Research Article

Extension Limit of a Straight-Swirling Mixed Jet Bit and Its Influential Factors in Radial Jet Drilling

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Received 3 April 2022; Revised 9 May 2022; Accepted 11 May 2022; Published 23 May 2022

Academic Editor: Yong Li

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Radial jet drilling (RJD) is applied to low-permeability and unconventional natural gas. A self-propelled bit chiefly affects the borehole length and drilling efficiency. Herein, for a straight-swirling mixed jet (SSMJ) bit, a prediction model of the drilling extension limit \( L_{EL} \) was established by analysing the forces and pressure loss of RJD system. \( L_{EL} \) of a specific project was calculated and the pressure loss and forces distribution were obtained. Additionally, the influence laws of the main factors on \( L_{EL} \) were studied using the established model. The results indicated that the high-pressure hose contributes the main system pressure loss, and the recoil force of backward nozzles is the sole driving force of RJD. The recoil force of forward nozzle and friction between the hose and borehole constitute the main resistances. Increasing the pump pressure \( p_b \), backward nozzle diameter \( d_b \), and jet diffusion angle \( \theta_x \) and reducing forward nozzle diameter \( d_f \), impeller central hole diameter \( d_m \), and backward nozzle inclination angle \( \theta_b \) are conducive to improving \( L_{EL} \). However, larger \( p_b \) and \( d_b \) increase the hydraulic consumption, besides larger \( \theta_x \) or smaller \( d_f \), and \( d_m \) will reduce the rock-breaking capability. From a sensitivity analysis, \( p_b \) and \( d_m \) have the maximum and minimum influence on \( L_{EL} \), respectively. Finally, prediction value \( L_{EL} \) of an oil well in Eastern Sichuan can be up to 63.7 m. The results provide a guidance for the hydraulic parameters and key component selection, additionally bit structure optimization of RJD.

1. Introduction

China is rich in unconventional natural gas resources of coalbed methane (CBM) and shale gas, etc. [1]. Of these, the total CBM resources in China that are within 2000 m from the ground are estimated to be 36.81 trillion cubic meters [2, 3]. Most of the production wells are located in the southern Qinshui Basin and eastern Ordos Basin [4, 5].

Radial jet drilling (RJD) technology was imposed in the 1980s [6]. The use of RJD to exploit low-permeability oil-gas reservoirs, CBM, and shale gas is a hot topic and an important direction for the development of oil-gas resource drilling [7–10]. A RJD technique utilizes hydraulic energy to create several lateral holes in different directions and levels with several different lengths. These lateral holes are made by milling the casing with a small bit and then extending these holes laterally using high-pressure hydraulic jetting, which can improve the recovery of oil and gas with lower cost [11]. In 2011, Petrobel Company drilled five 50 m radial wells and one 90 m well at two strataums at No.1 well in Belayin Oil Field [12]. The successful application of RJD in the world reflects its promising future.

Predicting the extension limit of the RJD can optimize the layout of boreholes, and it is significant to improve their output. To date, some authors researched the main factors influencing the extension limit, such as the self-propelled force of the bit and system pressure loss. Buset et al. researched the self-propelled force of multiple nozzle jet bits of a RJD system [13]; Ma et al. established a calculation model of pressure loss for RJD system by analysing the pressure loss of a coiled tube and high-pressure hose [14]; Zhang et al. designed a jet radial horizontal drilling simulation experiment system of the casing windowing and evaluated the self-propelled force of a multifluid nozzle [15].

A self-propelled bit, the “core” of RJD, chiefly affects the borehole length and drilling efficiency. RJD technology changes the direction from a vertical to horizontal direction using a diverter [15]. The turning radius of the interior trail...
within the diverter is small, which limits the dimension of the bit. Therefore, only a simple structure can be selected in the design of bit. Research [16–19] indicated that the jets used for drilling can be divided into three main types: straight, swirling, and a combination thereof. Li et al. researched sandstone-breaking characteristics by experiment and studied the influence of working conditions of lithology, axis length, jet pressure, and standoff distance [20]. Liu et al. adopted the FLUENT combined with RNG turbulence model to analyze the multinozzle jet flow field and study the effects of inclination angle of forward nozzles and standoff distance [21]. Du et al. researched the damage characteristics of straight jet, swirling jet, and SSMJ and then obtained the velocity fields of the three jets by 3DPIV [22]. Overall, a straight jet can drill a deep hole, yet the diameter is smaller because the energy of the jet is more centralized. A swirling jet can be used to drill a larger diameter hole, but it has a boss at the centre owing to the central low-velocity zone of the jet. A combination of a dual-jet nozzle or an SSMJ nozzle can combine the advantages of both a straight jet and swirling jet [23–25]. Few articles have been published on the research on predicting the extension limit of an SSMJ and its influential factors.

