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Paper

SEM ANALYSIS ON ROCK BREAKING MECHANISM BY SWIRLING-ROUND SC-CO_2 JET

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ABSTRACT

Swirling-round jet, combing both swirling and round jet, could highly improve rock erosion efficiency. Besides, supercritical carbon dioxide (SC-CO_2) fluid is characterized by low rock breaking threshold pressure and high rock breaking rate. This paper proposed a new type of jet, called swirling-round SC-CO_2 jet. Rock breaking mechanism of swirling-round SC-CO_2 jet was studied by means of rock-erosion experiment and scanning electron microscope (SEM) observation. 18 standard cylinder sandstone cores were used for rock erosion experiment, and the diameter, depth and volume of every erosion hole were measured. Then, slices with thickness of 4mm were cut off from these rock samples for SEM observation. Results show that the jet penetration efficiency of swirling-round SC-CO_2 jet is higher than that of round SC-CO_2 jet. SEM observation presents: numerous crystal particles were snapped; inter-crystalline rupture occurred, generating large number of micro fractures; shear failure of crystal particles appeared widely. Therefore, the major rock breaking mechanisms of swirling-round SC-CO_2 jet are tensile and shear failure, while the breaking mechanism of round SC-CO_2 jet is tensile failure. The reasons are divided into two aspects. For one thing, swirling-round SC-CO_2 breaks rock by combining axial impinging, radial tension and circumferential shear. For another, with characteristics of low viscosity, compressibility, strong diffusivity and permeability, numerous micro fractures are caused by SC-CO_2, and the existed fractures are expanded, led to fractures joining together and massive rocks split off.

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1. INTRODUCTION

When the temperature is above 304K and the pressure is above 7.38MPa, CO_2 will change into the supercritical state. It is a kind of non-gaseous, non-liquid, non- solid CO_2 with many unique physical and chemical properties (H. Wang et al.). Supercritical CO_2 (SC-CO_2) is with density similar to that of a liquid and viscosity comparable to a gas(Gupta, Gupta and Langlinais).

A new drilling method by SC-CO_2 jet was proposed in recent years (J. J. Kolle; Shen, Wang and Li; J J Kolle). SC-CO_2 jet has already been approved to reserve low rock threshold pressure and high penetration rate with comparison of water jet and has good application prospects (J. J. Kolle; H. Wang et al.; Du et al.). (R.-h. WANG et al.) experimentally simulated the distributions of pressure and temperature on the bottom of the hole during the SC-CO_2 jet drilling. Results show that the bottom hole temperature and pressure increases with the increase of the nozzle diameter, the jet length has an optimum value, and the increase of the inlet pressure has a positive effect on the drilling rate. (Gupta, Gupta and Langlinais) analyzed the feasibility of SC-CO_2 in deep underbalanced drilling operations. It shows that SC-CO_2 has the necessary density in the tubing to turn the downhole motor and the necessary density and viscosity to maintain underbalanced conditions in the annulus. (Long et al.) numerically investigated the impinging flow field in the bottom hole during drilling with SC-CO_2. Results show that the inlet temperature will increase the axial velocity but will slightly reduce both the mass flow rate and the impact of the carbon dioxide jet; an increase in the inlet pressure not only increase the mass flow rate and the dynamic pressure of the supercritical carbon dioxide jet but also increase both the pressure gradient and the temperature gradient along the impinging wall which are beneficial to the jet-assisted drilling process. (Z. Wang et al.) established a phase state prediction model during carbon dioxide drilling, showing that variations in the flow work affect the temperature field of the SC-CO_2 fluid significantly.

Herein, a new type of jet, called combined swirling and round jet of supercritical carbon dioxide, is proposed, to take advantages of both swirling-round jet and SC-CO_2 jet. As is shown in Figure1, the designed swirling-round SC-CO_2 jet nozzle is composed of nozzle body and impeller. Nozzle body mainly includes mixing chamber, convergent section, and divergent section. The nozzle’s working principle is as follows. After high-pressure SC-CO_2 fluid flowing into swirling-round SC-CO_2 jet nozzle, it is divided into two parts. One part flows through center orifice, forming round jet, while the other part flows through three spiral slots, forming swirling jet. Round jet and swirling jet meet in the mixing chamber, and they are accelerated after convergent section and flowed through orifice together. Finally, swirling-round SC-CO_2 jet is formed in the divergent section.

