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Rock-Cutting Performance Experimental Research of Particle Water Jet Based on Orthogonal Experimental Method

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Abstract

Particle Impact Drilling is an efficient drilling technology for deep-well hard formation which cuts rock mainly by high-speed spherical particle impacting rock with the help of hydraulic action and mechanical action. In order to determine main influence factors and their order of priority, the orthogonal experiment was designed and the experimental data was analyzed with both the general method and the variance method. The analysis indicates that the order of priority of the main influence factors of particle water jet rock-cutting performance is pump pressure ps, impacting range S, particle mass concentration ω, confining pressure P and particle diameter dp. Moreover, ps is highly important and S and ω are important. In addition, high ps, moderate S, moderate ω, moderate dp and low P could effectively promote particle water jet to impact and cut rocks.

Key words: Deep hard formation; Particle impact drilling; Particle water jet; Rock-cutting performance; Orthogonal experiment method; Analysis of variance

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INTRODUCTION

With the continuous depletion of shallow hydrocarbon resource, it becomes very important to find oil & gas in deep-well hard formations and under complex geologic conditions for land petroleum exploration and development. Although great progress has been achieved in hard formation drilling technology, operators still faces "80-20" Rule, which means complex interval takes up 20% of total drilling footage while its cost takes up 80% of the total drilling cost. This extreme asymmetry is caused by hard deep rock, low rate of penetration (ROP) and long drilling period (Gordon & Greg, 2008). In consequence, it is crucial to find new high efficient rock-cutting methods and technologies in deep-well hard formation.

Inspired by the idea of breaking rock by shot impact, American Particle Drilling Technology Incorporated (PDTI) introduced this method to drilling engineering and used high-speed spherical particle to impact hard formation rock, which enhanced rock-breaking efficiency. Indoor and field tests carried out by PDTI indicates that particle impact drilling method greatly improves energy efficiency and raises ROP to 3-4 times conventional drilling method. What's more, in hard formation, this method could save one third of drilling time as well as 1,000,000 $ for single well (Xu et al., 2009). In this paper, the orthogonal experiment method is applied to design the experiments for five influential factors, including pump pressure p_s, impacting range S, particle mass concentration ω, confining pressure P and particle diameter d_p. By the analysis of experiment data, the rules and the order of priority of these five factors are obtained.

1. PARTICLE WATER JET ROCK-CUTTING MECHANISM

Compared with water jet, particle water jet attacks rocks by high frequency impacting and grinding actions instead of continuous static pressure action of potential core, greatly improving rock-cutting performance (Ni et al., 2008; Shen, 1998). When particles suddenly strike rocks, stress waves will come about in a certain place and then, waves are transmitted toward the striking direction and around the striking point at a certain speed. The stress waves also strike surrounding rocks, so that pulling stress and shearing stress will come in contact boundary (Wu et al., 2008) Because rock tensile strength is only 1/80~1/16 of pressive strength and shear strength is merely 1/15~1/8 of pressive strength, small crevices, compressive cones, dominant and recessive microcracks will take shape in rocks and rocks could be broken if pulling stress and shearing stress exceed respectively the maximum tensile strength and shear strength (Fig. 1).

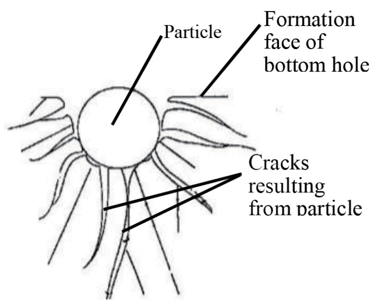

Figure 1
Sketch Map of Particle Impact Rock-Cutting Cracks

2. EXPERIMENTAL SETUP

Premixed jet steel particle impact rock-breaking experiments were done in High Pressure Water Jet Laboratory of China University of Petroleum. The experiment system consists of two highbaric pumps, an abrasive tank and a simulation borehole. During the experiments, steel particles firstly go into the abrasive tank by a filter. When high pressure water is pumped into the abrasive tank, vacuum is produced, particles are entrained into the blending silo and water and particles mix to produce particle water jet which enters simulation borehole at a very high speed, then blows out from Φ 3mm double-taper nozzle (40°/13°) and impact rock. Confining pressure surrounding is achieved by the tight tube full of water and confining pressure value is controlled by throttle valve or different nozzles. Figure 1 is steel particle impact rock-breaking experimental schematic diagram of setup.

