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Research Paper

Experimental investigation on the rock erosion characteristics of a self-excited oscillation pulsed supercritical CO_2 jet

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HIGHLIGHTS

- The rock erosion characteristics of SOPSJ were experimentally studied.
- SOPSJ erodes larger, shallower, and more irregular pit than continuous jet.
- SOPSJ can enhance erosion intensity at the initial several standoff distances.
- The maximum enhancement reduces with the growing inlet pressure.
- SOPSJ has a higher erosion rate regardless of inlet pressure.

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ABSTRACT

Supercritical CO_2 (SC-CO_2) jet is now widely considered to have great potential for application in oil-gas exploration and development. In order to further improve the performance of SC-CO_2 jet, the rock erosion characteristics of a self-excited oscillation pulsed SC-CO_2 jet (SOPSJ) were preliminarily analyzed and then experimentally studied as a pioneering effort. A Helmholtz oscillation nozzle was employed to generate a SOPSJ. Numerous rock erosion tests were conducted. Rock erosion area and depth, erosion intensity evaluated by mass loss, and erosion rate were applied to characterize the erosion performance of a SOPSJ. Results show that unlike the continuous SC-CO_2 jets, the erosion areas caused by the SOPSJs are almost unchanged at first and then decrease slowly with the growing standoff distance, while the erosion depths increase first and then decrease. The erosion pits caused by the SOPSJs are relatively large, shallow, and irregular, especially at the initial several standoff distances. Moreover, the SOPSJs can cause larger mass losses than the continuous jets, but this only happens at the initial several standoff distances. The SOPSJs generated with the use of the optimum chamber lengths can maximally enhance the mass loss by about 32.3%, 27.7%, 21.5%, and 17.3% at inlet pressures of 25, 30, 35, and 40 MPa, respectively. In addition, for all the jets, the erosion rates always remain the tendency to decrease with the increase of erosion time. Whereas, the specimens can be eroded by the SOPSJs at a higher rate than the continuous jets, which is independent of the inlet pressure.

1. Introduction

Water-based technology have been fully utilized in the field of oil and gas exploration and development during the last few decades, such as various kinds of water-based drilling fluids, widely used hydraulic fracturing, water jet assisted drilling, water jet perforation, and so on [1–4]. However, the inevitable problems including hold-down effect on cuttings, water-lock effect, formation damage, pollution of water resources, etc. are still the shackles of these water-based technologies [5–7]. Besides, unconventional hydrocarbon resource which has low reservoir permeability is becoming increasingly important [8]. Therefore, there is an urgent need for new fluids that can overcome the shortcomings of water-based drilling fluids to some extent.

Supercritical CO_2 (SC-CO_2) that has been well applied in a wide range of industries [9–12], is now widely considered to be a good working fluid in drilling and completion engineering [13–16], especially suitable for unconventional tight reservoirs [17–19]. This is due to the unique natural properties of SC-CO_2 fluid. Its low viscosity, high diffusivity, and high density can reduce the friction loss and increase the rate of penetration. Its high solubility of organic deposition and

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Nomenclature

A_0	cross-sectional area of Helmholtz resonator inlet	m_1	specimen mass before erosion
A_c	area of erosion area in CAD software	m_2	specimen mass after erosion
A_r	real area of erosion area	Δm	mass loss of specimen
c	local sound speed	N	model number
c_+	downstream propagation speed of disturbance waves	P_a	ambient pressure
c_-	upstream propagation speed of disturbance waves	P_c	pressure at the central area
c_j	shock propagation velocity in jet slug	P_i	inlet pressure
c_r	shock propagation velocity in rock	P_s	stagnation pressure
D	diameter of the oscillation chamber, 24 mm	S	dimensionless standoff distance
d_0	inlet diameter of the upstream nozzle, 13 mm	S_r	Strouhal number
d_1	outlet diameter of the upstream nozzle, 2 mm	T	fluid temperature
d_2	outlet diameter of the downstream nozzle, 2.4 mm	t_h	duration of the high pressure
d_j	diameter of jet slug	t_i	duration of the initial stage
f_n	natural frequency of Helmholtz oscillation nozzle	t_l	duration of the lateral jetting stage
f_s	jet structuring frequency	U	jet velocity
f_w	frequency of disturbance waves	V	volume of Helmholtz resonator
L	length of the oscillation chamber	v	impact velocity
L_c	length in CAD software	ρ_j	density of jet slug
L_r	real length on ruler	ρ_r	density of rock
l_0	length of Helmholtz resonator inlet	θ_1	convergent angle of the upstream nozzle, 13.5°
		θ_2	impinging angle, 120°
		δ	frequency correction factor of 0.6

high absorptive capability on rock substance can improve reservoir permeability and enhance recovery [5,20]. In addition, the utilization of CO_2 will make a contribution to reducing greenhouse gas emission and water resource pollution, while underground storage of CO_2 can be achieved to a certain extent [21,22]. With the increasing number of investigations on the applications of SC-CO_2 in the field of oil and gas development, it has been proven that SC-CO_2 can be feasibly and superiorly employed in a variety of ways, to name but a few, SC-CO_2 flooding, SC-CO_2 fracturing, SC-CO_2 sand removal, and SC-CO_2 jet assisted drilling [14,18,19]. Among them, SC-CO_2 jet, which is much superior to a conventional water jet in many aspects, has been the subject of numerous studies, mainly in the areas of the rock erosion mechanism, jet flow field dynamics, and performance enhancements.