With an SSMJ as the research objective, this study established a model to predict the extension limit of a RJD system by analysing the distributions of force and pressure loss. Thereafter, the drilling extension limit of a specific project was calculated and the pressure loss and forces were obtained. Finally, the influence laws of the main parameters (pump pressure, diameter of the forward nozzle and backward nozzle, diffusion angle of the jet, inclination angle of the backward nozzle, etc.) on the extension limit were studied using the established prediction model; additionally, the influence degree of parameters was investigated. We conducted these studies in an attempt to provide a guidance for the construction parameter selection of the RJD.

2. Mathematical Model

During drilling, the horizontal section of the RJD system has a self-propelled force of the bit \( F_p \), the pressure of an external fluid on the bit \( F_o \), friction between the diverter and high-pressure hose \( F_{rz} \), friction between the borehole and high-pressure hose \( F_{rk} \), and friction between the borehole and bit \( F_{sk} \), as shown in Figure 1. Owing to the lower flow rate of the system and the use of a pure water jet during operation, the viscosity is low, and the viscous resistance of the fluid in the borehole to the hose is also small, which can be ignored. The resultant force \( F \) on the RJD system is expressed as

\[
F = F_p - F_o - F_{rz} - F_{rk} - F_{sk}.
\] (1)

2.1. Self-Propelled Force of the Bit. An SSMJ bit comprises of a body and an impeller with a central hole and several slots (Figure 1). Its basic operating principle is as follows: the fluid flows into the mixing chamber through the central hole and slots of the impeller, generating a low-speed, straight-swirling flow. An SSMJ with a high axial velocity and peripheral rotational intensity is then created successively under the pressurization of the nozzle outlet, and the extended section ensures a specific target distance when breaking rock. In addition, the jets created by the backward nozzles can push the bit and high-pressure hose forward. A straight jet has only a one-dimensional velocity; however, for a swirling jet, the trajectory is approximately a helix, and the velocity of any particle is a space vector, its axial velocity \( u \) is parallel to the jet axis, and its radial and tangential velocities \( v \) and \( w \) are perpendicular to the jet axis [26, 27]. When the system is operating, the forces of the bit include the recoil force of the backward nozzles \( F_b \) and recoil force of the forward nozzle \( F_f \). Naturally, the self-propelled force of the bit \( F_p \) is \( F_b \) minus \( F_f \).

2.1.1. Recoil Force of the Forward Nozzle. The recoil force of the SSMJ forward nozzle was produced from two parts: straight jet and swirling jet. If the forward nozzle and the impeller central hole diameter are \( d_i \) and \( d_m \), respectively, the flow area of the swirling jet is the difference between the forward nozzle area and the central hole area, and the equivalent diameter of the swirling jet can be obtained:
\[ d_x = \sqrt{d_i^2 - d_m^2}. \] (2)

(a) Recoil Force of the Straight Jet. The equation to calculate the recoil force of the straight jet acting on the bit is [27]

\[ F_m = 1.56 \mu _i d_m^2 p_i, \] (3)

where \( p_i \) is the nozzle inlet pressure (MPa) and \( \mu _i \) is the flow coefficient of the forward nozzle.