3. ORTHOGONAL EXPERIMENT PRINCIPLE

Ronald A. Fisher, an English scholar, put forward an orthogonal optimum-seeking method based on mathematical statistics principle in 1920. This method reveals an inherent law that could reflect all the possible combinations of experimental conditions only by several

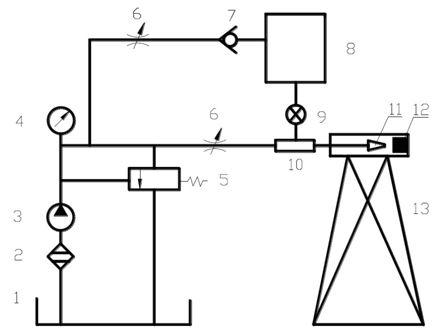

Figure 2
Schematic Diagram of Particle Water Jet Rock Breaking Experimental Setup
1. Water tank; 2. Filter; 3.Highbaric pump; 4.Pressure gauge; 5. Safety valve; 6. Control valve; 7. One-way valve; 8. Abrasive tank; 9. Globe valve; 10. Blending silo; 11. Nozzle; 12. Rock; 13. Confining pressure steel cylinder

tests. Fisher developed and firstly used variance analysis method as a basic method to direct statistics analysis in experiment design. By 10-year effort, Fisher and his partners created an integrated test system (Zheng & Jiang, 2003; Jin, 1988).

In this paper, the problems are complex and the influential factors are manifold. If all the combinations and levels are considered in multi-factor and multi-level experiments, too many experiments need doing, which will spend a great quantity of manpower and materials. Meanwhile, long operation also leads an unsuccessful outcome. On the promise of not changing experiment effects, orthogonal experiment is an effective solution (Hua et al., 2002). This experiment has 5 influential factors, each of which has 4 levels. It is uneconomic and unnecessary to consider every possible combination of factors, so 5-factor and 4-level orthogonal experiment is applied.

4. EXPERIMENT DESIGN

Premixed particle water jet rock-breaking experiments use abrasive tank to provide steel particles, which are mixed with high pressure water jet and impact rock at very high speed. These particles are high carbon steel shots, as shown in Fig. 3, whose diameters are between 0.2 to 0.8 mm and harness is between 40 to 50 HRC. The cement rock sample, as shown in Fig.4, is a 150mm long cylindrical body with a diameter of 110mm. It is made of G-level oil well cement and quartz sand. After conserved indoor for 30 days, its density reaches 2231.9kg/m^3. The average uniaxial compressive strength is 30 MPa. Double-taper nozzle diameter is 3mm, as shown in Fig. 5. Rock sample is crushed for 4 minutes. The factors and levels selection is based on Table 1. In Table 1, A is confining pressure, B is pump pressure, C is impacting range, D is particle diameter and E is particle mass concentration.