The current study is set to understand the rock failure mechanisms of swirling-round SC-CO_2 jet. To solve this problem, microscopic observation and analysis on rock erosion section is a necessity. With characteristics of large magnification, high resolution and good match of original appearance, SEM (Scanning Electron Microscopy) is justified to be able to reflect real microstructure of sample surface(Sondergeld et al.). In recent years, SEM is used to analyze rock breaking mechanics of high-pressure water jet(Zeng and Kim; Yi-an; Sun, Kang and Wang). (Z. He, G. Li, et al.) investigated rock failure mechanism by round SC-CO_2 jet impingement. Results showed that Rock erosion by SC-CO_2 jet mainly results from brittle tensile failure, and the mechanism is attributed to diffusivity and phase change of SC-CO_2.

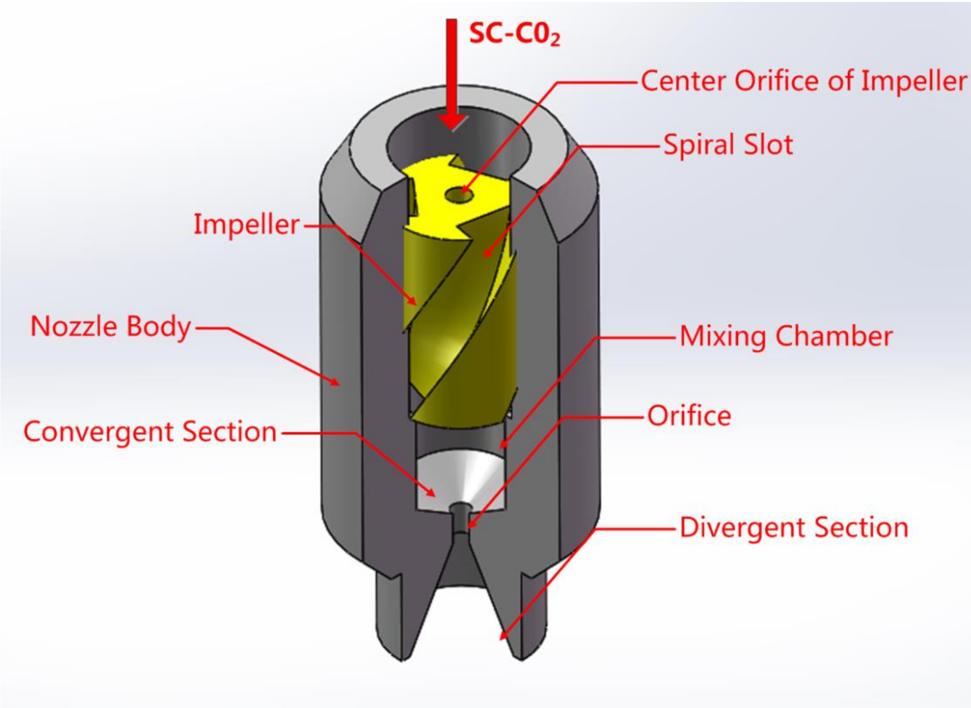

Figure 1. Structure of swirling-round SC-CO_2 jet Nozzle.

2. ROCK EROSION EXPERIMENT

2.1 Experimental Facilities Set-up

Rock-erosion Experiment with swirling-round SC-CO_2 jet was conducted at SC-CO_2 jet-eroding-rock experiment set-up of high-pressure water jet laboratory at China University of Petroleum (Beijing). As shown in Figure 2, the experimental set-up includes liquid CO_2 storage units, a high-pressure plunger pump, a SC-CO_2 storage unit, an ambient pressure body, filters, and supporting pipelines. The swirling-round SC-CO_2 jet nozzle is settled in the ambient pressure body. The maximum jet inlet pressure can be up to 50MPa, the SC-CO_2 temperature can be up to 373K, and the ambient pressure can be up to 40MPa. The experimental system can well simulate the down-hole condition of approximately 3000 meters depth.

