Study on parameters optimization of coalbed gas drilling drainage by high pressure water jet

Jialiang Liu1,2,3*, Kunyuan Li1
1School of civil engineering, Chongqing Jiaotong University, Chongqing, China
2Engineering research center of bridge structure and materials in mountain area, Chongqing Jiaotong University, Chongqing, China
3National and local joint engineering laboratory of traffic civil engineering materials, Chongqing Jiaotong University, Chongqing, China
*Corresponding author e-mail: liuacademic@hotmail.com

Abstract. Coalbed gas is a kind of non-conventional energy with non-pollution and high-quality. High pressure water jet technology has many advantages in coalbed gas drilling drainage, due to no heat effect, high flexibility, and high surface quality. To reduce the energy consumption of this technology, especially for the hard coal rock, the water jet parameters optimization is studied in this paper. Based on an established three-dimensional damage numerical model and the orthogonal design tests, it analyzes the influence characteristic of different water jet parameters on coal bed gas drilling drainage and obtains the optimal water jet parameters combination finally. The results could improve the efficiency of high pressure water jet drilling drainage.

1. Introduction
Coalbed is the associated resource of coal, with no pollution and high energy. The traditional mechanical drilling technologies have many drawbacks, like plugging and sticking and so on. However, these problems can be avoided by high pressure water jet technology. Meanwhile, this technology has extra advantages, such as no dust, no toxic gas, no spark and so on. So, the high-pressure water jet technology will be one of the main methods in coalbed gas mining engineering [1].

In recent years, high pressure water jet has made some progress in coal bed gas drilling drainage, but there are still some disadvantages, for example, the energy consummation is higher, especially for the hard coal rock (6-8 times higher than the mechanical drilling). Many scholars commit to the related researches, such as Ge et al studied the influence radius of the high-pressure water jet drilling [2], Li et al analyzed the stress distribution rule of the high-pressure water jet impacting coal [3]; Wang et al investigated the permeability variations around the coal seam after high pressure water jet drilling [4].

However, the work on parameters optimization of high pressure water jet is not enough, but it is one of the key scientific issues. Therefore, this paper conducts researches on the influence characteristics of different water jet parameters on water jet drilling efficiency and the optimal parameters combination of water jet drilling. It is significant that the results can provide technical supports to high pressure water jet application in coal bed gas drilling drainage.
The damage is the essential factor to high pressure water jet drilling drainage efficiency, for damage evolution will affect the permeability and stability of coal rock. Therefore, in this paper, it studies the drilling efficiency by the damage in coal rock under high pressure water jet. However, the damage in coal rock is hard to be measured, as it's a quite complex physical mechanics process that high pressure water jet drilling coal rock. So, in this paper it establishes a numerical model of high pressure water jet impacting coal rock to study the damage evolution in coal rock under high pressure water jet, based on the fluid mechanics, damage mechanics and the fluid-solid coupling penalty function algorithm.

2. Numerical simulation

2.1. Numerical model

Governing Equations:

\[
\frac{\partial \rho}{\partial t} = -\rho \frac{\partial v_i}{\partial x_i} - w_i \frac{\partial \rho}{\partial x_i} \quad (i, j = 1, 2, 3) \quad (1)
\]

\[
\nu \frac{\partial v_i}{\partial t} = \sigma_{ij,j} + \rho b_i - \rho w_i \frac{\partial x_i}{\partial x_j} \quad (2)
\]

\[
\rho \frac{\partial E}{\partial t} = \sigma_{ij} v_{ij,j} + \rho b v_i - \rho w_i \frac{\partial E}{\partial x_j} \quad (3)
\]

Where \(\rho\) is the material density, \(v_i\) is the material velocity, \(w_i\) is the relative velocity between material speed and mesh, \(\sigma_{ij}\) is Cauchy stress, \(b_i\) is the body force, \(E\) is the energy [5].

The constitute equations for coal rock, water jet, air are written as follows:

\[
\sigma^* = \left[ A(1 - D) + BP^N \right] \left( 1 + C \ln \varepsilon^* \right) \quad (4)
\]

\[
P = a_1 \mu + a_2 \mu^2 + a_3 \mu^3 + \left( h_0 \mu + h_1 \mu + h_2 \mu^2 \right) E \quad (5)
\]

\[
P = c_0 + c_1 \mu + c_2 \mu + c_3 \mu + (c_4 + c_5 + c_6 \mu) E \quad (6)
\]

