EXPERIMENTAL STUDY ON THE EFFECTS OF HYDRAULIC CONFINING PRESSURE ON IMPACTING CHARACTERISTICS OF JETS

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The high hydraulic confining pressure exhibited in oil-well downholes and deep water conditions affects jet dynamic characteristics remarkably. A set of devices and equipment were developed to study the influence of confining pressure on jet impact pressure and rock-breaking efficiency. The three most popular jet types—a conical water jet, a cavitating jet, and an abrasive jet—were studied with a maximum nozzle pressure drop of 25.0 MPa and maximum confining pressure of 20.0 MPa. Results clearly reveal the close relationship among confining pressure and jet impact pressure and rock-breaking efficiency. The axial jet impact pressure and rock removal volume decrease while as confining pressure increases, and the decreasing curve becomes flattened at a certain point. Under the same conditions, the rock-breaking efficiency of the cavitating nozzle jet is higher than the conical nozzle jet, and cavitating erosion and pressure fluctuation are the important factors affecting jet rock-breaking efficiency. Furthermore, under confining pressure conditions, pure water jets have an optimal standoff distance about 3 to 5 times that of the nozzle outlet diameter, at which the highest rock removal volume is achieved. According to the study, a drop of jet impact pressure with growth of confining pressure may be the main reason for the decreasing rock-breaking capability. The study could be used as a reference for setting and optimizing jet application conditions, and also could be adopted for developing working parameter selections as well as guiding the nozzle structure designs.

KEY WORDS: *jet, confining pressure, rock breaking, cavitating jet, abrasive jet*

1. INTRODUCTION

High-pressure water jet techniques have found growing applications in oil-well engineering and deep water environments in recent years, and play important roles in improving the drilling penetration rate and increasing the oil recovery ratio (Jacqueline et al., 2007;

NOMENCLATURE

p	nozzle pressure drop, MPa	p_i	axial jet impact pressure, MPa
		L	jet standoff, mm
p_a	confining pressure, MPa	d_o	nozzle diameter, mm

Nakhwa et al., 2007; Sun et al., 2012; Putra et al., 2012). The improvement of water jet energy utilizations has always been a key issue to water jet research. Many factors affect the impacting characteristics of water jets. Water jet applications in oil-well engineering invariably involve high confining pressure due to the hydrostatic pressure of a wellbore fluid column. Therefore it is necessary to study the confining pressure effects on the impacting characteristics of water jets.

The first study on the effects of confining pressure on the impacting characteristics of water jets was conducted in a self-developed autoclave to simulate the attenuation law of the axial dynamic pressure of submerged jets under high confining pressure (Voitsekhovsky et al., 1972). In the study, two levels of confining pressure were tested, 0.21 and 10 MPa, and four levels of driving pressure were selected: 50, 100, 150, and 200 MPa. In documents (Conn, 1979; Matsuki et al., 1990; Shimizu et al., 1998; Kalumuck et al., 1993), the attenuations of the axis dynamic pressure at different ranges were studied by experiments, and some regularities of the confining pressure affecting the rock-breaking capability of general high-pressure jets were obtained under confining pressure conditions. The article (Kole, 1987) established a test platform and made a preliminary analysis on the effect of the confining pressure and lateral stress on rock samples, where the scene of a water jet cutting rock in deep wellbore conditions was simulated. From the test results, confining pressure and lateral stress have a great effect on rock antierosion capability. Furthermore, super-high-pressure water jets of 200 and 350 MPa were used in rock-cutting tests at a confining pressure of 1.2 MPa and a formula for the cutting depth with the traverse speed was established (Hlaváč et al., 2001). In recent years, to reveal the effects of the hydraulic parameters and rock properties on the characteristics of high-pressure cavitating water jets, experiments to figure out the rock-breaking effect of the water jet on the rocks with different porosity rates were carried out under different confining pressures and pump pressures (Li et al., 2005, 2009; Lu et al., 2009). Also, a numerical model of breaking rock by a high-pressure water jet for rock in a state of high ambient pressure was developed (Liu and Si, 2011). A better understanding of the effect of confining pressure on jet impact characteristics has been acquired.