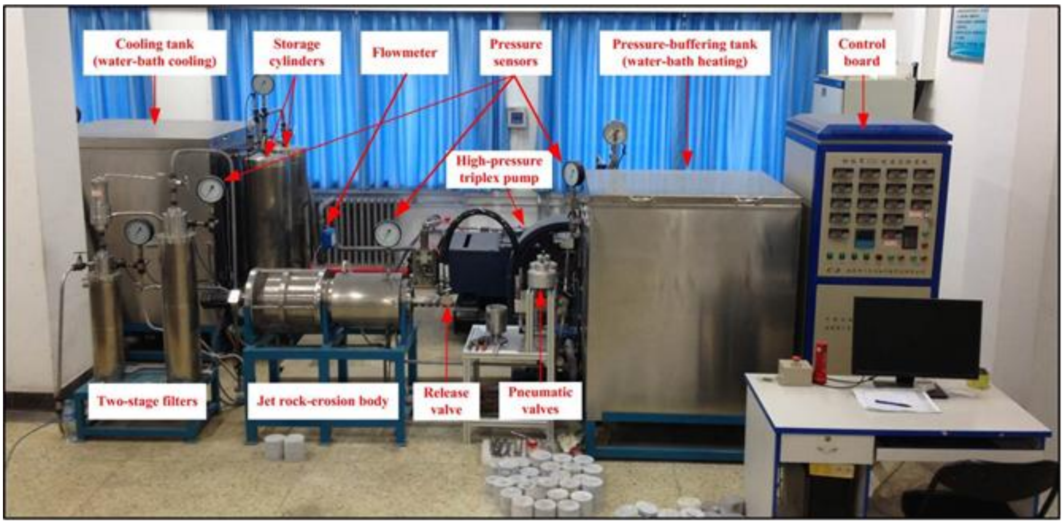

Figure 2. SC-CO_2 jet-eroding-rock experiment set-up

Figure 3 shows the flow diagram of the experiment. Liquid CO_2 is driven into the experimental set-up by the pressure in the bottles and remains liquid under high-pressure and low-temperature conditions provided by a cooling bath in the liquid CO_2 unit, where the water is chilled and circulated to cool the CO_2 below 278 K. Liquid CO_2 is stored in two storage cylinders and pumped into the pressure-buffering tank and the coiled pipes in the SC-CO_2 storage unit. The tank can temporarily store the CO_2 fluid, eliminating the pressure fluctuation caused by the three-plunger pump. The hot water bath in the SC-CO_2 unit heats the CO_2 fluid in the tank and the coiled pipes, and the pump rate is adjusted to pressurize the CO_2 fluid. Then, the SC-CO_2 is obtained, and the pressure and temperature can be continuously regulated. In the ambient pressure body, the SC-CO_2 jet is issued on the rock samples to form perforation holes. Impurities including cuttings and water vapor are carried out of the body and removed in the double filters to produce CO_2 of high purity that can be safely circulated.

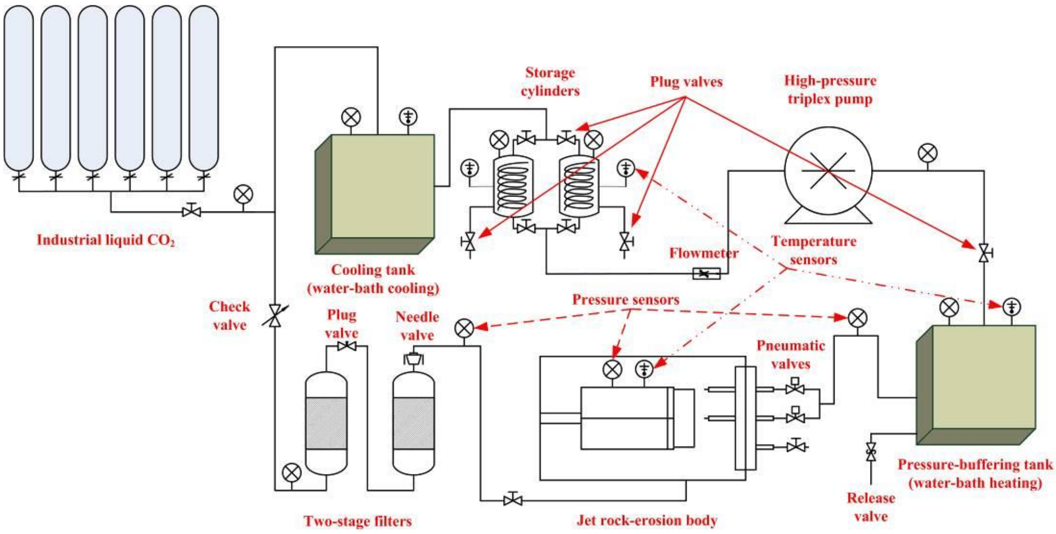

Figure 3. Flow diagram of the SC-CO_2 jet rock-erosion experiments

2.2 Rock Samples

Rock samples for experiment was sandstone collected from Junggar Basin in Xinjiang Uygur Autonomous Region of China, and rock mechanics parameters are listed in Table 1. Rock sample was cutting into standard cylinder cores with diameter of 25mm and length of 50mm. Every cylinder core was knocked off into two pieces by geological hammer. The knock of geological hammer rather than cutting machine, is used to make the rock fracture naturally, ensuring property of two pieces as similar as possible.