Where \(\sigma^*\) is the normalized equivalent stress, \(A\) is the cohesion parameter, \(B\) is the pressure hardening coefficient, \(C\) is the strain-rate sensitivity coefficient, \(N\) is pressure hardening exponent, \(P^*\) is the normalized pressure, \(\varepsilon^*\) is the normalized strain rate, \(\mu = V^{-1} - 1\), \(V\) is relative volume. Damage \((D)\) is accumulated from both the equivalent plastic strain increment and the equivalent plastic volumetric strain increment, which is expressed as,

\[
D = \sum \frac{\Delta \varepsilon_p^i + \Delta \mu_p^i}{\varepsilon_p^i + \mu_p^i} \quad (7)
\]
Where $\Delta \varepsilon_p$ and $\Delta \mu_p$ are the equivalent plastic strain and the equivalent plastic volumetric strain, respectively, $f(P) = \varepsilon_p^f + \mu_p^f = D_1 \left( P^* + T^* \right)^{\delta_2}$ is the material fracture plastic strain under actual pressure, $D_1$ and $D_2$ are the material constant. $T^*$ is the normalized hydrostatic tension [6-7].

The main mechanical parameters of coal rock are shown in Table 1.

**Table 1. The main mechanical parameters of coal rock.**

| $\rho$ ($g \cdot cm^{-3}$) | $G$/GPa | $f_c^f$/GPa | $T^*$/MPa | $P_{crush}$/GPa | $\mu_{crush}$ |
|---------------------------|--------|-------------|-----------|---------------|-------------|
| 1.4                       | 5.0    | 0.02        | 0.2       | 4             | 0.001       |

2.2. Geometrical model and boundary condition

The whole computational area is a cube, which is 50mm×50mm×50mm, and the coal rock is 50mm×50mm×30mm, water jet is 1.8mm(diameter)×20mm(height), 50mm×50mm×20mm for air shown in Figure 1. The down boundary of coal rock is at the support of gemels. Up and down surfaces and side surfaces are in non-reflecting boundary condition, and $Y=0$ in $XOZ$ coordinate plane, $X=0$ in $YOZ$ coordinate plane [7].

![Figure 1. The overall geometrical model.](image)

3. Orthogonal design tests

3.1. Principle of orthogonal design

All $A, B, C...$ represent factors; $R$ is the level of each factor; $A_i$ is the level $i$ ($i = 1, 2, 3, ...$) of the factor $A$ with number; $X_{ij}$ is the value of the factor $J$ with level $i$ ($i = 1, 2, 3, ..., j = A, B, C, ...$).

$Y_{ij}$ is the experimental result of the factor $J$ with level $i$, following the normal distribution, $K_{ij}$ is the summation of the experimental results from 1 to $n$, and $K_{ij}$ is defined as:

$$K_{ij} = \sum_{k=1}^{n} Y_{ij} (k = 1, 2, 3, ..., n) \quad (8)$$

It studies the factors sensitivity by the range analysis method. When one factor is changed, it can calculate the influence of changing factors on the experimental results by keeping other factors unchanged. And then, the similar comparison of another factor is carried out. The range $R_i$ of factor $i$ is:
$$R_i = \max \{K_{i1}, K_{i2}, K_{i3}, ..., K_{iy}\} - \min \{K_{i1}, K_{i2}, K_{i3}, ..., K_{iy}\}$$

(9)

### 3.2. Orthogonal design tests

According to the high-pressure water jet parameters feature, the water jet diameter, the water jet velocity and the abrasive concentration, are selected as the factors, as shown in Table 2. A $L_9(3^4)$ orthogonal design is selected in the paper, and Table 3 is one of the typical $L_9(3^4)$ orthogonal tables. Because the three parameters do not affect each other directly, it is unnecessary to consider their interaction. From the experimental results, as shown in Table 4, it can be seen that the damage in test 7 is 0.64 as the largest one, so the optimal parameters combination is $A_3B_1C_3$ from the orthogonal design test.

### Table 2. The factors and levels of the orthogonal tests.

| Level | Diameter /mm($A$) | Velocity /m/s($B$) | Abrasive concentration/%($C$) |
|-------|-------------------|--------------------|-----------------------------|
| 1     | 1.0               | 250                | 0                           |
| 2     | 1.5               | 400                | 5                           |
| 3     | 2.0               | 500                | 10                          |

$A$ is the water jet diameter, $B$ is the speed of water jet and $C$ is the abrasive concentration. 1, 2, 3 represent each level of factors.

