect. The gas data before and after slotting would be the index to evaluate its cutting capacity.

2 PHYSICAL AND NUMERICAL MODEL

2.1 Geometry description

At present, there are three typical water jet nozzles being used in field work, including cylindrical nozzle, conical nozzle, and conical-straight nozzle, as shown in Figure 3. Obviously, they have different geometrical structures and parameters of internal flow channels, which may influence the flow field of water jet. The geometrical parameters mainly include the
inlet diameter \((D)\), conic angle \((\alpha)\), outlet diameter \((d)\), total length \((L)\), and cylindrical section \((l)\).

### 2.2 Physical model

Taking the conical nozzle as an example, a geometric model for impinging jet was established using simplified conditions for the field, as shown in Figure 4. It is noted that the same work was also conducted for other nozzles. A structured quadrilateral grid is used for mesh division, and the mesh number is 35000. The calculation boundary conditions are set as shown in Figure 4. Obviously, the polygon of ABCUHJ is the water jet nozzle, and the rectangle DEFG is the calculation domain. Edge AJ is taken as the entrance of the calculation domain. The distance between the end of the water jet nozzle and the impinging surface can be represented by the length of DE or GF. Besides, the inlet and outlet boundaries are the pressure inlet and outlet, respectively. The wall surface is a nonslip wall.

### 2.3 Governing equations

To investigate the flow field of the water impinging jet, ANSYS FLUENT was employed. For high-pressure water jet flow field, the RNG k–\(\varepsilon\) turbulence model was used in this paper. The governing equations for the standard k–\(\varepsilon\) turbulence model are as follows:\(^\text{27}\):

**Mass balance equation**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\] (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 
\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho 
\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho 
\text{where} \text{div} \text{and grad are vector symbols, that is}
\[
\text{div}(a) = \frac{\partial a_x}{\partial x} + \frac{\partial a_y}{\partial y} + \frac{\partial a_z}{\partial z}
\] (5)

\[
\text{grad}u = \left( \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z} \right) 
= \left( \frac{2x}{x^2+y^2+z^2}, \frac{2y}{x^2+y^2+z^2}, \frac{2z}{x^2+y^2+z^2} \right)
\] (6)

And \(S_u\), \(S_v\), and \(S_w\) are generalized source terms in momentum conservation equation, that is
\[
S_u + F_x + s_x
\] (7)

\[
s_x = \frac{\partial}{\partial x} \left( \eta \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \eta \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( \eta \frac{\partial w}{\partial z} \right) + \frac{\partial}{\partial x} (\lambda \text{div}U)
\] (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; \(\lambda\) is the second viscosity.

**Energy balance**

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

### 3 NUMERICAL RESULTS AND ANALYSIS

#### 3.1 General characteristics of the flow field of impinging water jet

Generally, the high-pressure free water jet can be divided into three stages, including initial stage, basic stage, and dissipation stage, as shown in Figure 5A. In the initial stage, the dynamic pressure (DP) and velocity of jet flow do not change both in magnitude and direction. And there is no jet atomization phenomenon occurring in this stage. In the basic stage, the turbulent characteristics of jet flow are fully developed, and the atomization phenomenon becomes more obvious with the increase in jet distance. Due to the high velocity and pressure of the jet flow in this stage, it is beneficial for rock or coal breaking. In the dissipation stage, the jet flow is fully mixed with the air medium, and the DP and velocity are low, which no longer has rock breaking ability. Figure 5B illustrates the velocity contours of impinging water jet for cylindrical nozzle. Obviously, it has a similar structure to the free water jet. The wall surface is basically in the basic section of the jet flow. After the jet comes out of the nozzle, there is a certain atomization phenomenon due to the rapid drop of pressure. Figure 5C shows the corresponding velocity vector of impinging water jet. After impinging on the wall, the jet diffuses along the wall toward both ends in the impinging zone. Meanwhile, due to the interaction of the high velocity water jet and the reflected jet, two strong local eddies are formed on both sides of the jet.
The effect of nozzle structure on the impinging jet flow field

For the numerical simulations in this subsection, the inlet pressure $P_{in} = 10$ MPa and the outlet $P_{out} = 0.1$ MPa. The variation characteristics of the impinging flow field induced by the nozzle structure are analyzed in terms of physical fields (axial DP, axial velocity magnitude, and SP on the wall). The specific parameters of different nozzles are set as shown in Table 1, which have been defined in Section 2.1. The target distance $S$ represents the distance between the end of the water jet nozzle and the impinging wall.