(b) Recoil Force of the Swirling Jet. Swirling jet is approximately shaped as "M"; therefore, for ease of calculation, we can assume that all fluid particles of the swirling jet are distributed on the cone with a diffusion angle of \( \theta _r \). Moreover, the approximate relationship between the axial velocity flow rate \( q_a \) and total flow rate \( q_s \) can be obtained:

\[ q_a = q_s \cos \frac{\theta _r}{2}. \] (5)

Additionally, \( q_s \) is

\[ q_s = 2.1 \mu _i d_s^2 \sqrt{p_i}. \] (6)

Combining Equations (4), (5), and (6), we obtain

\[ F_x = 1.56 \mu _i (d_i^2 - d_m^2) p_i \cos \frac{\theta _r}{2}. \] (7)

Finally, the forward nozzle recoil force is

\[ F_f = F_m + F_x = 1.56 \mu _i p_i \left[ d_m^2 + (d_i^2 - d_m^2) \cos \frac{\theta _r}{2} \right]. \] (8)

2.1.2. Recoil Force of Backward Nozzles. Referring to the analysis method in the previous section, the equation for the backward nozzle recoil force can be written as

\[ F_b = \sum_{b=1}^{n_b} 1.56 \mu _b d_b^2 p_i \cos \theta _b, \] (9)

where \( n_b \) is the number of backward nozzles and \( d_b, \theta _b, \) and \( \mu _b \) are the diameter, inclination angle, and flow coefficient of a backward nozzle, separately.

Combining Equations (8) and (9), the self-propelled force of the SSMJ bit can be obtained:

\[ F_p = 1.56 p_i \left[ \sum_{b=1}^{n_b} \mu _b d_b^2 \cos \theta _b - \mu _i d_m^2 - \mu _i (d_i^2 - d_m^2) \cos \frac{\theta _r}{2} \right]. \] (10)

2.2. Pressure of the External Fluid on the Bit. In the axial direction, the drill bit is subjected to the pressure of the fluid in the hole on the front end face. The following equation of this pressure \( F_o \) is obtained:

\[ F_o = \frac{\pi}{4} p_o (d_o^2 - d_i^2), \] (11)

where \( d_o \) is the outer diameter of the bit (mm) and \( p_o \) is the pressure of the external fluid on the front end face of the bit (MPa). To be specific, \( p_o \) is the sum of the annulus pressure loss and ground pressure, and the ground pressure is 0; thus, the value of \( p_o \) is the annulus pressure loss, which can be calculated according to the relevant research [14].

2.3. Friction Resistance of the System. The friction resistance \( F \) of the RJD system primarily includes the friction between the diverter and hose \( F_{ki} \), the friction between the borehole and the hose \( F_{ki} \), and the friction between the borehole and the bit \( F_{sbk} \). Of these, \( F_{ce} \) can be obtained through a laboratory test, while

\[ F_{ki} = \mu _k G_i I_{ki}, F_{sbk} = \mu _g G_k, \] (12)

where \( \mu _k \) is the friction coefficient between the hose and borehole, \( G_i \) is the submerged weight of a unit length of the hose (N/m), \( I_{ki} \) is the friction section length of the hose (m), \( \mu _g \) is the friction coefficient between the bit and borehole, and \( G_k \) is the submerged weight of the jet bit (N).

Substituting Equations (10), (11), and (12) into (1), the force model of the RJD system can be obtained:

\[ F = 1.56 p_i \left[ \sum_{b=1}^{n_b} \mu _b d_b^2 \cos \theta _b - \mu _i d_m^2 - \mu _i (d_i^2 - d_m^2) \cos \frac{\theta _r}{2} \right] \]
\[ - \frac{\pi}{4} p_o (d_o^2 - d_i^2) - F_{ce} - \mu _k G_i I_{ki} - \mu _g G_k. \] (13)

2.4. Pressure Loss of the System. We need to calculate the pressure loss of the RJD system to obtain the inlet pressure of the bit \( p_i \). Ignoring the leakage at the joint and the local pressure loss such as hose diameter variation and bending, the system pressure loss is primarily generated by the coiled tubing \( \Delta p_{cti} \) and the high-pressure hose \( \Delta p_{hp} \):

\[ p_i = p_b - \Delta p_{cti} - \Delta p_{hp}, \] (14)

where \( p_b \) is the pump pressure (MPa).
2.4.1. Theoretical Pressure Loss. The pressure loss along the coiled tubing \( \Delta p_{\text{cti}} \) includes the spiral section loss \( \Delta p_{\text{cti}} \) and straight section loss \( \Delta p_{\text{cti2}} \), i.e., \( \Delta p_{\text{cti}} = \Delta p_{\text{cti1}} + \Delta p_{\text{cti2}} \), which can be obtained from the previous studies [14].