The water jet rock-breaking mechanism is still a complicated problem and there are many arguments concerning the effect of confining pressure. In all the above studies, the tests of confining pressure affecting jet characteristics were performed due to limited experimental conditions, where confining pressure ranged from 6.0 to 10.0 MPa, also being discontinuous and scattered. However, in oil wellbores or deep ocean conditions, confining pressure formed by hydrostatic pressure of a fluid column is generally greater than 10.0 MPa. In this study, a new testing system is developed which can obtain a large range of confining pressures. During rock-breaking tests, the maximum confining pressure reached 20.0 MPa at a maximum nozzle pressure drop of 25.0 MPa. The regularities of confining pressure affecting jet impact pressure and rock-breaking efficiency were investigated, and the mechanism of confining pressure affecting the rock-breaking capability of the jet was analyzed. It is expected that the study will be helpful for nozzle structure design and hydraulic parameter optimization in specialized applications of water jet environments.

2. FACILITIES AND METHODS

2.1 Experimental Facilities

Two kinds of devices were used in conducting the tests at the High-Pressure Water Jet Research Center of the China University of Petroleum. The one for a jet impact pressure measuring device, as shown in Fig. 1, was mainly composed of a high-pressure pump package, a pressuring vessel, a nozzle assembly, pressure gauges, and jet impinging distance control rods, etc. A jet is sprayed from the nozzle to the tiny pressure hole with 0.5 mm diameter, from which jet impact pressure value could be transferred to pressure gauge 3, while pressure gauges 1 and gauge 2 separately indicate the nozzle pressure drop and confining pressure. The other one for the jet rock-breaking test includes mainly a wellbore simulator, a hydraulic system, and a data acquisition and control system, as shown in Fig. 2. The structure is as follows: (1) The wellbore simulator mainly con-

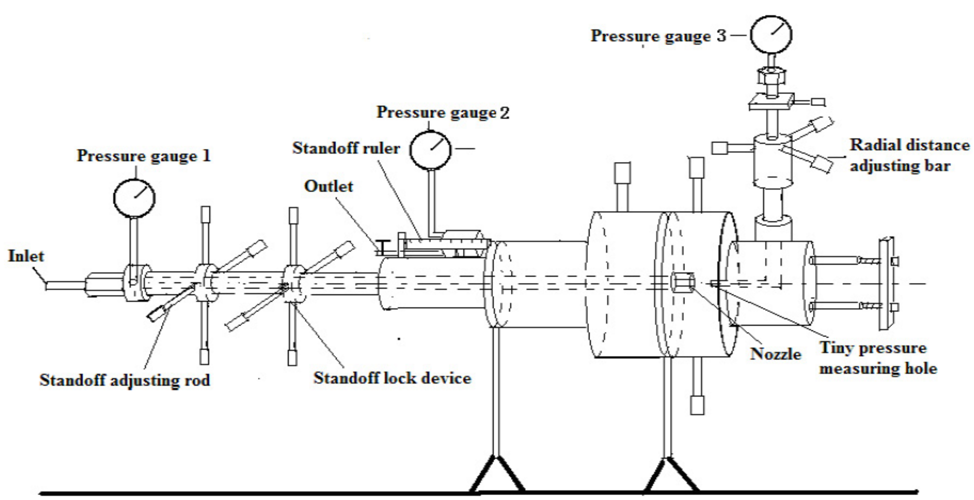

FIG. 1: The test device for measuring jet impact pressure.