Figures 6-8 show the contours of physical fields for three typical nozzles with different structures. The DP field of impinging water jet for different nozzles is shown in Figure 6. Dynamic pressure is an index characterized by the kinetic energy per unit volume of a moving fluid. The water flows through the nozzle, and the DP is significantly enhanced. However, the maximum DP of water jet for the cylindrical nozzle occurs inside the nozzle, while that of the conical and conical-straight nozzle appear outside the nozzle. Besides, an interesting phenomenon can be found that the DP increases abruptly where the nozzle cross section changes, which indicate that the cross-sectional area of the nozzle has a great influence on the flow field of water jet. This is due to that, for the incompressible flow, the smaller the cross section of the nozzle, the higher the flow velocity. And the sharp corner changes abruptly the fluid flow direction. Near the sharp corner region, the variation gradient of DP and velocity is stronger.29-32 In two-dimensional model, the cross-sectional area can be represented by the diameter of nozzle. The distributions of the axial DP of impinging water jet are shown in Figure 9. The maximum DP of water jet for three nozzles is 68.28 MPa, 70.53 MPa, and 70.79 MPa, respectively. In addition, the axial DP of water jet for conical and conical-straight nozzles decays at 11 mm from the nozzle exit, while that for cylindrical nozzle begins to decay at 8 mm. Besides, the key area of water jet for conical and conical-straight nozzle is mainly distributed outside the nozzle, while that for cylindrical nozzle is mainly distributed inside the nozzle. Through comparison, the conical and conical-straight nozzle may have more advantages in terms of DP distribution and magnitude.

Figure 7 shows the velocity field of impinging water jet for different nozzles. Obviously, the water flows through the nozzle and is accelerated, forming high-speed water jet at the nozzle exit. The distributions of the axial velocity of water jet

![FIGURE 5](image_url) Flow field of water jet. A, Basic structure of free water jet dynamics. B, Velocity contours of impinging water jet. C, Velocity vector of impinging water jet

| Geometric parameters of different nozzles | $d$ (mm) | $D$ (mm) | $\alpha$ (°) | $L$ (mm) | $l$ (mm) | Target distance ($S$) (mm) |
|------------------------------------------|---------|---------|-------------|---------|---------|-------------------------|
| Cylindrical nozzle                       | 2       | 4       | –           | 14      | 14      | 18                      |
| Conical nozzle                           | 2       | 4       | 4.1         | 14      | –       | 18                      |
| Conical-straight nozzle                   | 2       | 4       | 7.1         | 14      | 6       | 18                      |

![FIGURE 6](image_url) The DP field of impinging water jet for different nozzles. A, Cylindrical nozzle. B, Conical nozzle. C, Conical-straight
are shown in Figure 10. The maximum velocity of water jet for three nozzles is 369.88 m/s, 375.92 m/s, and 376.63 m/s, respectively. Similar to the variation in DP, the maximum velocity of water jet for the cylindrical nozzle occurs inside the nozzle, while that of the conical and conical-straight nozzle appear outside the nozzle. Meanwhile, the axial velocity of water jet for conical and conical-straight nozzles decays at 11 mm from the nozzle exit, while that for cylindrical nozzle begins to decay at 8 mm. The water jet is an incompressible flow, that is, the physical properties of the density and quality of each point of the fluid are the same. Therefore, it has similar variation characteristics as DP. From Figure 7B,C, the velocity of water jet inside the conical-straight nozzle is higher than that inside conical nozzle, which may cause serious jet attaching effect, leading to more energy loss.33-35 On the other hand, serious jet attaching effect can wear the
nozzle, causing it to fail. Therefore, the conical nozzle may be a good choice for the field application.