The theoretical pressure loss of the hose can be obtained using the following equation [28]:

\[
\Delta p_r = K_r \times \frac{59.7 q^2 l_r}{d_r^7 \text{Re}^{0.25}},
\]

where \( K_r = 1 \), \( d_r \) is the hose inner diameter (mm), \( q \) is the volume flow rate (L/min), \( l_r \) is the total length of the hose (m), and \( \text{Re} \) is the Reynolds number, which should be written as \( \lambda q / d_r \), and the coefficient \( \lambda \) is \( 1.12 \times 10^4 \) under turbulent condition. According to the previous studies [14], the theoretical value of hose pressure loss is quite deviation from the actual, and then, it will greatly affect the judgment of the inlet pressure value of the bit. The correction of Equation (15) is necessary to be performed through an experimental test.

2.4.2. Experimental Test. In this study, several groups of tests were executed under different factors of the flow rate, hose inner diameter, and length; then, the measured pressure loss values under different factors were obtained; moreover, the parameters under each factor were substituted into Equation (15) to obtain the calculated value. By comparing the measured and calculated values, the correction factor \( K_r \) is introduced to Equation (15), and the deviation of \( K_r \) is analyzed to evaluate the effectiveness of the test. Eventually, \( K_r \) is taken as an average value.

The following apparatuses were used (Figure 2): a high-pressure pump, an SSMJ bit, high-pressure hoses of 1/4” (inner diameter of 6.35 mm) and 3/8” (inner diameter of 8 mm), a flowmeter, and two pressure gauges. The two gauges were, respectively, allocated at the inlet and outlet of the tested hose; therefore, the difference reading between pressure gauges No.1 and No.2 was the pressure loss value of the hose when the system operated steadily. The test results are listed in Table 1. \( K_r \) is introduced to correct Equation (15). The values of \( K_r \) under different conditions range from 0.23 to 0.27, with the relative standard deviation of 1.3%. A small deviation rate proves the effectiveness of the test; then, the final correction factor is taken as an average value, i.e., \( K_r = 0.25 \).

2.5. Mathematical Model of the Extension Limit. When the resultant force \( F > 0 \), the RJD system can continuously drill forward. As the drilled radial borehole length increases, the friction increases and \( F \) decreases gradually until \( F = 0 \). Herein, the system is in an equilibrium condition of forces and the bit will not continue to drill forward with the hose; eventually, the value \( l_{zk} \) under this condition is exactly the extension limit of the RJD system. Substituting \( F = 0 \) into Equation (13), we can obtain the prediction model of the extension limit \( L_{EL} \):

\[
L_{EL} = \frac{1.56 \rho_1 \left[ \sum_{b=1}^{n_b} \mu_k d_b^2 \cos \theta_b - \mu_i (d_{in}^2 + d_{out}^2 - d_b^2) \cos (\theta_b/2) \right] - (\pi/4) \rho_1 (d_{in}^2 - d_b^2) - F_{rZ} - \mu_k G_z}{\mu_r G_z}.
\]

3. Results and Discussion

3.1. Project Setting. A field construction condition of an oil well in Eastern Sichuan, China, with a radial well depth of 1500 m and casing model of 7” (inner diameter of 168.6 mm) was selected as the analyzed case of this study, and the working pressure of the field pump is 60 MPa. A pure water jet, with a temperature of approximately 90°C.
under this operating condition, a density of \(965.4 \text{ kg/m}^3\) and a viscosity of \(0.315 \times 10^{-3} \text{ Pa-s}\) was used. A drilling experiment using an SSMJ bit has been executed previously; then, a borehole with a diameter of 25 mm was obtained, and \(\mu_{rk}\) and \(\mu_{zk}\) are both 0.3. According to experience and the previous laboratory tests, the flow coefficients of the forward and backward nozzles \(\mu_f\) and \(\mu_b\) are both set as 0.83; furthermore, the friction between the hose and diverter \(F_{rz}\) was obtained as 20 N through a ground test.