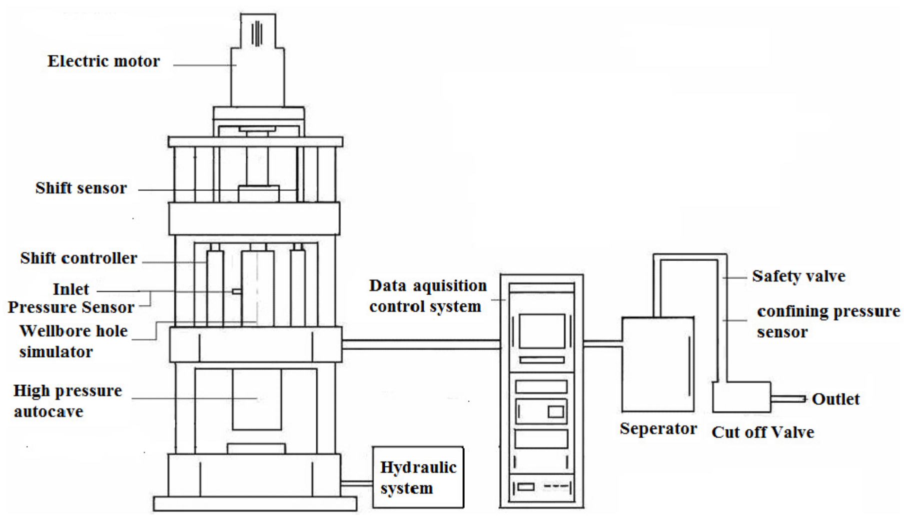

FIG. 2: The test device for jets breaking rock.

sists of an electric motor, an upper separator, a walking beam, a wellbore hole, and an autoclave. The wellbore hole inside which a nozzle can be placed and installed with measuring sensors for tests, and the autoclave is the platform of high-pressure jets breaking rock. (2) The hydraulic system, whose chief function is to regulate and simulate the distance between the nozzle outlet and rock sample in the autoclave by using a special hydraulic cylinder. (3) The data acquisition and control system mainly comprises a computer, a control panel, a display screen, a sensor translation unit, and so on, and has the major functions of controlling operation pressures and standoff distance, as well as the acquiring and processing of test data, etc.

Conical nozzles and a self-resonating cavitating nozzle were used in the tests, whose schematic diagram and structural parameters are shown as Fig. 3 and Table 1.

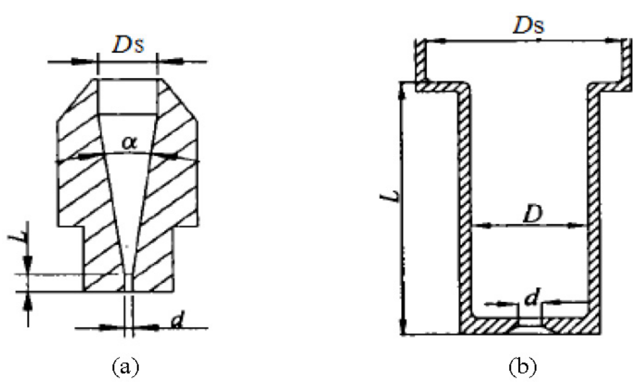

FIG. 3: Schematic diagram of nozzles for the test. (a) Conical nozzle and (b) cavitating nozzle.

TABLE 1: Nozzle parameters for the tests.

Nozzle type	d/mm	D_s/mm	D/mm	L/mm	α/°
Conical (#1)	1.0	6.4	/	3.0	13.5
Conical (#2)	3.0	6.4	/	7.0	13.5
Cavitating	1.0	6.4	3.2	20.0	/

2.2 Experimental Methods

2.2.1 Jet Impact Pressure Test

The driving pressure, confining pressure, and impact pressure of a water jet could be indicated by pressure gauge 1, gauge 2, and gauge 3, as shown in Fig. 1. During a test, the distance from the nozzle outlet to the tiny pressure measuring hole was regulated by a standoff adjusting rod. Thus, the regularity of jet impact pressure varying with different standoff distances could be obtained. With a fixed standoff distance, different combinations of confining pressure and nozzle pressure drop were obtained by means of regulating an inlet control valve and an outlet control valve for a water jet. When measuring jet impact pressure, through regulating the radial distance bar, at the point where the value on gauge 3 reached maximal, the maximum pressure is the centerline impact pressure of a water jet. Due to the sealing limitation, confining pressure at tests was set within 0$\sim$10 MPa.

2.2.2 Jet Rock-Breaking Test

During a test, the nozzle pressure drop was fixed, while confining pressure was regulated by the controlling system. The rock-breaking efficiency of a jet was evaluated by measuring the rock removal volume with a sand filling method or the hole depth was measured with a vernier caliper.