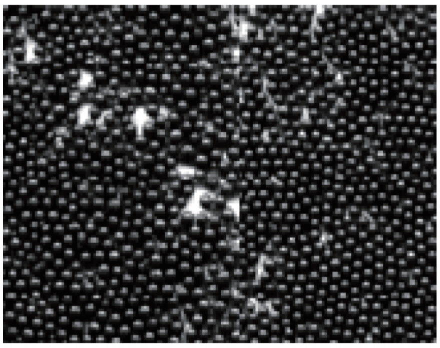

Figure 3
High-Carbon Cast Steel Shots

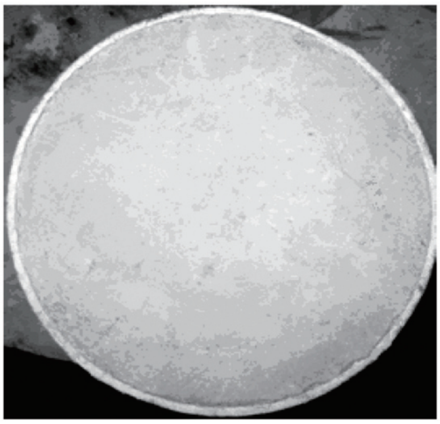

Figure 4
Set Cement Rock Sample

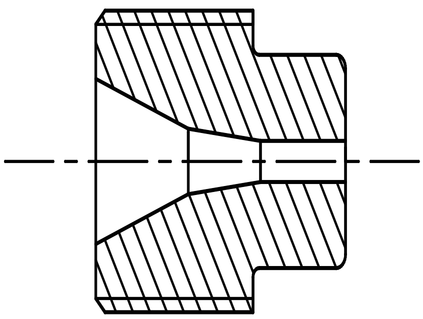

Figure 5
Double-Taper Nozzle

Table 1
Orthogonal Experimental Factors and Levels

level	A/MPa	B/MPa	C/mm	D /mm	E /%
1	0	12	10	0.3	14.6
2	3	15	20	0.4	18.6
3	5	18	30	0.5	22.2
4	6.2	20	40	0.6	25.5

Orthogonal experiment layout is designed according to the factors and levels in Table 1. This layout gives experiment number and factor-level combinations in each experiment. This orthogonal experiment has 5 influential factors and each factor has 4 levels. Orthogonal table with interactional rows is applied because maybe there are some interactions among the 5 influential factors. To reduce experiment number, this experiment choose $L_{16}(4^5)$ orthogonal layout, in which 16 experiments are required. The orthogonal layout is shown in Table 2.

Table 2
Orthogonal Layout $L_{16}(4^5)$ (Experimental Program)

No.	A	B	C	D	E	Result
1	1	1	1	1	1	
2	1	2	2	2	2	
3	1	3	3	3	3	
4	1	4	4	4	4	
5	2	1	2	3	4	
6	2	2	1	4	3	
7	2	3	4	1	2	
8	2	4	3	2	1	
9	3	1	3	4	2	
10	3	2	4	3	1	
11	3	3	1	2	4	
12	3	4	2	1	3	
13	4	1	4	2	3	
14	4	2	3	1	4	
15	4	3	2	4	1	
16	4	4	1	3	2	

5. ORTHOGONAL EXPERIMENT ANALYSIS

According to the factors and levels of orthogonal experiment in Tab.1, particle water jet rock-cutting experiment is taken on under different conditions. In order to reduce the error, the penetration depth and erosion volume of rocks are calculated by averaging multiple measurements to obtain the 16 sets of experimental results. The following analysis is done by orthogonal method.

5. 1 Experimental Result General Analysis

The experimental result is given in Table 3 by general analysis. The general analysis and calculation of orthogonal experiment is to analyze the experimental results by simple mathematical operation and the method is simple and practical. In practical application, penetration depth and erosion volume of rocks are expected to be as large as possible. Based on this idea, penetration depth H and erosion volume V are respectively put in order by the value under different experimental condition. For H, the maximum condition is assigned 1, the following is 2 and so on, until 16; for V, V is assigned like H. As a result, two columns of new data are obtained, which are integers from 1 to 16. Briefly, H_i and V_i are used to stand for the integers.

In Tab.3, "comprehensive index of rock-cutting" is a comprehensive assessment of particle water jet rock-breaking performance, signed by T. In this paper, T is calculated by Eq.1:

$$T=\sqrt{\frac{16}{H_i}+\frac{16}{V_i}} \qquad \text{(Eq.1)}$$

Every parameter in Tab.3 as follows: $L_{16}(4^5)$ is to arrange five-factor and four-level experiments and the total number of experiments is 16; the experimental results are recorded by T1, T2, …Ti, …, T16; every factor has four levels and every level involves four experiments. Ki is the mean of four experiment results of level i. R is the difference between the maximum value and minimum value of the mean of four experiments for different levels and single factor, called extreme difference.

Calculation and analysis go as follows:

(1) Calculate the mean of experimental results of different levels of every factor;

(2) Calculate the extreme difference of experimental result summations of different levels of every factor;

(3) Determine the key factor , important factor and possible optimal experimental program;

(4) Take the trend of the levels into consideration, explore the optimal program.