### Table 3. $L_9(3^4)$ orthogonal table.

| Test number | $A$ | $B$ | $C$ | $D$ |
|-------------|-----|-----|-----|-----|
| 1           | 1   | 1   | 1   | 1   |
| 2           | 1   | 2   | 2   | 2   |
| 3           | 1   | 3   | 3   | 3   |
| 4           | 2   | 1   | 2   | 3   |
| 5           | 2   | 2   | 3   | 1   |
| 6           | 2   | 3   | 1   | 2   |
| 7           | 3   | 1   | 3   | 2   |
| 8           | 3   | 2   | 1   | 3   |
| 9           | 3   | 3   | 2   | 1   |

### Table 4. The Orthogonal test results.

| Numble | Factors | Damage ($D$) |
|--------|---------|--------------|
|        | $A$     | $B$ | $C$ | $D$ |
| 1      | 1       | 1  | 1   | 0.34|
| 2      | 1       | 2  | 2   | 0.54|
| 3      | 1       | 3  | 3   | 0.53|
| 4      | 2       | 1  | 2   | 0.57|
| 5      | 2       | 2  | 3   | 0.61|
| 6      | 2       | 3  | 1   | 0.49|
| 7      | 3       | 1  | 3   | 0.64|
| 8      | 3       | 2  | 1   | 0.51|
| 9      | 3       | 3  | 2   | 0.61|
3.3. Range analysis
The range $R$ represents the quantitative influence of factors on experimental results. From the range analysis in Table 5, it can be seen that the influence of parameters on damage ($D$) is: $K_1 > K_2 > K_3$. Therefore, factor $C$ (the abrasive concentration) is the most important factor that affects the efficiency of water jet drilling drainage, factor $A$ (the water jet diameter) is second, and factor $B$ (the water jet velocity) is third.

Table 5. Range analysis.

| Factors | A  | B  | C   |
|---------|----|----|-----|
| $K_1$   | 0.470 | 0.517 | 0.447 |
| $K_2$   | 0.557 | 0.553 | 0.573 |
| $K_3$   | 0.587 | 0.543 | 0.593 |
| Range $R$ | 0.117 | 0.036 | 0.146 |

3.4. Effect curves
For further study on the influence of parameters on coal rock damage, the effect curves of damage and factors are established. The horizontal ordinate is factor level and the vertical coordinate is investigation target, as shown in Figure 2. It can be seen that there is the greatest damage in the level 3 with the water jet diameter 2.0mm, the water jet velocity 400m/s and the abrasive concentration 10%. Since there is no the above combination in the orthogonal test, it is simulated with the parameters combination. After numerical calculation, it shows that damage $D=0.67>0.64$, and it accords with the effect curves. Therefore, the optimal parameters of high pressure water jet drilling drainage are: the water jet diameter is 2.0mm, the water jet velocity is 400m/s and the abrasive concentration is 10%.

From Figure 2, the influence rules of the parameters on the damage can be obtained. It can be seen that the damage grows with the water jet diameter and abrasive concentration increasing. And, with the water jet velocity increasing, the damage grows firstly and then decreases.

Figure 2. Effect curves of water jet parameters.

4. Conclusion
Based on an established three-dimensional damage numerical model and the orthogonal design tests, in this paper it studies the parameters optimization of coalbed gas drainage by high pressure water jet. The results show that the influences of water jet parameters on damage ($D$) is: the abrasive concentration $>$ the water jet diameter $>$ the water jet velocity. And by the orthogonal design test results and range analysis, the optimal parameters combination of high pressure water jet drilling drainage is obtained: the water jet diameter is 2.0mm, the water jet velocity is 400m/s and the abrasive concentration is 10%.
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References
[1] Yong Liu, An He, Jianping Wei, et al. Plugging factor and new plugging method to hydraulic relieving stress, J, Journal of China Coal Society. 41(2016) 1963-1967.
[2] Zhaolong Ge, Xudong Mei, Yajie Jia, et al. Influence radius of slotted borehole drainage by high pressure water jet, J, Journal of Mining & Safety Engineering. 31(2014) 657-664.
[3] Jingguo Li, Guanglong Dai and Jingmin Wu, Around the seam stress distribute on after hydraulic punching, J, Coal Mine Safety. 46(2015) 48-51.
[4] Kai Wang, Bo Li, Jianping Wei, et al. After hydraulic punching drilling permeability change rule of around the seam, J, Journal of Mining & Safety Engineering. 30(2013) 778-784.
[5] Gadala M.S., Recent trends in ALE formulation and its applications in solid mechanics, J, Computer Methods in Applied Mechanics and Engineering. 193(2004) 4275-4275.
[6] Yitian Wang and Jiazhong Zhang, An Improved ALE and CBS-based Finite Element Algorithm for Analyzing Flows around Forced Oscillating Bodies, J, Finite Elements in Analysis and Design. 47(2011) 1058-1065.
[7] Jialiang Liu and Hu Si, Gas Disaster Controlling Based on High Pressure Water Jet, J, Disaster Advances. 5(2012) 1618-1625.