A coiled tubing with a model of 1.5” was used, and its main parameters of length \(l_{ct}\) and outer and inner diameter \(d_{cto}\) and \(d_{cti}\) are shown in Table 2; additionally, Table 2 shows the length \(l_r\) and outer and inner diameter \(d_{ro}\) and \(d_{ri}\) and submerged weight \(G_r\) of high-pressure hose with a model of 5/16”; the self-propelled bit was made by cemented carbide, and its specific dimensions are also shown in Table 2, such as density \(\rho_z\), length \(l_z\), outer diameter \(d_o\), inner diameter \(d_i\), forward nozzle diameter \(d_f\), impeller central hole diameter \(d_m\), jet diffusion angle \(\theta_x\), number of backward nozzles \(n_b\), diameter of backward nozzle \(d_b\), and inclination angle of backward nozzle \(\theta_b\).

### Table 1: Test data of the high-pressure hoses.

<table>
<thead>
<tr>
<th>Hose length (m)</th>
<th>Hose inner diameter (mm)</th>
<th>Flow rate (L/min)</th>
<th>Tested (\Delta p_r) (MPa)</th>
<th>Calculated (\Delta p_r) (MPa)</th>
<th>Correction factor (K_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.35</td>
<td>117</td>
<td>10.8</td>
<td>41.68</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>6.35</td>
<td>55</td>
<td>2.8</td>
<td>11.18</td>
<td>0.25</td>
</tr>
<tr>
<td>20</td>
<td>6.35</td>
<td>117</td>
<td>20.0</td>
<td>83.35</td>
<td>0.24</td>
</tr>
<tr>
<td>20</td>
<td>6.35</td>
<td>55</td>
<td>5.6</td>
<td>22.35</td>
<td>0.25</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>117</td>
<td>3.4</td>
<td>13.13</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>55</td>
<td>0.8</td>
<td>3.52</td>
<td>0.24</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>117</td>
<td>7.1</td>
<td>26.26</td>
<td>0.27</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>55</td>
<td>1.6</td>
<td>7.04</td>
<td>0.23</td>
</tr>
</tbody>
</table>

### Table 2: Main parameters of the project.

<table>
<thead>
<tr>
<th>(l_{ct}) (m)</th>
<th>(d_{cto}) (mm)</th>
<th>(d_{cti}) (mm)</th>
<th>(l_r) (m)</th>
<th>(d_{ro}) (mm)</th>
<th>(d_{ri}) (mm)</th>
<th>(G_r) (N/m)</th>
<th>(\rho_z) (g/cm(^3))</th>
<th>(l_z) (mm)</th>
<th>(d_o) (mm)</th>
<th>(d_i) (mm)</th>
<th>(d_f) (mm)</th>
<th>(d_m) (mm)</th>
<th>(\theta_x) (°)</th>
<th>(n_b)</th>
<th>(d_b) (mm)</th>
<th>(\theta_b) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>38.1</td>
<td>31.75</td>
<td>120</td>
<td>14.3</td>
<td>8</td>
<td>2.3</td>
<td>15</td>
<td>30</td>
<td>18</td>
<td>8</td>
<td>1.8</td>
<td>1</td>
<td>60</td>
<td>3</td>
<td>1.3</td>
<td>30</td>
</tr>
</tbody>
</table>

### Figure 3: Hose pressure loss influenced by the hose length.

3.2 Pressure Loss Analysis. The construction parameters were substituted into Ma et al.’s study [14] and Equation (15) to obtain the pressure loss distribution along the coiled tubing and high-pressure hose, separately. The main pressure loss of the system was observed to emanate from the high-pressure hose, which was 20.1 MPa, accounting for 92.6% of the total.

The hose parameters (inner diameter \(d_{ct}\) and length \(l_{ct}\)) have a significant impact on the pressure loss (Figure 3). The pressure loss increases as a quadratic function with the increase in \(l_{ct}\), which will reduce the extension limit. Therefore, the length of the hose should be as short as possible. During engineering construction, \(l_{ct}\) must be chosen according to the designed radial borehole length, and a little longer than the designed borehole length should be most suitable. The pressure loss is highly sensitive to the variation in \(d_{ct}\); therefore,
should be as large as possible, provided that the high-pressure hose can smoothly pass through the diverter.