3. ANALYSIS OF EXPERIMENTAL RESULTS

3.1 Effect of Confining Pressure on Water Jet Impact Pressure

Figure 4 shows the variation of axial jet impact pressure p_i at the centerline with the confining pressure p_a at three nondimensional jet standoffs (the ratio of the distance from the nozzle outlet to the rock sample surface to nozzle diameter d_o) when the nozzle pressure drop p is set at 15.0 and 20.0 MPa with a #1 conical nozzle. It is clear that within a confining pressure from 0 to 2.0 MPa, axial jet impact pressure at the centerline (expressed with nondimensional pressure, the ratio of p_i to p) decreases very fast with the increase of confining pressure. Within a confining pressure from 2.0 to 6.0 MPa, the decreasing trends of jet impact pressure are slowed down; within the confining pressure from 6.0 to 10.0 MPa, the curves tend to level off and maintain an almost imperceptible

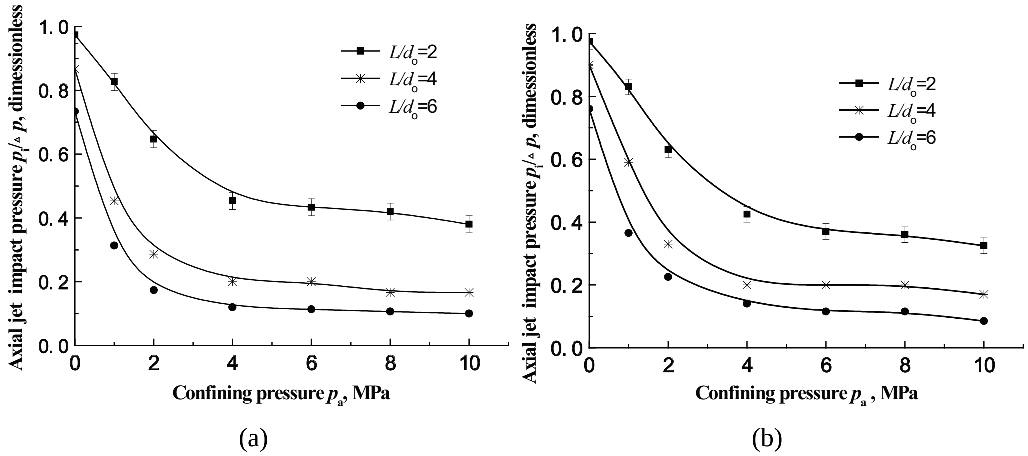

FIG. 4: The relationship between axial jet impact pressure and confining pressure at different nondimensional standoffs. (a) Δp = 15.0 MPa and (b) Δp = 20.0 MPa.

decline. Figure 5 shows the regularity of jet impact pressure variation with nondimensional standoffs under different confining pressures when p is set at 15.0 and 20.0 MPa. It can be seen clearly that jet impact pressure decreases gradually with an increasing standoff distance. Within nondimensional standoffs from 2 to 6, the jet impact pressure reduces rather rapidly with increasing confining pressure; within standoffs from 6 to 10, the drop of jet impact pressure slows down. From these results, the influence of confining pressure on jet impact pressure is mainly related to the values of confining pressure and jet standoff distance. According to numerical simulation and experiments of jet flow structure (Thomas, 2005; Zhou, et al., 2010), in a range of jet potential core from 0 to 2

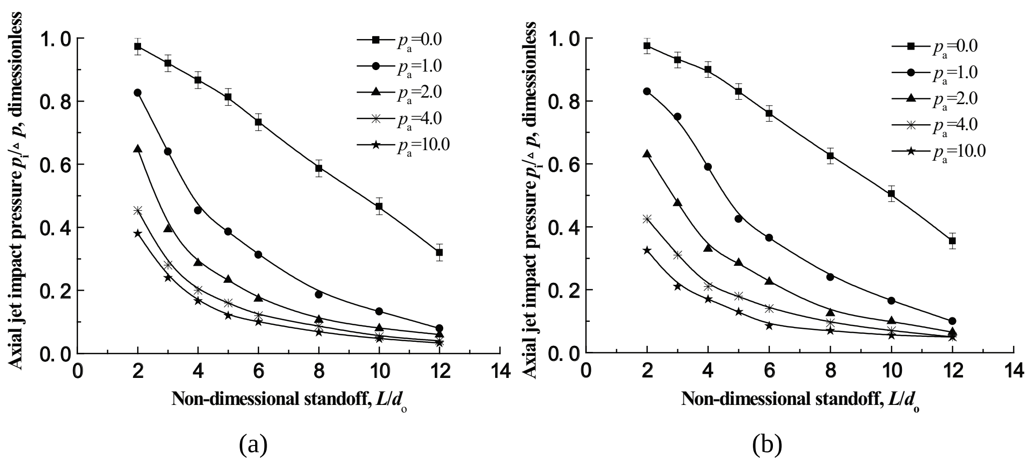

FIG. 5: The relation between axial jet impact pressure and nondimensional standoffs under different confining pressures. (a) Δp = 15.0 MPa and (b) Δp = 20.0 MPa.

