Rock-Breaking Properties Under the Rotatory Impact of Water Jets in Water Jet Drilling

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Abstract: Water jet drilling is widely used to develop coalbed methane reservoirs. The water jet drill bit is the core component, and a self-rotating bit is an economical bit because of its high rock-breaking efficiency and low energy consumption. Because the important parameters concerning the rock-breaking efficiency of these drill bits are unclear, this study carried out rock-breaking experiments on water jet rotation under different conditions of drill bit rotation speed, jet pressure, and jet impact angle. How the rock was fractured and eroded under these different conditions was analyzed. The results show that the volume of rock broken under rotary jet erosion increases exponentially with increasing jet pressure. The rock-breaking depth is the most important factor that influences the volume of rock broken, whereas the diameter of the area broken is a secondary factor. There is an optimum water jet rotation speed for the most efficient rock breakage, and this rotation speed is positively correlated with jet pressure. There is also an optimum water jet impact angle for rock breaking, and, in our experiments, this angle was 10°. The rotary impact of the water jet causes the rock to be in a three-way tension state, and this reduces the water cushion effect and jet reflection. This study can be used as a reference and guide for optimizing the design of self-rotating water jet bits and the determination of reasonable drilling parameters.

Keywords: coalbed methane development; water jet drilling; self-rotating bit; rock breaking

1. Introduction

Coalbed methane (CBM) is a high-quality source of clean energy but also the main factor responsible for coal mine gas disasters. Hence, the efficient development of CBM resources is an important component of both the readjustment of China’s energy structure and continued safe coal mining. However, the CBM reservoirs in China are complex in that they are characterized by low permeability, low saturation, low reservoir pressures, and relatively high metamorphic grades [1,2]. It is therefore necessary to adopt methods for increasing the permeability of coal seams.

Some methods have been employed to improve the permeability of coal seams and some results have been achieved, with techniques such as hydraulic fracturing [3,4], deep hole pre-splitting blasting [5], water jet drilling [6,7], and other techniques used to increase CBM production. Water jet drilling is widely used for CBM development. It has the advantages of temperature reduction and dust removal, and this drilling technique does not produce sparks and is very effective at breaking rock [8]. Existing water jet bits include rotary jet bits, combined jet bits, and straight-swirling integrated
jet bits. Rotary jet bits break a large area but because of relatively low jet velocities near the bit axis, their rock-breaking efficiency is low. A boss is formed at the center of the borehole and this boss hinders drill bit advance and reduces drilling efficiency [9]. A combined jet bit can integrate different jet characteristics, but designing an effective bit of this type is difficult. The two kinds of water jet are easy to interact, and these bits are large [10,11]. The straight-swirling integrated jet bit is very good at breaking rock and is reliable, but the large bit is not conducive to field application [12]. Hence, some investigators have proposed using self-rotating bits: bits that have high rock-breaking efficiency, low specific consumption, and produce large diameter holes [13–16]. Liu et al. introduced a self-rotating bit for ultra-short radius self-propelled horizontal drilling of CBM wells [17]. They analyzed the bit’s drilling speed and hole diameter but did not investigate the influence of any hydraulic parameters or the jet operating parameters on hole diameter. Li et al. developed a model for calculating the rotation speed of a self-rotating bit and analyzed the influence of structural parameters on the bit’s rotation speed [14]. Wang et al. simulated the effects of jet angle and bit rotation speed on the jet flow field [18]. However, these previous self-rotating drill bit studies have focused on optimizing the bit structure and analyzing the fluid flow around the bit. Moreover, there are few studies which focus on the effect of different water jet parameters.

Rock-breaking efficiency is determined by water jet parameters. Hence, this paper has carried out rock breaking experiments under different rotating speeds, jet pressures, and incident angles. The influences of jet pressure, rotation speed, and impact angle on the rock-breaking efficiency of a self-rotating jet were obtained. Self-rotating bit design considerations were analyzed. The conclusions from this study can provide a reference and guidance for self-rotating bit design optimization and the determination of performance parameters.