3.3. Extension Limit Results and Analysis. The construction parameters of an oil well in Eastern Sichuan were placed into Equation (16), and the extension limit of the RJD system \( L_{\text{EL}} \) was calculated as 63.7 m. The force distribution in the horizontal section of RJD is shown in Figure 4. We observe that the recoil force \( (F_b) \) of the backward nozzle is the sole driving force for the system to drill forward; thus, increasing the equivalent diameter of the backward nozzles (any nozzle diameter or number) is the most effective method of increasing the drilling depth. The recoil force \( (F_f) \) of the forward nozzle is the main resistance of the system, accounting for 66.96% of the total resistance. Therefore, the diameter of the forward nozzle should be appropriately reduced, provided that its rock-breaking performance satisfies the design requirements. The friction between the hose and borehole \( (F_{rk}) \) increases with the increase in drilling depth. When the axial force of the system is balanced, \( F_{rk} \) also reaches the maximum. Herein, \( F_{rk} \) accounts for 20.42% of the total resistance. A hose with a light weight and smooth outer surface should be selected to reduce \( F_{rk} \). In the bit structure design, the roundness of the drilled hole is used as an evaluation index. The friction between the hose and diverter \( (F_{rz}) \) accounts for 9.3% of the total resistance. A hose with a small turning radius should be selected in a RJD system to reduce \( F_{rz} \). In the design of diverter, the hose and bit should be investigated on whether they can pass through the diverter smoothly.

3.4. Influential Factor Analysis for Extension Limit

3.4.1. Pump Pressure. We changed the pump pressure \( p_b \) and maintained other parameters in the engineering example to obtain the variation law of extension limit \( L_{\text{EL}} \) with \( p_b \) under different inner diameters of the hose (Figure 5). We observed that the extension limit increases approximately linearly with the increase in \( p_b \). Besides, the inner diameter of the high-pressure hose has a significant influence on \( L_{\text{EL}} \). When the inner diameter is 6.4 mm, the drill bit can drag the high-pressure hose forward after \( p_b \) reaches 45 MPa, whereas when the diameter is 8 mm, the drill bit can drag the high-pressure hose forward when \( p_b \) reaches 25 MPa. The larger the inner diameter, the greater the slope, additionally the higher the rise rate of \( L_{\text{EL}} \), which indicates that the increase in the inner diameter of the hose can effectively reduce the pressure loss and improve the inlet pressure of the bit.

3.4.2. Forward Nozzle Diameter. We changed the forward nozzle diameter \( (d_f) \) and maintained other parameters in the engineering example to obtain the variation law of \( L_{\text{EL}} \) (Figure 6). We observed that when the pump pressure is 60 MPa, the decline rate of \( L_{\text{EL}} \) is greater than that when 40 MPa. This is because when the pump pressure is relatively high, the flow rate of the system is relatively large. As \( d_f \) increases, the increase rate of the system pressure loss is also faster, which increases the decline rate of the nozzle inlet pressure compared with when the pump pressure is relatively low, and finally increases the decline rate of the drilling extension limit. Under the same pump pressure, \( L_{\text{EL}} \) decreases approximately linearly with the increase in \( d_f \);
therefore, reducing the diameter of the forward nozzle is conducive to increasing $L_{EL}$. However, the main function of the forward nozzle is to generate an SSMJ for rock-breaking to enable the system to continuously drill forward. The smaller diameter of the forward nozzle weakens the energy of the jet and the rock-breaking performance of the bit becomes worse. Therefore, when selecting $d_f$, we should also combine with rock-breaking research and appropriately reduce $d_f$ under the premise that the rock-breaking efficiency satisfies the operating requirements.

3.4.3. Jet Diffusion Angle. We changed the jet diffusion angle ($\theta_x$) by adjusting the slot dip angle of the impeller and maintained other parameters in the engineering example to obtain the variation law of $L_{EL}$ (Figure 7). We observed that under the same pump pressure, $L_{EL}$ increases as a cosine curve with the increase in $\theta_x$. By increasing $\theta_x$, the axial velocity of the swirling jet decreases, and then, the recoil force of the forward nozzle decreases. The decrease in the system resistance can improve $L_{EL}$ of the system, but an excessively large diffusion angle will also weaken the rock-breaking efficiency of the SSMJ. Therefore, the flow field and erosion performance analysis must be combined to obtain the optimal $\theta_x$.