nondimensional standoff, the jet spray velocity equals the nozzle outlet velocity under zero confining pressure. Therefore, the impact pressure data error is about 0.5 MPa, which is mainly caused by the tiny measuring hole with 0.5 mm diameter that gets average impact pressure instead of the precise value at the nozzle centerline.

3.2 Effect of Confining Pressure on Rock-Breaking Efficiency with Pure Water Jets

Figure 6 shows the variation of rock removal volume under varying confining pressures by the #1 conical nozzle at different nondimensional standoffs. In the test, the jet driving pressure and the confining pressure were regulated simultaneously at a given standoff with nozzle pressure drop fixed at 20.0 MPa. From Fig. 6, the curves decrease and drop trends become slow with the increase of confining pressure. At the beginning, a sharp decrease occurs, then slows down, and at last the profile becomes approximately a horizontal line. Figure 7 shows the variation of rock removal volume with standoffs under different confining pressures. When the nondimensional standoff is equal to 2 under zero confining pressure, the rock removal volume is 0.6 cm^3; while the confining pressure grows to 10.0 MPa, the rock removal volume drops to 0.09 cm^3; and once the confining pressure reaches 20.0 MPa, the rock removal volume changes to 0.065 cm^3. This indicates that the confining pressure has a significant effect on the rock-breaking ability of a water jet. At the same time, as the standoff increases, the rock removal volume increases until a turning point appears where the rock removal volume starts dropping. That is to say, there is a range of standoff distance where the rock removal volume reaches its maximum. Under the test conditions, the optimal nondimensional standoff distance is about 3–5 times that of the nozzle outlet diameter. On one hand, in a short standoff distance, rock erosion increases slowly because of the return flow counteracting parts of the jet

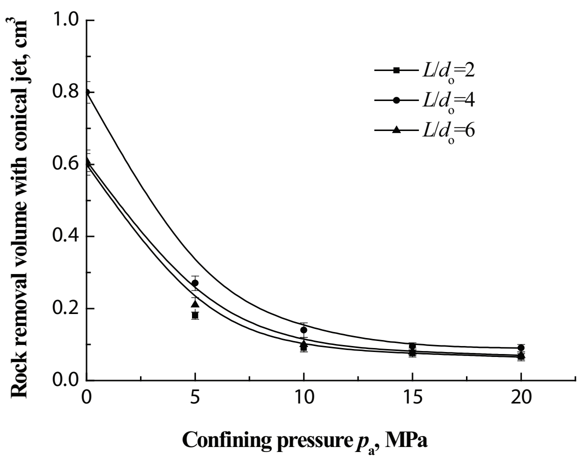

FIG. 6: Rock removal volume by conical nozzle #1 varies with confining pressure.

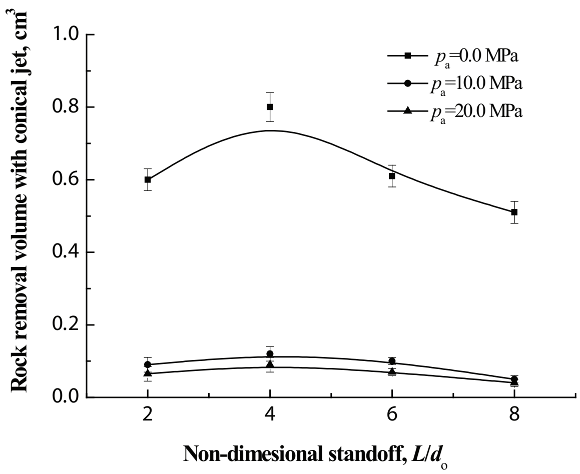

FIG. 7: Rock removal volume by conical nozzle #1 at different standoffs.

energy. On the other hand, the jet effective impinging area enlarges as an increment of standoff distance in a certain range. This is why an optimal standoff distance exists.