Table 3
Orthogonal Layout $L_{16}(4^5)$ (Experiment Result Calculation and Analysis)

No.	A/MPa	B/MPa	C/mm	D/mm	E/%	H/mm	V/cm^3	T
1	1	1	1	1	1	33.76	3.25	1.57
2	1	2	2	2	2	67.07	23.00	2.53
3	1	3	3	3	3	83.05	20.75	4.32
4	1	4	4	4	4	44.84	8.25	1.67
5	2	1	2	3	4	54.40	19.25	1.84
6	2	2	1	4	3	66.57	17.50	2.07
7	2	3	4	1	2	59.29	25.75	2.40
8	2	4	3	2	1	60.40	20.50	2.00
9	3	1	3	4	2	25.63	2.00	1.46
10	3	2	4	3	1	42.39	12.50	1.67
11	3	3	1	2	4	63.39	27.25	2.76
12	3	4	2	1	3	78.13	32.75	4.00
13	4	1	4	2	3	26.70	2.75	1.51
14	4	2	3	1	4	24.67	1.50	1.41
15	4	3	2	4	1	76.90	37.75	4.62
16	4	4	1	3	2	67.85	20.50	2.51
k1	2.52	1.60	2.23	2.35	2.47			
k2	2.08	1.92	3.25	2.20	2.23			
k3	2.47	3.53	2.30	2.59	2.98			
k4	2.51	2.55	1.81	2.45	1.92			
R	0.44	1.93	1.44	0.39	1.06			
Priority		B>C>E>A>D						
Best level	A1	B3	C2	D3	E3			
Combination		A1B3C2D3E3						

To be continued

Continued

Exploring level trend need to analyze the inner link between the levels and the experiment results and look for the optimal level, which may not emerge in the experiments, and lastly find the optimal experimental program. Effect Curve Chart, as shown in Fig.6, is a curve chart whose abscissa is level and ordinate is T_i. In this chart, mark the corresponding points and then connect the points of the same factor to form a curve. Generally, effect curve chart is applied to the involved and quantifiable levels. Extreme difference R is used to determine the order of priority of the factors, which are sorted as B>C >E>A>D by the descending order. Effect curve chart gives the variation trend of comprehensive index of rock-cutting with the levels of the factor.