Table 1. Rock mechanics parameters of the samples

Type	Density, g/cm^3	Elastic modulus, GPa	Poisson's ratio	Cohesive strength, MPa	Friction angle, °	Comperssive strength, MPa
Sandstone	2.45	5.525	0.256	23.121	39	37.85

2.3 Jet Nozzles

As shown in Figure 4a, swirling-round SC-CO_2 jet nozzle was designed, with construction parameters of each part listed in Figure 5 and their values listed in Table 2. Figure4 b shows round SC-CO_2 jet nozzle, with inclined angle of convergent section 30.5°, and nozzle diameter 1mm. Both swirling-round SC-CO_2 jet nozzle and round SC-CO_2 jet nozzle are made of tungsten carbide, which could effectively resist CO_2 chemical erosion and cavitation damage owing to high-speed flow.

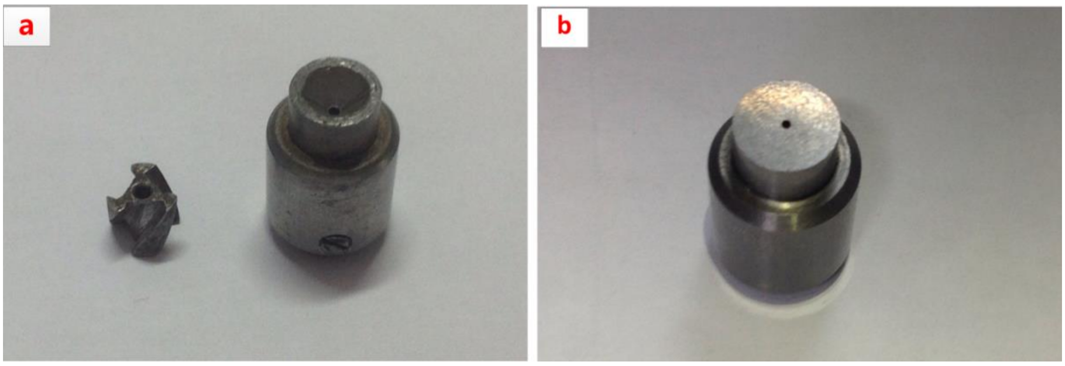

Figure 4. Jet nozzles for experiments.(Left: swirling-round SC-CO_2 jet nozzle; right： round SC-CO_2 jet nozzle)

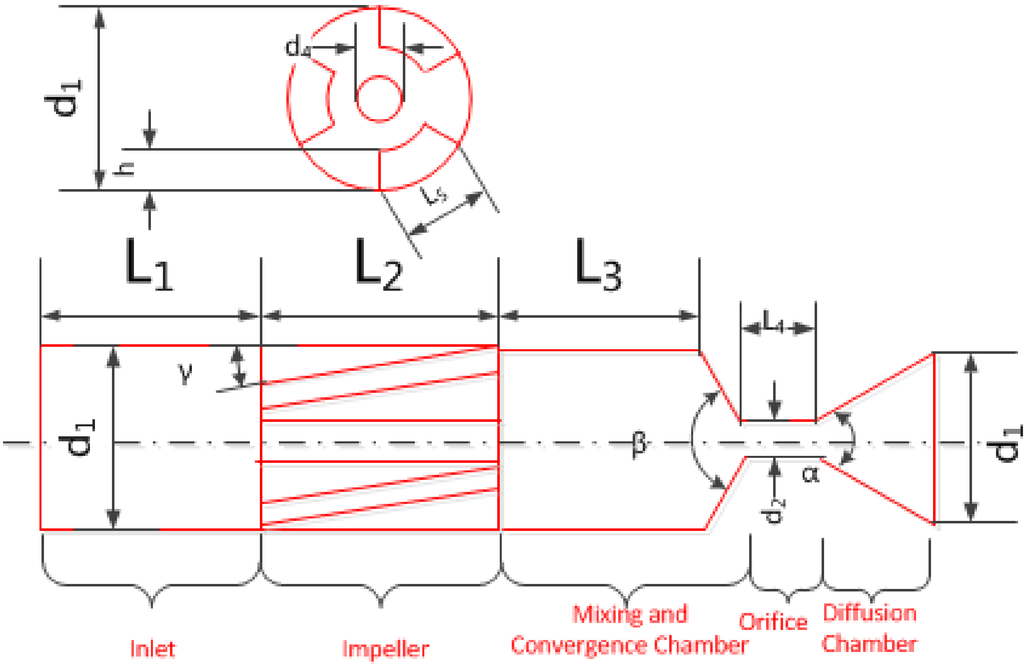

Figure 5. Plane sketch of swirling-round SC-CO_2 jet nozzle

Table 2. Structural Parameters of nozzle

Parameter name	Value	Parameter name	value
d_1	6mm	h	1.5mm
L_1	6mm	L_3	5mm
d_4	1.5mm	β	120°
γ	30°	d_2	1mm
L_2	6mm	L_4	2mm
L_5	4mm	α	60°