2. Materials and Methods

Jet pressure determines the speed at which a rock can be broken, and this is one of the most important parameters for jet rock-breaking efficiency. Research has shown that the jet’s impact angle has a significant influence on rock breaking, but the details are not known. Rotation will not only accelerate the jet’s energy attenuation, causing the jet to atomize, but will also weaken the water cushion effect and increase the rock breaking times. The effect of different water jet parameters on rock breaking is unknown. This study therefore analyzed the effects of jet pressure, rotation speed, and the jet’s impact angle on rock breaking by conducting experiments using a purpose-built four-dimensional water jet platform.

2.1. Experimental Equipment and Sample Preparation

The experimental device is shown in Figure 1. It allowed the water jet pressure, rotation speed, and impact angle to be adjusted.

![Figure 1. Four-dimensional water jet platform experimental system.](image-url)
The most important pieces of equipment and samples used in the experiments are described below.

(1) A high-pressure water pump was used which was a five-pulse fracturing pump (Nanjing Liuhe Company, Nanjing, China) with a rated pressure of 56 MPa and a flow rate of 200 L/min.

(2) The synthetic coal specimens used were of the same composition as those described by Gao (2016) [19]. They were molded from a mixture of cement, pulverized coal, gypsum, and water; the aggregate was 60–80 mesh coal powder, and the binder cement and gypsum. The proportions of the material were cement to gypsum to pulverized coal 32:32:17. The appropriate amount of water (water–cement ratio = 0.4) was added and the mixture was stirred until uniform and then poured into a 100 mm cubic mold for curing. This produced specimens like that shown in Figure 2. The average physical and mechanical properties of a fully cured specimen briquette were density 1498 kg/m³, compressive strength 2.45 MPa, Poisson ratio 0.19, elastic modulus 1.59 GPa, internal friction angle 26.8°, and cohesion 0.74 MPa. These properties met the experimental requirements.

(3) A nozzle was used. The water jet bit was a high-speed jet generating mechanism that used a conical convergence nozzle with an aperture 1.2 mm in diameter. The nozzle was located 10 mm from the bit axis, as shown in Figure 3.

![Figure 2. A synthetic coal specimen, i.e., a 100 mm cube.](image)

![Figure 3. Illustration showing the water jet bit used in the experiments: (a) top view of the bits; (b) front view of the bits.](image)

2.2. Experimental Methods

Different jet stream pressures, impact angles, and water jet bit rotation speeds were used to study the effects of water jets on the specimens. The common experimental parameters were an erosion time of 30 s (starting when the jet pressure was stable) and a jet impact distance of 20 mm. The depth, width, and volume of the crushed pit formed in the specimen were used as indexes for evaluating rock-breaking performance. The depths and widths of the crushed pits were measured by digital vernier calipers and the pit volumes were determined by measuring the volume of sand needed to fill each pit. Each specimen was tested three times and the results were averaged. The specimens
were named by numbers representing the pump pressure, the rotation speed, and the impact angle. For example, the specimen name 6-100-0 indicates that the specimen was tested with a 6 MPa jet rotating at 100 rpm impacting at an angle of 0°.

The schemes for the three sets of water jet rotary impact rock-breaking tests performed are described below.

Experimental suite 1: water jet impact angle 0°; bit rotation none (0 rpm) and 100 rpm; and water jet pressures 3, 6, 9, 12, 15, and 18 MPa. Experimental suite 2: water jet impact angle 0°; bit rotation speeds 0, 50, 100, 150, 200, and 250 rpm; and water jet pressures 6 and 12 MPa. Experimental suite 3: tests were conducted with water jet bits providing different impact angles (0°, 10°, 20°, and 30°); the erosion test was carried out at rotation speeds of 0 and 100 rpm and water jet pressures of 6 and 12 MPa.

3. Results and Discussion

3.1. Effect of Jet Pressure on Rock Breaking

Figure 4 is a comparison diagram showing the rock-breaking effect on erosion specimens with no bit rotation (0 rpm) and with the bit rotating at 100 rpm for different water jet pressures. When the jet pressure was 3 MPa under either rate of rotation, the specimens showed only scour marks and no obvious crushed pit was formed. This indicates that the jet energy was below the critical energy needed for specimen failure; the water jet could not break the specimen effectively but the continuous action of the water jet left scour marks on the specimen’s surface. When the jet pressure was 6 MPa or higher, more energy was transferred to the specimen and a crushed pit was formed on the surface of the specimen. A ring-shaped crushed pit was formed on the specimen’s surface when the bit was rotated at 100 rpm. When the jet pressure was increased further, the crushed pit in the specimen was gradually enlarged, but when the bit did not rotate, no hole was drilled. When the jet bit was rotated at 100 rpm, the volume of the ring-shaped crushed pit increased, the boss was formed, and most of the 18-100-0 specimens were holed.