Figure 8 shows the SP field of impinging water jet for nozzles with different structures, and Figure 11 shows the distributions of SP on the wall. Obviously, the jet impinging area is 8.9 mm. The maximum pressure for different nozzles is 31.38 MPa, 54.76 MPa, and 54.94 MPa, occurring at the center of the impinging area. From Figures 6-11, the closer to the wall, the lower DP and velocity of the water jet, but the higher the SP on the wall. Actually, the damage of coal or rock body under the action of water jet is mainly caused by the combined action of impinging dynamic load and quasi-static load. And the impinging load plays a dominant role in the initial stage of coal or rock breaking, while the quasi-static load plays a dominant role in the later stage. Therefore, the DP, velocity, and SP are used as the key jet flow parameters to optimize the nozzle.

From aforementioned analysis, the conical nozzle has more advantages than other two nozzles.

3.3 The effect of geometrical parameters of nozzle on the impinging jet flow field

3.3.1 The effect of outlet diameter (d) of nozzle

Based on last Section 3.2, the conical nozzle and its related parameters are selected for further simulation optimization. In this subsection, the effect of outlet diameter (d) of

FIGURE 12 The flow field of impinging water jet for nozzles with different outlet diameters

FIGURE 13 Spray angles of water jet. A, Field test. B, Numerical test
The effect of conic angle ($\alpha$) of nozzle

In this subsection, the effect of conic angle ($\alpha$) of nozzle on the impinging jet flow field is investigated, and the simulation boundaries are set as follows: $P_{\text{in}} = 60$ MPa; $P_{\text{out}} = 0.1$ MPa; $d = 3$ mm; $\alpha = 4^\circ$, $7^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$; $L = 14$; and $S = 18$ mm. From the contour of DP and velocity in Figure 15, the length of key area of water jet roughly decreases with the increase in conical angle. Besides, from the contour of SP in Figure 15, with the increase in conical angle, the maximum pressure transfers from the wall to the interior of the nozzle. The specific flow characteristics of water jet on rock breaking, the outlet diameter of 3 mm and 4 mm has approximate magnitude, which is larger than that for the nozzle with outlet diameter of 2 mm. Considering the effect of spray angle of water jet on rock breaking, the outlet diameter of 3 mm and 4 mm may be a better choice for water jet in field work.
for nozzles with different conical angles are shown in Figure 16, and the key-related parameters are listed in Table 2. As shown in Figure 16A,B, inside the nozzle, the DP and velocity of water jet decrease with the increase in conical angle. Outside the nozzle, the DP and velocity first increase and then decrease with the increase in the distance from the nozzle exit. However, when the conical angle increases to 25°, the DP and velocity no longer increase but directly decrease from the value of the nozzle exit. From Figure 16C, the maximum SP on the wall of the water jet also decreases with the increase in conical angle.

Some detailed flow characteristics of water jet for nozzles with different conical nozzles can be obtained in Table 2. It is noted that DP<sub>max</sub> is the maximum DP of the water jet. The same definition is given to maximum velocity (<i>V</i><sub>max</sub>) and maximum SP on the wall (SP<sub>max</sub>). And <i>s</i> represents the distance of the DP<sub>max</sub> or <i>V</i><sub>max</sub> from the nozzle exit, which can reflect the length of the key area of water jet. Obviously, when the conical angle increases to 7° from 4°, the DP<sub>max</sub>, <i>V</i><sub>max</sub>, SP<sub>max</sub>, and <i>s</i> all increase to some extent. However, when the conical angle exceeds 7°, these parameters decrease with the continuous increase in conical angle. Although the impinging area also increases with the increase in conical angle, a larger reduction occurs in the corresponding SP<sub>max</sub>. In addition, the spray angle of water jet generally increases with the increase in conical angles from 4° to 25°, but it remains the same values in the interval from 7° to 20°. Through comprehensive consideration, the conical angle of 7° may be a good choice for further optimization.
3.3.3 | The effect of length (L) of nozzle