The first research on the rock erosion characteristics of a SC-CO_2 jet was conducted by Koller [23] in the late 1990s, stimulated by the demand of improving the drilling efficiency and reducing the working pressure in coiled-tubing drilling. The experimental results showed that a SC-CO_2 jet has a stronger rock erosion ability than a water jet. In more specific terms, the threshold pressures of SC-CO_2 jets are 2/3 and less than half those of water jets in the granite and the shale, respectively. The specific energies for eroding granite and Mancos Shale using SC-CO_2 jets are less than 50% and only 3% those of water jets, respectively. The rate of penetration in Mancos Shale applying a SC-CO_2 jet was 3.3 times that observed while drilling with a water jet. Years later, by the use of a well-designed experimental facility, the effects of the major factors on the rock erosion performance of a high-pressure SC-CO_2 jet was investigated by Du et al. [24]. They found that the erosion ability of a SC-CO_2 jet increases first and then decreases with the growth of nozzle diameter or standoff distance. Under the same conditions, a SC-CO_2 jet always has a better rock erosion performance than a liquid CO_2 jet. Similarly, a large amount of rock erosion experiments with SC-CO_2 jet were conducted in the lab by Wang et al. [25] to disclose the rock erosion law and establish a better theoretical basis for the field application. They concluded that with the increasing ambient pressure, the rock erosion efficiency of SC-CO_2 jet reduces under constant inlet pressure and can reach the maximum around the critical pressure of CO_2 under constant pressure difference. Simultaneously, by methods of CT, SEM/EDX, XRD and XRF, Huang et al. [26] carefully studied the microscopic changes between the original shale sample and the eroded sample by a SC-CO_2 jet. The results illustrated that the surface of shale sample shot by a SC-CO_2 jet shows a grid-like breakage, while the sample was broken into layers of large volume overall. The erosion of shale mineral induced by the SC-CO_2 jet impingement can change the microstructure of shale and then reduce its mechanical strength. In addition, to further clarify the rock failure mechanism, He et al. [27] conducted rock erosion experiments using SC-CO_2 jets on different rocks and made subsequent in-depth SEM observation and analyses. They demonstrated that a SC-CO_2 jet erodes rock substances mainly in the brittle tensile failure mechanism and facilitates the rock to be further broken, accompanied with the shear failure mechanism in particular locations of the erosion hole.

On the other side, many researchers are focusing on the flow field dynamics of SC-CO_2 jets to reveal the impinging characteristics of the jet and further optimize the operating parameters. Specifically, Lv et al. [28] carried out a numerical study of SC-CO_2 flowing through a conical nozzle, and found that under the same conditions the decay of dimensionless central axial velocity and dynamic pressure of a water jet is quicker than that of a SC-CO_2 jet, while the core length of a SC-CO_2 jet is longer than that of a water jet. Wang et al. [29] experimentally and numerically investigated the distributions of pressure and temperature on the bottom of hole during the SC-CO_2 jet drilling, and reported that the bottom hole temperature and pressure increase with the rising nozzle diameter, while the growth of standoff distance reduces the temperature, and increases first and then reduces the pressure. A following numerical simulation [30] showed that a SC-CO_2 jet has higher impact pressure and velocity than those of a water jet under the same conditions, and the increase of fluid temperature hardly affects the impact pressure of a SC-CO_2 jet but can increase its maximum velocity. Then, Tian et al. [5] numerically and experimentally demonstrated that a SC-CO_2 jet has satisfactory jet impingement and perforation performance, although both the ambient pressure and standoff distance increase with the bottom going deeper. Simultaneously, by using a model including the real gas effects of CO_2, Long et al. [31] numerically investigated the impinging flow filed of a SC-CO_2 jet in the bottom hole. They concluded that an increase in inlet pressure can increase both the pressure gradient and the temperature gradient along the impinging wall, which is beneficial to the jet-assisted drilling process. Also, Zhou et al. [32] performed a numerical study to further investigate the flow characteristics of a SC-CO_2 jet and found that liquid and gas CO_2 appear in the jet flow field and the crossflow velocity is high enough to effectively remove the bottom cuttings.

Additionally, for the purpose of further enhancing the erosion