![Figure 4](image-url)  
Figure 4. Diagram comparing the rock breaking of water jets during tests with no bit rotation (0 rpm) and with 100 rpm bit rotation.

Figure 5 shows the rock-breaking volume fitting curves for two erosion conditions. The volumes of crushed pits for specimens eroded without bit rotation (that is, eroded under “fixed erosion”) show gradual linear growth, whereas the rock-breaking volumes for specimens under rotary erosion show exponential growth. Within the range of our experiments, the volume of pits crushed by an 18 MPa
water jet under fixed erosion reached 2.25 mm³, but the volume of pits crushed by the same 18 MPa jet under rotary erosion reached 27.11 mm³. This indicates that for the same jet energy, the average crushed pit volume eroded under a rotating jet is greater than the pit volume eroded under a fixed jet. The main reason for this difference in the volume of rock eroded is that the tensile and shear strength of rock are much lower than its compressive strength; hence, rock is more likely to be broken by shear and tensile stresses than by compressive stress. The rotating water jet has a tangential velocity and where the jet contacts the rock, the oblique impact of the jet shears the rock and the rock surface is damaged by the shear stress. A ring-shaped crushed pit is generated. When the rotating water jet contacts the rock, the radial and tangential stresses in the rock generated by the jet impact are converted into tensile stress and enter a three-dimensional stress state. Thus, a rotating jet is more efficient at breaking the rock than a non-rotating jet [20]. In addition, the rebounding water from a rotating jet flows back along the outside of the jet stream and does not contact the incoming water to reduce the force needed for the subsequent crushing of the rock. This reduces energy losses.

![Figure 5](image-url)

**Figure 5.** Influence of jet pressure on rock-breaking volume by non-rotation jet and rotary jet.

The volume of each crushed pit was defined by the depth and diameter of the crushed pit. Figure 6 shows curves for crushed pit depths and diameters for different jet pressures for both rotating and nonrotating jets. For a nonrotating jet, the depth of the crushed pit was 2.63 mm/MPa, but for a jet rotation at 100 rpm, the depth of the crushed pit was 6.33 mm/MPa. The diameters of the crushed pits formed by the two kinds of jets increased quadratically. Under fixed jet erosion the rate of crushed pit diameter growth gradually decreased as the pump pressure increased. When the pump pressure reached a certain value, the diameters of the crushed pits stopped increasing. However, the growth rate of the crushed pit diameters under rotary jet erosion continued to increase slightly as the pump pressure increased. This behavior was consistent with the fixed erosion results reported by Liu et al. [21]. The depth of the crushed pits under rotary erosion was the dominant factor for the volume of the crushed pits. The growth rate for the depth of the crushed pits under rotary erosion was 2.41 times that of the pit depth growth rate for fixed erosion. The main reason for the difference in growth rates was that the impact velocity and impact kinetic energy of the jets correlated positively with jet pressure. As the jet pressure increased, the jet impact velocity increased significantly. This increased the jet’s effective rock-breaking distance so that the pit depth continued to increase with increasing...
pump pressure. However, the jet geometry (diffusion angle and jet section width, etc.) was mainly determined by the geometry of the nozzle, so the jet pressure only affected the jet’s velocity.

![Graphs showing the relationship between jet pressure and crushed pit depth and diameter.](image)

**Figure 6.** Influence of jet pressure on the depth and diameter of crushed pits by two kinds of water jets: (a) influence of jet pressure on the depth of crushed pits; (b) influence of jet pressure on the diameter of crushed pits.

### 3.2. Effect of Rotation Speed on Rock Breaking by Jet Rotation Impact

Figure 7 shows the depth, diameter, and volume of the crushed pits at different bit rotation speeds. As shown in the figure, there was an optimal rotation speed for maximum erosion.