In this subsection, the effect of length (L) of nozzle on the impinging jet flow field is investigated, and the simulation boundaries are set as follows: \( P_{\text{in}} = 60 \text{ MPa}; \ P_{\text{out}} = 0.1 \text{ MPa}; \ d = 3 \text{ mm}; \ \alpha = 7^\circ; \ L = 6 \text{ mm, 9 mm, 12 mm, 14 mm}; \text{ and } S = 18 \text{ mm}. \) Figure 17 shows the flow characteristics of water jet for nozzles with different length, and Table 3 lists the key-related parameters. The DP and velocity of water jet for nozzles with different length show similar variation characteristics, which indicates that the length of nozzle has little influence on the distribution of flow field of water jet. However, with the increase in length of nozzle, the related key jet flow parameters show different variation characteristics. From Table 3, when the length of nozzle increases to 9 mm from 6 mm, the \( \text{DP}_{\text{max}}, \ V_{\text{max}}, \) and \( \text{SP}_{\text{max}} \) increase to some extent; However, when the length of nozzle exceeds 9 mm, they begin to decrease as the length of nozzle increases. But the value of \( s \) shows opposite variation characteristics, and 9 mm is still the turning point. This indicates that the length of 9 mm is the critical value for the variation in these parameters. In addition, the length of nozzle may have no effect on the impinging area and spray angle. At least, they remain the same values as the length of nozzle increases to 14 mm from 6 mm. Therefore, the length of 9 mm is selected for the further simulation.

3.4 | The effect of inlet pressure (\( P_{\text{in}} \)) and target distance (\( S \)) on the impinging jet flow field

From the above simulation results, the conical nozzle with outlet diameter (\( d \)) of 3 mm, conical angle (\( \alpha \)) of 7°, and length (\( L \)) of 9 mm can be identified as the best water jet nozzle. In this subsection, the effects of inlet pressure (\( P_{\text{in}} \)) and target distance (\( S \)) on the impinging jet flow field are investigated.

### Table 2

| \( \alpha \) | \( \text{DP}_{\text{max}} \) (MPa) | \( V_{\text{max}} \) (m/s) | \( s \) (mm) | \( \text{SP}_{\text{max}} \) (MPa) | Impinging area (mm) | Spray angle (°) |
|---|---|---|---|---|---|---|
| 4  | 71.63 | 378.84 | 10.1 | 59.49 | 8.18 | 10 |
| 7  | 75.13 | 388.00 | 10.4 | 60.88 | 8.90 | 11 |
| 10 | 75.10 | 387.90 | 10.4 | 60.18 | 8.90 | 11 |
| 15 | 73.96 | 385.00 | 10.1 | 56.35 | 8.90 | 11 |
| 20 | 68.70 | 371.00 | 9.8 | 46.45 | 9.26 | 11 |
| 25 | 59.90 | 346.38 | 6.7 | 36.15 | 9.64 | 12 |

**FIGURE 16** Flow characteristics of impinging water jet for nozzles with different conic angles. A, Distributions of the axial DP. B, Distributions of the axial velocity. C, Distributions of SP on the wall.
Figure 18 shows the variation characteristics of water jet flow for fixed nozzle under different inlet pressure. The variation in inlet pressure exerts no effect on the distribution of the DP, velocity, and SP. However, it has a great influence on the magnitude of these parameters. Table 4 lists the variation in key jet flow parameters of water jet under different inlet pressures. Obviously, $\text{DP}_{\text{max}}$, $V_{\text{max}}$, and $\text{SP}_{\text{max}}$ all increase with the increase in inlet pressure, but the impinging area, spray angle, and $s$ remain the same value. From Figure 19, it can be concluded that $\text{DP}_{\text{max}}$, $V_{\text{max}}$, and $\text{SP}_{\text{max}}$ linearly increase with the inlet pressure. Thus, it is difficult to determine which inlet pressure is the best from the perspective of the jet dynamic parameters. Undoubtedly, the larger the inlet pressure, the greater the DP, velocity, and impinging SP of the water jet, the better the rock breaking effect, but the higher the requirements for equipment performance. Therefore, to obtain better rock breaking effect and guarantee operation safety, the inlet pressure should be selected according to the coal seam properties and the actual underground conditions.