2.4 Experimental Scheme

18 standard cylinder cores were selected and numbered from 1 to 18 respectively. Every 3 cores were divided into a group and there are 6 groups totally. Then, every core was knocked off into two pieces, signed as A and B. Piece A was for swirling-round SC-CO_2 jet eroding-rock experiment and Piece B was for round SC-CO_2 jet eroding-rock experiment. The experimental scheme is listed in Table 3. Swirling-round SC-CO_2 jet and round SC-CO_2 jet eroding-rock experiments were conducted separately as experimental scheme. Experimental period is set as Δt=3min.

Table 3. Experimental Scheme

Group	Core Number	Confining Pressure (MPa)	Temperature (℃)	Standoff Distance (mm)	Jetting Pressure (MPa)
1	1/2/3	4	70	3	30
2	4/5/6	8	70	3	30
3	7/8/9	8	50	3	30
4	10/11/12	8	90	3	30
5	13/14/15	8	70	3	20
6	16/17/18	8	70	3	40

3 RESULTS AND DISCUSSION

3.1 Experimental Results

As shown in Figure 7, compared with erosion hole by round SC-CO_2 jet, the diameter of erosion hole by swirling-round SC-CO_2 are relatively large and the hole deep are appropriate.

Diameter, depth and volume of erosion-hole are three main parameters that reflect rock erosion effect of nozzle. All parameters of number 1~18 cores are measured respectively. Diameter, depth of erosion-hole is measured by vernier caliper and precision is improved by averaging the testing values of repeated measurements. Volume of erosion-hole was measured by the sand-filling method. This method can be divided into three steps: (1) The quality of core is measured; (2) fine sand is filled in the erosion hole; (3) the quality of core after filling sand is measured. All those trials were performed at least three times for each set of process parameters and rock specimen to verify the repeatability of the results.

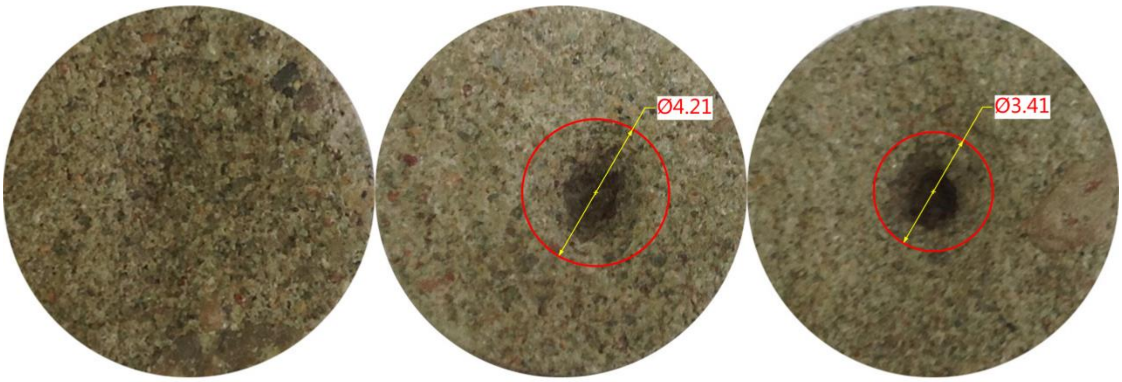

Figure 7. Images of erosion hole of No.1 core

Finally, the average diameter, depth and volume of every group were calculated (Figure 8a, 8b and 8c). As shown in Figure 8a, for every group, the depth of erosion hole by swirling-round SC-CO_2 jet is less than that of round SC-CO_2 jet (average of 0.725 times); as shown in Figure 8b, for every group, the average depth of erosion hole by swirling-round SC-CO_2 jet is larger than that of round SC-CO_2 jet (average of 1.371times); as shown in Figure 8c, for every group, the average volume of erosion hole by swirling-round SC-CO_2 jet is larger than that of round SC-CO_2 jet (average of 1.349times). The average diameter, depth and volume of erosion hole by both swirling-round SC-CO_2 jet and round SC-CO_2 jet were calculated (Figure 8d), showing that the average erosion depth of swirling-round SC-CO_2 is less than that of round SC-CO_2 jet (0.725 times); the average erosion diameter of swirling-round SC-CO_2 jet is more than that of round SC-CO_2 jet (1.371 times); the average erosion volume of swirling-round SC-$CO_2$is more than that of round SC-CO_2 jet (1.349 times). So, rock breaking efficiency of swirling-round SC-CO_2 jet is larger than that of round SC-CO_2 jet. Similar with round SC-CO_2 jet, axial velocity of swirling-round SC-CO_2 jet is very high, so the depth of its erosion hole is large. Besides, the divergent angle of swirling-round SC-CO_2 jet is large and rotational energy is converging in circle ring domain at a certain distance from the impinging surface, eroding hole with large area. In conclusion, the jet penetration efficiency of swirling-round SC-CO_2 is higher than that of round SC-CO_2 jet.