3.4.4. Impeller Central Hole Diameter. The variation law of $L_{EL}$ was obtained by changing the diameter of the impeller central hole $d_m$ (Figure 8). Under the same pump pressure, $L_{EL}$ decreases in a quadratic function with the increase in $d_m$. Therefore, the diameter can be appropriately reduced to increase $L_{EL}$. However, according to the previous research, when $d_m$ is small, the central boss easily appears in the bore-hole bottom, which hinders the advancement of the bit and reduces the drilling speed. Therefore, the size of the central hole should satisfy the larger $L_{EL}$ and drilling speed. When $d_m$ is greater than 1.5 mm, $L_{EL}$ decreases to a lower value, and the decline rate reaches 40% under the pump pressure of 60 MPa. Thus, $d_m$ less than 1.5 mm is more appropriate; additionally, the specific results can be further investigated combining the drilling efficiency test.

3.4.5. Backward Nozzle Diameter. We changed the backward nozzle diameter ($d_b$) and maintained other parameters in the engineering example to obtain the variation law of $L_{EL}$ (Figure 9). Under the same pump pressure, $L_{EL}$ increases approximately linearly with the increase in $d_b$. According to the data, the increase rate of $L_{EL}$ decreases with the increase in $d_b$. For example, under the condition of a pump pressure of 60 MPa, when $d_b$ changes from 1.22 to 1.24 mm, $L_{EL}$ increases by 8.55 m, whereas for a $d_b$ changes from 1.36 to 1.38 mm, $L_{EL}$ increases by 7.85 m. Increasing $d_b$ is the most effective method of increasing the drilling depth. However, at the same pump pressure, the increase in $d_b$ increases the flow rate, additionally increases the water consumption and pressure loss of the system, and reduces the increase rate of $L_{EL}$. Therefore, considering the system loss and economy, $d_b$ cannot increase indefinitely and should be determined according to the drilling extension limit required by the construction design.
mine the in

sequences. The detailed calculation process is as follows:

\[ \theta \]

\[ \theta \]

111.91 m. When \( \theta_b \) increases to 20°, 30°, and 40°, \( L_{EL} \) decreases to 90.20, 63.68, and 27.69 m, respectively. When \( \theta_b \) reaches 48.4°, \( L_{EL} \) is 0. Overall, \( L_{EL} \) decreases relatively rapidly when \( \theta_b \) exceeds 30°. Therefore, it is reasonable to select \( \theta_b \) of 30° to ensure both a large \( L_{EL} \) and borehole diameter.

3.5. Parameter Sensitivity Analysis. In this study, the method of grey relational analysis (GRA) was used to investigate the influence degree of six factors above on the extension limit, such as pump pressure \( p_b \), forward nozzle diameter \( d_l \), jet diffusion angle \( \theta_x \), impeller central hole diameter \( d_m \), backward nozzle diameter \( d_b \), and backward nozzle inclination angle \( \theta_b \). GRA refers to the uncertain correlation between objects or between subsystems and between factors and main behavior. Its basic assignment is to analyze and determine the influence degree between factors or the contribution degree of factors to main behavior, based on the micro or macro geometric proximity of behavior factor sequences. The detailed calculation process is as follows:

1. Determine the reference and comparison sequences: taking the reference sequence reflecting the characteristics of system behavior as \( y \), and the comparison sequence affecting system behavior as \( x_i \), the corresponding equation is as follows:

\[
\begin{align*}
    y &= \{ y(k) | k = 1, 2, \ldots, n \}, \\
    x_i &= \{ x_i(k) | k = 1, 2, \ldots, n \},
\end{align*}
\]

where \( k \) and \( i \) are the group \( k \) and column \( i \) of a specific quantity value in the matrix composed of sequences, \( y(k) \) is the reference sequence value of the data group \( k \) and its unit is related to the chosen physical quantity, and \( x_i(k) \) is the value of the \( i \)th influential factor of data group \( k \) and its unit is also related to the selected physical quantity

2. Dimensional normalization processing of the data: it is necessary to unify the unit for different parameters, usually the dimensional normalization methods including mean value, initial value, maximization, and minimization. The initial value method was adopted, since it is suitable for the data with a tendency and regularity and is often used in comprehensive evaluation, such as GRA