![Images of crushed pits at different rotation speeds.](image)

**Figure 7.** Influence of rotation speeds on rock-breaking efficiency.

The data shown in Figure 7 were fitted to different jet pressures and rotation speeds (Figure 8). As shown in Figure 8, the depths, diameters, and rock-breaking volumes for the crushed pits increased quadratically with increasing rotation speed, and there was an optimum rotation speed to maximize pit depth, diameter, and volume. When the jet pressure was 6 MPa the maximum crushed pit diameter was reached at 150 rpm, but when the pressure was 12 MPa, the maximum pit diameter was reached at 200 rpm. However, there was little difference between the maximum pit diameters at those two rotation speeds, even though the crushed pit depths were quite different. The maximum crushed pit depth at 6 MPa and 150 rpm was 35 mm, whereas the pit depth at 12 MPa and 200 rpm was 60 mm. This indicates that rock-breaking depth played a dominant role in the rotary erosion of the jet flow and that the diameter of the crushed pit was subordinate. In addition, for the jet to have produced
the maximum volume of the crushed pit, the rotation speed needed to be different for different jet pressures. Under the conditions used for our experiments, the maximum volume of the crushed pit generated by the 6 MPa jet was produced at 150 rpm, whereas the maximum rock-breaking action by the 12 MPa jet occurred at 200 rpm. This indicates that the optimum rock-breaking rotation speed for a water jet bit is positively correlated with jet pressure, and for maximum rock breaking, the higher the jet pressure is, the faster the optimal rock-breaking rotation speed is.

The reasons for the jet rotating at the optimum speed eroding the rock are as follows. When the jet rotates and erodes the rock, it is difficult for water to collect in the bottom of the groove being cut. This reduces the water cushion effect and enhances the ability of the water jet to break the rock. In addition, according to the definition of rotation intensity [22], the faster the jet is rotated, the greater the swirling intensity is, the larger the jet diffusion angle becomes, and the more intense the turbulent mixing with the surroundings. The more the surrounding medium participates, the greater the capacity for increased exchange. This causes the jet to attenuate fast and shortens the effective rock-breaking distance. Furthermore, the shape of the jet is significantly affected by rotation; excessively rapid rotation will perturb the water jet and may deflect or atomize it, and either of those perturbations will weaken the jet’s rock-breaking ability [23].

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Figure 8. The influence of rotation speed on rock breaking by two kinds of water jets: (a) influence of rotation speed on depth of crushed pits; (b) influence of rotation speed on depth of crushed pits; and (c) influence of rotation speed on volume of crushed pits.

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3.3. Effect of Water Jet Impact Angle on Rock Breaking

The results from the experiments testing water jet impact angles are shown in Figure 9. From the data plotted in this figure, we were able to draw the following conclusions.

1. There is an optimal jet impact angle that maximizes crushed pit depth for both rotational and fixed erosion tests. In the range examined by our experiments, an impact angle of 10° resulted in the deepest pits. The main reason for this is that the water jet eroded the rock to form a slot and there was high-pressure water in the slot. This high-pressure water acts as a “water cushion,” and when the water jet impacts the rock at a specific angle, the water cushion can reduce the jet’s reflection angle. After a groove is formed by the water jet, the flow of water is facilitated and the cuttings are washed away. However, if the impact angle is increased too much, the impact force transmitted from the jet to the rock will be reduced, resulting in decreased erosion [24,25]. Our experiments run at different flow velocities, rotation rates, and impact angles resulted in no significant change in crushed pit diameter. The diameters of the crushed pits for the 12-100-30 specimens increased by only 0.4 mm, and the diameter of the crushed pits varied by ±5%. The change was not large and may have been caused by differences in specimen strength or may have only been an apparent change caused by measurement errors.

2. Under fixed erosion, when the jet pressure was 6 MPa, the variations in rock-breaking depth for different impact angles were small; the maximum crushed pit depth was 14.60 mm. The rock-breaking depth under rotating jet erosion was much greater, and the maximum pit depth was 28.80 mm, which was essentially twice the depth of the fixed erosion pits. This shows that for low-pressure water jets, jet rotation speed is the dominant factor for breaking rock and the jet impact angle is of secondary importance.