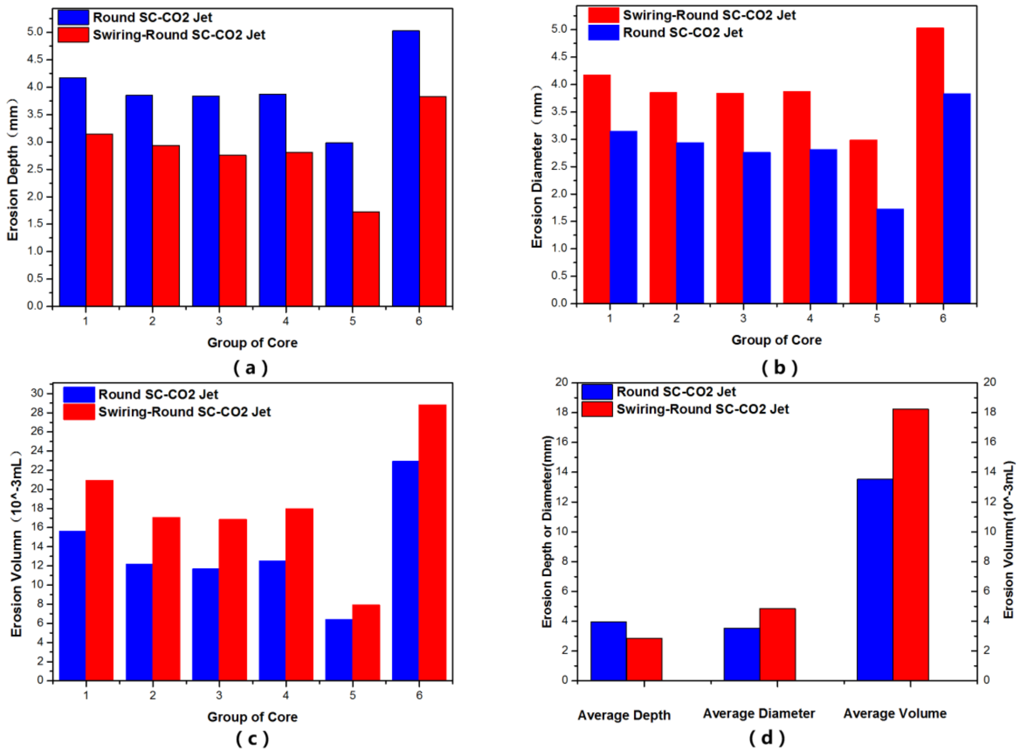

Figure 8. Comparison of rock erosion effect between swirling-round SC-CO_2 jet and round SC-CO_2 jet

3.2 SEM Observations on Sandstone Erosion Section

3.2.1 Swirling-Round SC-CO2 jet erosion

Figure 9 shows specimen SEM images of areas that are not eroded by swirling-round SC-CO_2 jet. It is observed that surface is smooth and compact overall, mineral particles are bonding strongly with each other, surface is covered by cement, and there are rare pores and fractures.