Figure 20 shows the contours of flow field of impinging water jet at different target distances. When the target distance is small, the jet cannot fully develop, resulting in the low velocity of water jet. As the target distance increases to a certain value, the jet flow fully develops, leading to higher velocity and larger impinging pressure of water jet on the wall. With the continuous increase in the target distance, the jet velocity and impinging pressure gradually decrease due to that the momentum exchange and turbulent diffusion occur between the water jet and air. Figure 21 plots the distribution curves of DP, velocity, and SP at different target distances. When the target distance increases from 15 mm to 18 mm, the DP, velocity, and SP increase to some extent. However, when the target distance exceeds 18 mm, these jet dynamic parameters decrease with the increase in target distances. Especially, when the target distance exceeds 21 mm, the jet dynamic parameters decrease abruptly. Since then, the jet parameters decrease slowly with the increase in target distance. Table 5 clearly lists the variation in key jet flow parameters at different target distances. The $\text{DP}_{\text{max}}$, $V_{\text{max}}$, and $\text{SP}_{\text{max}}$ first increase then decrease with the increase in target distance.

**TABLE 3** Variation in key jet flow parameters with the length ($L$) of nozzles

| $L$ (mm) | $\text{DP}_{\text{max}}$ (MPa) | $V_{\text{max}}$ (m/s) | $s$ (mm) | $\text{SP}_{\text{max}}$ (MPa) | Impinging area (mm) | Spray angle (°) |
|----------|-----------------|-----------------|------|-----------------|------------------|-----------------|
| 6        | 71.51           | 378.51          | 10.38| 58.34           | 8.90             | 10              |
| 9        | 75.73           | 389.52          | 10.10| 61.49           | 8.90             | 10              |
| 12       | 75.34           | 388.52          | 10.24| 61.07           | 8.90             | 10              |
| 14       | 75.14           | 388.00          | 10.44| 60.88           | 8.90             | 10              |

**FIGURE 17** Flow characteristics of impinging water jet for nozzles with different length. A, Distributions of the axial DP. B, Distributions of the axial velocity. C, Distributions of SP on the wall.
distance, and 18 mm is the critical value. In addition, the variation in target distance exerts no influence on the impinging area and spray angle. Although with the increase in target distance, \( s \) increases to some extent, and 18 mm is considered as the best target distance due to the larger pressure reduction.

4 | FIELD INVESTIGATION

4.1 | Field overview

Rujigou Coal Mine belongs to Shenhua Ningxia Coal Group, located in Pingluo County, Shizuishan City, Ningxia Province, as shown in Figure 22. The upper elevation of the coalfield is +2300 m, and the lower elevation is +1800 m. The south-north toward length and east-west tendency width of coalfield are 8.9 km and 2.31 km, respectively. Its production capacity is 1.2 million tons/a. Besides, it was identified by China Coal Technology Engineering Group Chongqing Research Institute as a high gas content coal mine. The inclined shaft development method is employed.

4.2 | Test site and experimental layouts

The test site was selected at the mechanical roadway of 32211 working face, Rujigou coal mine. The mining area

### TABLE 4 Variation in key jet flow parameters under different inlet pressure

| \( P_{in} \) (MPa) | \( \text{DP}_{max} \) (MPa) | \( V_{max} \) (m/s) | \( s \) (mm) | \( \text{SP}_{max} \) (MPa) | Impinging area (mm) | Spray angle (°) |
|----------------|----------------|----------------|--------|----------------|----------------|-----------------|
| 15             | 18.91          | 194.68         | 10.10  | 15.37          | 8.90           | 10              |
| 30             | 37.79          | 275.27         | 10.10  | 30.74          | 8.90           | 10              |
| 45             | 56.29          | 337.19         | 10.10  | 46.11          | 8.90           | 10              |
| 60             | 74.82          | 389.52         | 10.10  | 61.49          | 8.90           | 10              |

### FIGURE 18 Flow characteristics of impinging water jet for fixed nozzle under different inlet pressures. A. Distributions of the axial DP. B. Distributions of the axial velocity. C. Distributions of SP on the wall

### FIGURE 19 Water jet flow parameters versus inlet pressure
measures 220 m × 1102 m. The mining seam was 2#1 coal seam. It has an average thickness of 8.75 m ranging from 8.30 to 9.20 m and an average dip angle of 10° ranging from 8° to 12°. And the consistent coefficient (\(f\)-value) is 1.5. The geological setting is shown in Figure 23. The gas pressure and content are 0.56 MPa and 5.2 m³/t, respectively. And the absolute gas emission rate is 14 m³/min. The coal seam permeability is 6.7 m² MPa⁻² day⁻¹. Identified by China Coal Technology Engineering Group Chongqing and Fushun Research Institutes, the 2#1 coal seam is at risk of outburst.