3. Calculation of relation coefficient: the equation is as follows:

\[
\xi_i(k) = \frac{\min_{0 \leq k \leq n} |y_0(k) - x_i(k)| + \rho \cdot \max_{0 \leq k \leq n} |y_0(k) - x_i(k)|}{|y_0(k) - x_i(k)| + \rho \cdot \max_{0 \leq k \leq n} |y_0(k) - x_i(k)|},
\]

where \( \rho \) is the resolution coefficient and has a value range between 0 and 1, usually as 0.5. The smaller \( \rho \), the greater the difference between relation coefficients, and the stronger the discrimination ability. After calculating the relation coefficient, take the average value of each coefficient as the grey relation coefficient of the factor, and the calculation equation is

\[
r_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k),
\]

where \( r_i \) is the relation degree of the \( i \)th influential factor

Take the extension limit \( L_{EL} \) of the jet bit under different parameters as the reference sequence, which is \( y_0 \), and take \( p_b, d_l, \theta_x, d_m, d_b, \) and \( \theta_b \) as the comparison sequence, which are \( x_i \) to \( x_e \), respectively. It is found that taking \( L_{EL} \) as the
evaluation index, the order of parameter sensitivity from large to small is $p_b$, $\theta_c$, $d_l$, $d_m$, $\theta_b$, and $d_m$ (Table 3).

4. Conclusions

Through analysing the force and pressure loss of the RJD system, a model to predict the drilling extension limit $L_{EL}$ was established. The $L_{EL}$ value of a specific project was calculated and the pressure loss and forces were obtained. The influence laws of the main parameters on $L_{EL}$ were studied using the established prediction model. The conclusions are summarized as follows:

1. The sensitivity of pressure loss to the variation in the inner diameter is higher, because the diameter of high-pressure hose is significantly lower than that of the coiled tubing, and the main pressure loss of the system results from the high-pressure hose. The backward nozzle recoil force is the only driving force of the system, and the forward nozzle recoil force and friction between the hose and borehole contain the main resistance of the system. The drilling extension limit prediction value of the project in this article can reach up to 63.7 m.

2. Under the same pump pressure, $L_{EL}$ of the system increases approximately linearly with the increase in backward nozzle diameter, yet this will significantly increase hydraulic consumption and pressure loss; it decreases linearly with the increase in the forward nozzle diameter. Therefore, the design of the rear nozzle should not blindly pursue the large $L_{EL}$ but also consider that the hydraulic consumption and pressure loss are within a reasonable range; the forward nozzle diameter can be as small as possible on the premise of ensuring rock-breaking efficiency. $L_{EL}$ increases with the increase in the swirling jet diffusion angle; the diffusion angle can also be reduced to ensure the capability of rock-breaking rock. $L_{EL}$ decreases as a quadratic function with the increase in the backward nozzle installation angle; when the angle is larger than 30°, the decrease in $L_{EL}$ rate is high. From parameter sensitivity analysis, the factors that have the greatest and least influence on $L_{EL}$ are $p_b$ and $d_m$, respectively. Hence, increasing $p_b$ is the most direct and effective way to raise $L_{EL}$, while the design of $d_m$ does not depend on the requirements of $L_{EL}$, but on its rock-breaking capacity.

3. This research provides a theoretical guideline for predicting the extension limit of RJD under a specific working condition, optimizing the bit structure, and choosing high-pressure hose and hydraulic parameters. The specific bit structure parameters should be further obtained through rock-breaking performance tests combined with this study. In addition, laboratory simulation of RJD experiment and field test will be performed in the future.

Data Availability

All data generated or used during the study appearing in the submitted article are available from the corresponding author upon request.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

This study was financially supported by the National Natural Science Foundation of China (NSFC) under Grant No. 51804007.

References


predict the effectiveness of radial jet drilling technology in various geological conditions,” *Applied Sciences*, vol. 11, no. 10, p. 4487, 2021.


[24] D. J. Ma, G. S. Li, X. N. Zhang, and Z. W. Huang, ”Experimental study on rock breaking by a combined round straight jet with a swirling jet nozzle,” *Atomization and Sprays*, vol. 21, no. 8, pp. 645–653, 2011.