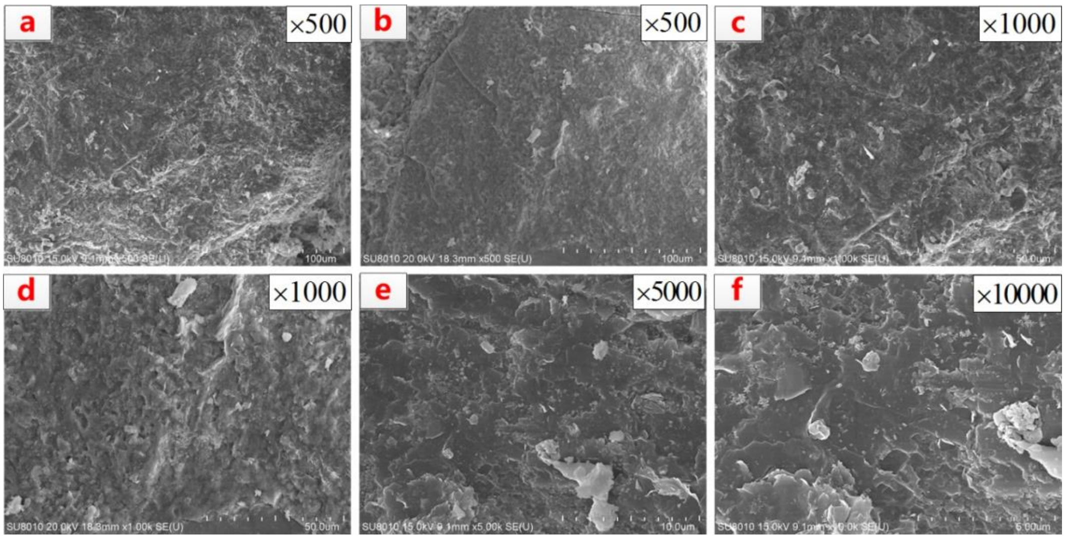

Figure 9. Specimen SEM images of areas that are not eroded by swirling-round $SC\text{-}CO_2$ jet

Comparatively, specimen SEM images of areas on rock samples eroded by swirling-round $SC\text{-}CO_2$ jet is shown in Figure 10. There are mainly two kinds of rock failure mechanisms that is tensile failure and shear failure(Russo; Martins et al.; Nemati; Junxiang).

Tensile Failure. Under the effect of tensile stress, on the one hand, crystal particles of sandstone are snapped, i.e. cleavage fracture. Cleavage fracture of crystal particles is ladder-like (Figure 10a and Figure 10b). With internal defect, crystal particle crack along many parallel or ladder-like fracture surfaces. Sectional shape is complex and micro fractures exist. Cleavage fracture of crystal particles is river-like and crystal clastics distribute around cleavage surface, which is the characteristic of tensile failure (Figure 10c). On the other hand, inter-crystalline rupture occurs under the effect of tensile stress. Large-scale fractures exist widely in the erosion hole (Figure 10d and Figure 10e). Micro-fissures exist and are net-distributed (Figure 10f).

Shear Failure. Shear failure exists widely near the edge of erosion hole. Crystal particles of sandstone are cut off along the direction perpendicular to the bedding plane and crystal clastics distribute at the bottom (Figure 10g). Shear stress acts on crystal particle along the direction having a certain angle with the bedding plane and the fracture is sharp with several parallel strips for internal defect of crystal particle (Figure 10h). Under the effect of shear stress, owing to several shearing surface interfering with each other, fracture of crystal particles was irregular wave-like and crystal clastics distribute at the bottom (Figure 10i).