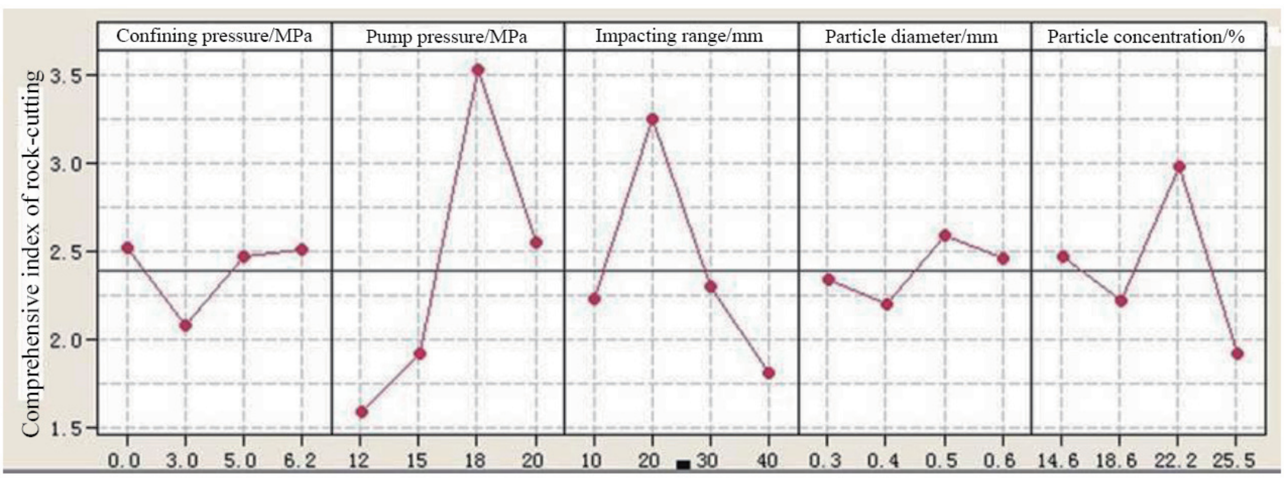

Figure 6
Orthogonal Experiment Effect Curve Chart

The above analysis indicates: comprehensive index of rock-cutting doesn't make a big change with confining pressure and particle diameter and it's better to select appropriate levels of pump pressure, impacting range and particle mass concentration. The order of priority of the five factors is: B (Pump pressure)→C (Impacting range)→E (Particle mass concentration)→A (Confining pressure)→D (Particle diameter). For confining pressure, it can be seen that the corresponding mean is the biggest when i is 1(P=0MPa); for pump pressure, the rock-breaking effect is the best when i is 3 (Ps=18MPa); for impacting range, the corresponding mean is the best when i is 2(S=20mm); for particle diameter, the rock-cutting effect is the best when i is 3 (S=20mm); for particle mass concentration, the corresponding mean is the biggest when i is 3(ω=22.2%). It can be drawn that the optimal program under this experimental condition is $A_1B_3C_2D_3E_3$. Meanwhile, the optimal experimental program is not included among 16 sets of experiments. Therefore, the optimal experiment was made up for. Penetration depth turned out 79.68mm, the second deepest, and erosion volume is 39.25cm3, the largest one. It is in consistent with theoretical analysis. It can be concluded from the effect curve chart that each factor has no significant intersecting trends and there is no interaction among various factors (Wang et al., 2004).

5.2 Experimental Result Variance Analysis

The above general analysis does not consider the influence of error on experiment result. In order to eliminate this impact, variance analysis should be considered and significance tests should be done. Calculation and analysis are as follows (Sheng et al., 2005):

(1) Calculate sum of square of deviations $SS_{\text{factor}} = 4Q - \frac{G^2}{16}$, where $Q = \sum_{i=1}^{4} k_i^2, G = \sum_{j=1}^{16} T_j$;

(2) Calculate degrees of freedom $df_{\text{factor}} = m - 1$, where m is the number of the level of the factor;

(3) Calculate the mean of variance $MS = \frac{SS}{df}$;

(4) Construct statistic F $F = \frac{MS_{\text{factor}}}{MS_{\text{error}}}$;

(5) Finish variance analysis table (Tab.4) and do F tests.

Table 4
Variance Analysis Table

Variance source	Sum of squares	Degrees of freedom	Mean square	F
A	0.55	3	0.18	1.20
B	8.67	3	2.89	19.27
C	4.40	3	1.47	9.80
D	0.32	3	0.11	0.73
E	2.38	3	0.79	5.27
Variance	0.87	6	0.15	
Sum	17.19	21		

Variance analysis shows that the priority order of five factors is B, C, E, A, D, which conforms with the intuitive analysis. Significance test is used to determine whether the influence of a factor is significant. In this paper, the orthogonal table has no blank column and there are no repeated experiments, so it is difficult to evaluate error (Yang et al., 2006). However, it is discovered that the variance of factor D (Particle diameter) is the smallest and D could be chosen as the experimental error. SS_D is used to take place of SS_e. Because of $MS_A<2MS_e$, the sum of square of deviations and degree of freedom of factor A (Confining pressure) are added to that of the error, which helps to improve the sensitivity of F test. Choose a significance level a=0.05 and F attribution table shows $F_{0.05}(3,6)=4.76$. From variance analysis table, $F_D<F_A<F_{0.05}(3,6)<F_E<F_C<F_B$. So it is indicated that pump pressure, impacting range and particle mass concentration have great influence on comprehensive rock-cutting index while confining pressure and particle diameter do not. Particularly, $F_{0.01}(3,6)=9.78$ is much smaller than $F_B=19.27$, so pump pressure is highly significant for comprehensive index of rock-cutting.

CONCLUSION

In this paper, from the simulation experiments of particle water jet rock-breaking in laboratory, particle water jet rock-cutting performance is preliminary understood. Orthogonal experimental method not only reduces the experiment number, but also allow data analysis done based on the given table, which simplifies data analysis and do not affect the conclusion. The orthogonal experimental analysis shows that the order of priority of the main influential factors of particle water jet rock-cutting performance is pump pressure ps, impacting range S, particle mass concentration ω, confining pressure P and particle diameter d_p. Moreover, p_s is highly important while both S and ω are important. In addition, high p_s, moderate S, moderate ω, moderate d_p and low P could bring the optimal particle impact rock-breaking effect.

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