Figures 8 and 9 show the confining pressure influence on the rock removal volume by the cavitating nozzle listed in Table 1, with same test conditions as the conical nozzle above. The results are similar to those by conical nozzle #1. With an increment of confining pressure, the rock removal volume decreases. Under low confining pressure, the jet rock-breaking efficiency decreases faster. After confining pressure amounts to a certain value, the decrease of rock-breaking efficiency becomes slow. The comparative statistics show that the rock removal volume by the self-resonating cavitating nozzle is about 1.1–1.6 times that by the conical nozzle under the same conditions.

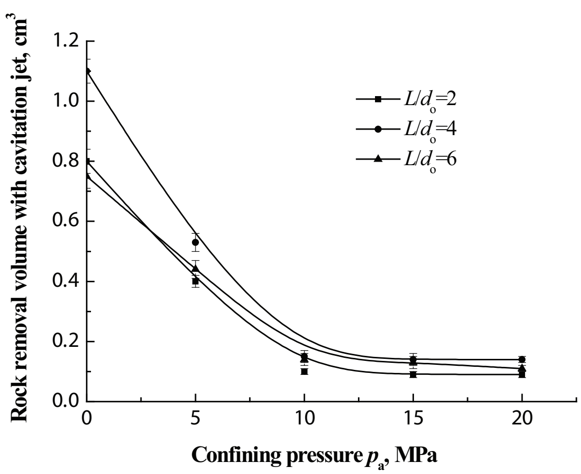

FIG. 8: Rock removal volume, the cavitating nozzle under different confining pressures.

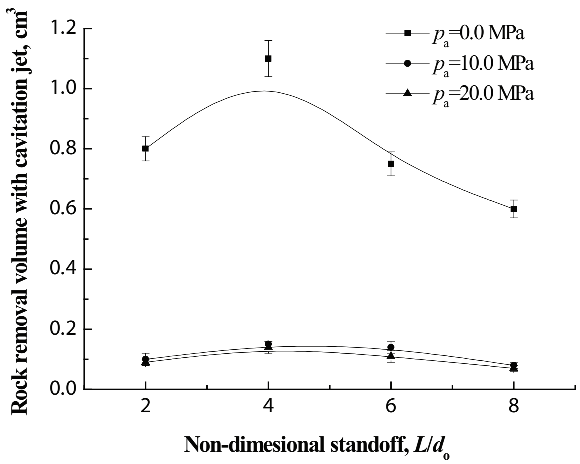

FIG. 9: Rock removal volume by the cavitating nozzle at different standoffs.

According to measuring the time-domain characteristics of the cavitating jet noise, it is found that the cavitating jet has a strong pulse characteristic. Figure 10 shows a time-domain waveform for the self-resonating cavitating jet at a nozzle pressure drop of 20.0 MPa, and a confining pressure of 0.5 and 6.0 MPa separately. At a confining pressure equal to 0.5 MPa, the waveform performance takes on an obvious pulse with a frequency of about 2.8 kHz. While at a confining pressure equal to 6.0 MPa, the jet cavitating noise fluctuation characteristic is significantly weakened, and a certain confining pressure has a strong inhibitory effect on the jet pulse characteristic.

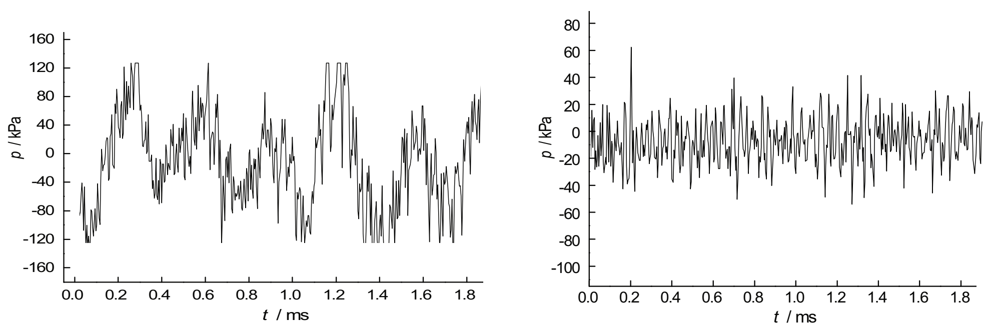

FIG. 10: The time domain diagram formed by the cavitating jet noise.