3. The volume of rock broken during the rotation and fixed erosion experiments showed completely different growth modes. Under our experimental conditions the rock-breaking volume increased exponentially as impact angle increased. Although the effective rock-breaking distance exceeded the effective rock-breaking distance of the jet as the impact angle of the jet increased, the depth to which the rock was broken became significantly shallower as the impact angle increased. However, as shown in Figure 10, an oblique jet impact exerted a tensile force on the surface of the rock. The rock was rapidly damaged in an area extending radially from the jet and the radius of the crushed pit increased dramatically. This resulted in an increase in the rock-breaking area of the jet so that the rock-breaking volume by jet rotary erosion presented an exponential growth mode.

![Figure 9. Cont.](image-url)
Figure 9. Effect of water jet impact angles on depth, diameter, and volume of crushed pits: (a) water jet impact angles on depth for a nonrotating jet; (b) water jet impact angles on depth for a rotary jet; (c) water jet impact angles on diameter for a nonrotating jet; (d) water jet impact angles on diameter for a rotary jet; (e) water jet impact angles on volume of crushed pits for a nonrotating jet; and (f) water jet impact angles on volume of crushed pits for a rotary jet.

Figure 10. Illustration showing the influence of different impact angles on rock-breaking range by jet rotational impact.

3.4. Self-Rotating Bit Design Considerations

Pump pressure is one of the most important parameters determining how well the jet bit will break rock. The higher the pump pressure is, the better the jet bit will break rock. However, high pump
pressures mean that this better rock breaking will use more water and that the energy used by the pump will increase. When the jet pressure is too high, the energy of the jet cannot be fully utilized. Hence, when a self-rotating jet bit is used to break rock, the pump pressure should be adjusted according to the performance of the drilling system. The self-rotating bit has an optimal rock-breaking rotational speed, and this speed correlates positively with the pump pressure. A speed-limiting mechanism must therefore be added when designing the bit to prevent the bit from rotating too fast. In addition, the speed at which the bit rotates should be adjustable. When the pump pressure is high, the bit rotation speed can be increased appropriately. The optimal rock-breaking angle for the jets on a self-rotating bit is about 10°. When a large volume of crushed pit is desired, the impact angle can be increased.

4. Conclusions

This study’s aim was to understand the mechanisms contributing to self-rotating water jet bit rock breaking that had not been studied previously. The water jet parameters bit rotation speed, jet pressure, and impact angle were studied. Our conclusions are:

1. The volume of crushed pit by rotary jet erosion increases as the jet pressure increases. The erosion from a rotating bit increases quadratically with pump pressure but the increase is consistent with the results from fixed jet erosion. The depth to which the rock is broken is the dominant factor that defines the volume of broken rock; the diameter or the area broken is of secondary importance.

2. There is an optimum jet bit rotation speed for rock-breaking erosion, and this speed correlates positively with pump pressure. The reason there is an optimum speed is that it is difficult for pressurized water to collect at the bottom of the cutting groove when the jet rotates and erodes the rock, and this lack of water in the groove reduces the water cushioning effect and enhances the breaking ability of the water jet. However, excessive rotation speed causes the jet to deflect and atomize, and the effective erosion range becomes shorter, leading to the weakening of the jet’s rock-breaking ability.

3. An optimum rock-breaking impact angle (10°) exists for the jet to break the rock. The reason for this is that the water cushion effect and reflection of the jet are reduced when the jet impacts at an oblique angle, but the angle must not be too large. If the jet impact angle is increased too much, the large impact angle causes the jet’s impact force to decrease, resulting in a weakening of the jet’s erosion ability. However, when the jet is rotated to erode the rock, the rock eroded in an area radially around the jet increases because of the tensile forces on the rock surface. This leads to an exponential increase in the volume of rock broken by the jet.

4. Concerning self-rotating water jet drill bit design, it can be concluded that: (1) the higher the pump pressure is, the greater the rock-breaking ability of the self-rotating bit will be. However, in this case the water consumption is higher, and the bit should be designed to match the performance of the other equipment in the drilling system (like the high-pressure pump). (2) The self-rotating bit has an optimum rock-breaking rotation speed, and this speed is positively correlated with the jet pressure. Hence, when designing the bit, it is necessary to add a speed-limiting mechanism to the bit to prevent bit rotation speeds that are too high. (3) The optimum rock-breaking angle for the self-rotating bit is about 10°. When a large volume of broken rock is to be obtained, the nozzle angle can be increased appropriately.

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