According to the geological and gas condition of 32211 working face in Rujigou coal mine, the high-pressure water jet technique was proposed to improve the gas drainage efficiency. The total length of the test section of the mechanical roadway was 130 m. Six sets of cross-boreholes with interval of 20 m were drilled, and each group contains 3 boreholes with interval of 1.2 m. The borehole diameter and elevation angle are 75 mm and 12°-16°, respectively. After the completion of the boreholes, the rotary water jet was employed to cut the coal body around the inside of the borehole into slots with certain width and height using MK-50 drilling machine. The slotting time for each borehole was 3-5 min. In order to guarantee the safety of construction, the pump pressure was set at 45 MPa. In addition, the distance between the final slotting position and the end of the borehole should be no less than 5 m.

4.3 Testing procedures

The test procedures of water jet slotting are as follows:

1. According to the design requirement, drill gas drainage boreholes into coal seam. And relevant equipment such as high-pressure water pumps is transported to designated locations.
2. Connect the high-pressure water jet slotting system through high-pressure hose.
3. Check the volume of water in the tank and whether the water supply system can work properly.
4. Send the drill pipe installed with cutting nozzle to the bottom of the borehole using the drilling machine.

FIGURE 20 The flow field of impinging water jet at different target distances (\(S\))
5. Open the pressure valve of the high-pressure water pump, so that the pressure gradually reaches 45 MPa.
6. Use the drilling machine to control the traverse speed of the cutting nozzle and conduct the slotting work. Besides, the target distance can be also controlled using drilling machine and different types of drilling pipe.
7. When the cutting nozzle is 5-6 m away from the end of borehole, stop cutting and close the high-pressure pump. Thus, the slotting work would be completed.
8. The sealing work should be conducted for slotting boreholes to prevent gas leakage. Generally, the sealing length should be 5-10 m and the position should be in the stress concentration zone of slotting boreholes. Besides, a small amount of cement expansion agent should be mixed into the sealing materials to prevent shrinkage and deformation of cement from affecting the sealing effect. When sending the cement mortar into the borehole, put a cork with a diameter slightly larger than the borehole every 0.3-1.0 m and tamper it firmly.
9. Repeat steps (3)-(8) and conduct a new slotting operation.

Considering the safety problem during slotting operation, the workers should keep away from the rotating parts of high-pressure pump and connecting parts of pipeline. The gas inspectors should check the gas concentration at the construction site 24 hours a day. Once the gas overlimit is found, the power must be cut off first to withdraw people and report to the ventilation team in time. It is noted that the nozzle used in field test is a conical nozzle, the structural parameters of which are obtained from the numerical simulation.

4.4 Results and analysis

Before the slotting work of drainage boreholes, the exposed coal wall at the end section of the mechanical roadway was firstly conducted for cutting test to examine the slotting effect by water jet. It can be found that the depth and height of slots

### TABLE 5 Variation in key jet flow parameters at different target distances ($S$)

| $S$ (mm) | DP$_{\text{max}}$ (MPa) | $V_{\text{max}}$ (m/s) | $s$ (mm) | SP$_{\text{max}}$ (MPa) | Impinging area (mm) | Spray angle ($^\circ$) |
|---------|-------------------------|-------------------------|----------|------------------------|---------------------|----------------------|
| 15      | 53.43                   | 327.18                  | 7.65     | 45.52                  | 8.90                | 10                   |
| 18      | 56.74                   | 337.20                  | 10.10    | 46.11                  | 8.90                | 10                   |
| 21      | 56.40                   | 336.17                  | 12.92    | 42.30                  | 9.28                | 10                   |
| 24      | 50.26                   | 317.33                  | 14.10    | 31.72                  | 9.64                | 10                   |
| 27      | 48.32                   | 311.15                  | 15.10    | 28.87                  | 9.64                | 10                   |
| 30      | 47.12                   | 307.27                  | 8.88     | 25.77                  | 9.64                | 10                   |