3.3 Effect of Confining Pressure on Rock Breaking with Abrasive Water Jets

Figure 11 shows the influence of confining pressure on the rock-breaking efficiency of the abrasive jet at a nozzle pressure drop of 20.0 and 25.0 MPa with a #2 conical nozzle.

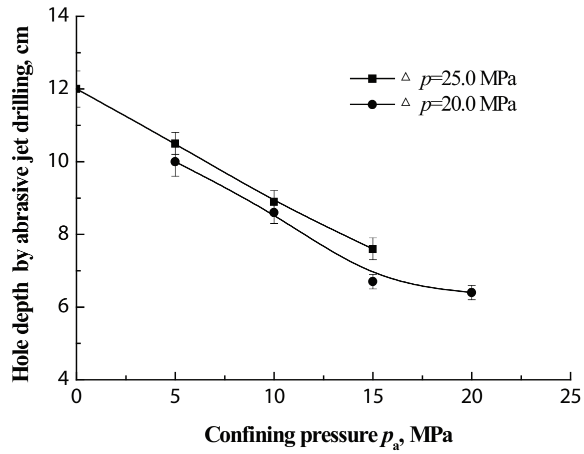

FIG. 11: Hole depth by abrasive jet drilling under different confining pressures.

In the test, the jet standoff distance was fixed at 15.0 mm with 5 min erosion duration, and the abrasive particles were quartz sand with a concentration of about 6% and grain size from 0.4 to 0.6 mm. Since abrasive jets have been applied in oil-well engineering mainly for perforating and slotting, hole depth is adopted to evaluate rock-breaking efficiency.

It is clear that confining pressure also causes the hole depth to decrease by the abrasive jets. When confining pressure is lower than 15.0 MPa, the hole depth exhibits an approximately linear decrease. After that point, the attenuation of hole depth slows down.

4. DISCUSSION

According to the test and data analysis, two main factors contribute to the decrease in rock-breaking efficiency under confining pressure conditions. The first factor is the effect of confining pressure directly working on the jet dynamic pressure, and the second factor is the effect of confining pressure on rock strength.

On the one hand, confining pressure has significant effects on jet dynamic pressure and axial spray speed. Under confining pressure conditions, the attenuation of axial dynamic pressure of jets is accelerated significantly. When a jet reaches the impact surface, jet stagnation pressure decreases with increasing confining pressure. For an abrasive jet, the velocity of abrasive particles reduces with decreasing water jet speed, since the velocity of abrasive particles is mainly determined by the velocity of the water jet, which causes the rock-breaking efficiency of the abrasive jet to reduce. Furthermore, confining pressure has a restraining effect on the pressure fluctuations and cavitating inception of the jet. When the confining pressure exceeds a certain value, the cavitating erosion effect disappears, and the rock erosion mainly depends on jet dynamic pressure.

On the other hand, the confining pressure has significant effects on the mechanical properties of rock. According to the rock mechanical properties study (Jaeger et al., 2007), rock strength increases with an increment of confining pressure. The rock strength increases clearly under low confining pressure while the increasing trend tends to drop off under a higher confining pressure. In addition, an increment of confining pressure also causes an increment of resistance to rock cracks initiating and expanding. Consequently, jet rock-breaking efficiency is decreased.

5. CONCLUSIONS

1. Confining pressure at a certain range has a significant influence on the impact pressure and rock-breaking efficiency of water jets. Jet impact pressure and rock removal volume decrease with growing confining pressure, and the decreasing trends slow down.

2. Under the same conditions, the rock-breaking efficiency of a self-resonating cavitating nozzle is higher than that of a conical nozzle. Cavitating erosion and pressure fluctuation are the important factors affecting the rock-breaking efficiency of a water jet, which are also influenced by confining pressure.

3. Under the experimental conditions, the optimal standoff distance achieving maximum rock removal volume with pure water jets is about 3 to 5 times that of the nozzle outlet diameter.

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