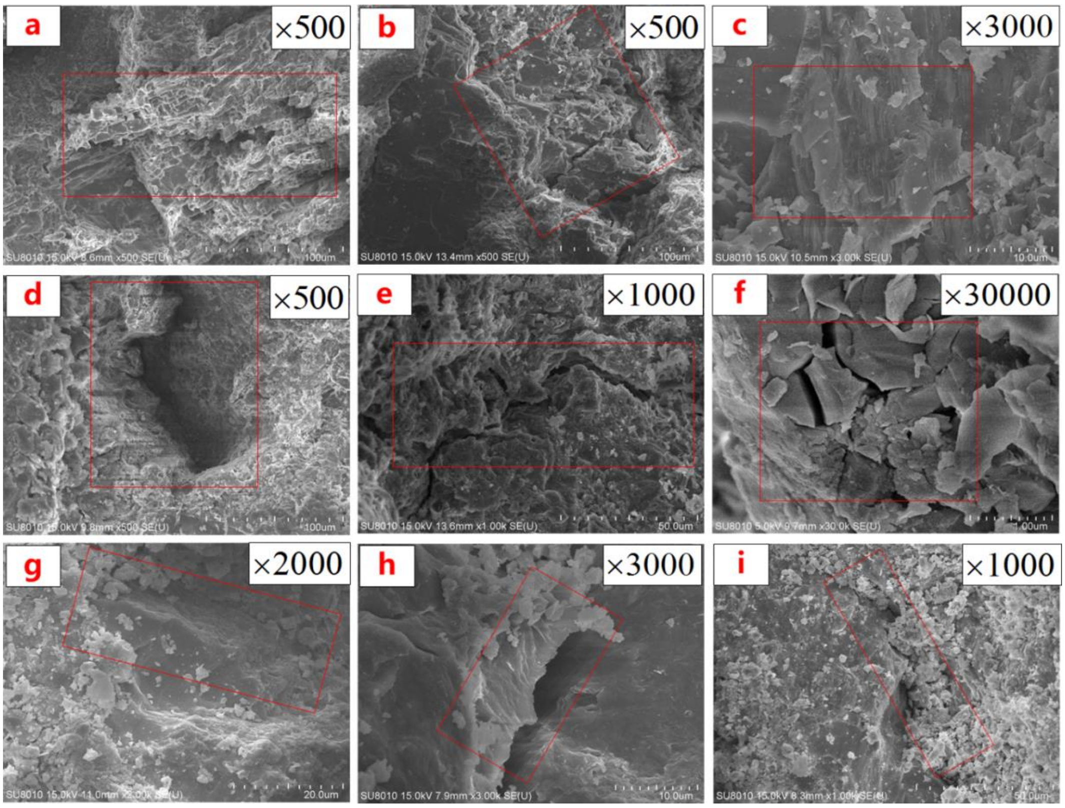

Figure 10. Typical SEM images of erosion hole by swirling-round SC-CO_2 jet

3.3 Analysis of rock breaking mechanisms

The tensile and shear failure are observed to be the major rock failure mechanisms of swirling-round SC-CO_2 jet, and reasons are divided into two aspects:

1 Dual impinging of round jet and swirling jet. Swirling-round SC-CO_2 jet consists of round jet and swirling jet. The energy of round jet is concentrated around central axis. Under axial impinging by round jet, rock is compressed and the tensile stress is the maximum at the edge of impinging area. When tensile stress exceeds tensile strength, crack is formed and the compressed rock of impinging area is stretched transversely. In microcosmic level, mineral grain is fractured or split off, while in macro level, tensile failure occurs. For swirling jet, fluid flow has three dimensional velocities that are axial velocity, radial velocity and tangential velocity. Swirling jet could exert radial tension, circumferential shear force as well as axial force on rock. Under the common effect of tensile stress and shear stress, tensile failure and shear failure tend to occur to the mineral grain, or the mineral grain is completely split off. Furthermore, with relatively high radial velocity, CSRJ-SC-CO_2 exerts radial stretch on rock. Fracture occurs and extends radially. In microcosmic level, mineral grain is fractured or split off, and in macro level, radial fractures joins together and massive rocks are split off. Therefore, larger breaking area is achieved.

2 Strong penetration and diffusion of SC-CO_2. SEM observation of erosion hole shows that there exist numerous micro-fractures. Compared with conventional fluid, the viscosity of SC-CO_2 is much lower, the permeability as well as diffusivity is much stronger. Therefore, SC-CO_2 could permeate and diffuse into almost any pores and micro-fractures, transmitting hydrostatic pressure and exerting fluctuating pressure by phase change mechanism. Numerous micro-fractures occurred and original fractures expand in a further step under the effect of tensile stress. Finally, fractures join together and massive rocks are split off.

Comparison of rock breaking mechanisms of swirling-round SC-CO_2 jet with that of round SC-CO_2 jet. The impinging of round SC-CO_2 jet is mainly axial, and the majority of jet energy is dissipated by compression deformation of rock. On the one hand, tensile failure occurs to injection area. On the other hand, if impinging force is large enough, fault movement occurs by shear stress. But shear failure is not apparent. The density of SC-CO_2 is lower than water, and the viscosity of SC-CO_2 is much lower, the permeability as well as diffusivity is much stronger. Therefore, impinging force is dissipated, and shear failure is not oblivious, only occur in the center of erosion hole.

For round SC-CO_2 jet, after impinging the rock, particles return and interfere with subsequent particles, and jet energy is loss. For swirling-round SC-CO_2 jet, particle return with swirling velocity, not interfere with subsequent particle, and jet energy is utilized fully on rock erosion.

4. CONCLUSIONS

This paper proposes a new type of SC-CO_2 jet, swirling-round SC-CO_2 jet. By means of rock-erosion experiment and scanning electron microscope (SEM) observation, rock breaking mechanism of swirling-round SC-CO_2 jet was studied. We got the following conclusions:

1 Compared with erosion hole by round SC-CO_2 jet, the diameter of erosion hole by swirling-round SC-CO_2 jet is relatively large and the hole deep is appropriate. Jet penetration efficiency of swirling-round SC-CO_2 jet is higher than that of round SC-CO_2 jet.

2 SEM observation on erosion sections shows that rock breaking mechanisms of swirling-round SC-CO_2 jet are tensile and shear failure, while the breaking mechanism of round SC-CO_2 jet is tensile failure.、

3 On the one hand, swirling-round SC-CO_2 jet breaks rock by combining axial impinging, radical tension and circumferential shear. On the other hand, with characteristics of low viscosity, compressibility, strong diffusivity and permeability, numerous micro fractures were caused by SC-CO_2 and existing fractures were expanded, which led to rock broken finally.

5. ACKNOWLEDGMENT

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