**FIGURE 21** Flow characteristics of impinging water jet at different target distances. A, Distributions of the axial DP. B, Distributions of the axial velocity. C, Distributions of SP on the wall.
by water jet were 500 mm and 50 mm, respectively. It can achieve the expected slotting effect. Besides, the variation in gas concentration and quantity of several drainage boreholes before and after slotting was shown in Figure 24. The gas drainage concentration and quantity after slotting abruptly increased significantly and maintained at a high level in about 20 days. As the drainage time increased, the gas concentration and quantity decrease gradually and entered a decay state.

Figure 25 shows the gas variation before and after slotting for gas drainage boreholes. From Figure 25A, the gas concentration was 46.48%–64.64% before slotting. After slotting, the gas concentration was 63.38%–88.77%, which was enhanced significantly. This is due to that the slots formed by water jet increased the gas migration channels. On the other hand, the original stress field in coal seam was destroyed by slotting, resulting in the stress relief in coal seam. Thus, a large amount of gas would desorb. As shown in Figure 25B, the gas quantity was quite low, 0.0021–0.0246 m³/min, before slotting. After slotting, the gas quantity was improved to 0.0023–0.1533 m³/min. The water jet slotting can effectively create a large amount of new fractures in coal body around the borehole. Meanwhile, the original fractures would expand continuously because of the stress releasing of coal body. Under the function of geo-stress, the nonuniform deformation and failure of coal body treated by water jet slotting occurred, resulting the increase in the number, length, and opening degree of the fractures. The gas desorption rate and gas flow rate correspondingly increased.

5 | CONCLUSIONS

To optimize the nozzle and further improve the rock breaking ability of water jet, the effects of different nozzles, inlet pressure, and target distance on the flow field of impinging water jet are investigated through CFD software Fluent14.0. Additionally, the improved nozzle designed based on the numerical simulation was used in the field test to verify its cutting effect.

The geometrical structure exerts great influence on the flow field of impinging water jet. The nozzles with conical and conical-straight have higher DP, velocity, and SP. Considering the jet attaching effect, the conical muzzle may have more advantages. The variation in outlet diameter of nozzle exerts little effect on the physical field of impinging water jet, but the jet dynamic parameters increase with the outlet diameter, as well as the spray angle of water jet. There exist critical values for conical angle and length of nozzle, after which the jet dynamic parameters would decrease abruptly. Therefore, the conical nozzle with outlet diameter of 3 mm, conical angle of 7°, and length of 9 mm can be identified as the best.

Besides, the jet dynamic parameters linearly increase with the inlet pressure. However, to obtain better rock breaking effect and guarantee operation safety, the inlet pressure should be selected according to the coal seam properties and the actual underground conditions. The jet dynamic parameters first
increase then decrease with the increase in target distance, and 18 mm is the critical value. When the target distance exceeds 21 mm, the jet dynamic parameters decrease abruptly.

Based on the simulation results, the optimized nozzle is used in field application in Rujigou coal mine, in which the inlet pressure was selected as 45 MPa, and the target distance was set as 18 mm. After slotting, the gas concentration and quantity are enhanced from 46.48%-64.64% and 0.0021-0.0246 m³/min to 63.38%-88.77% and 0.0023-0.1533 m³/min, respectively. This indicates that

**FIGURE 24** Gas drainage efficiency of boreholes before and after slotting. A, 1# borehole. B, 3# borehole. C, 8# borehole. D, 15# borehole

**FIGURE 25** Gas variation before and after slotting. A, Gas concentration. B, Gas quantity
the water jet technique can effectively improve the coal seam permeability and further enhance the gas drainage efficiency.

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CONFLICT 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.

AUTHOR CONTRIBUTIONS

XueLin Yang and Tingkan Lu conceived and designed the experiments; Lipeng He and Guang Luo performed the experiments; Yanbao Liu and Xuelong Li analyzed the data; XueLin Yang, Jie Cao and Huiming Yang wrote the paper.

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