STUDY ON FRACTURE PROPAGATION OF HYDRAULIC AND SUPERCRITICAL CO_2 FRACTURING IN DIFFERENT ROCK

by

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In this study, the performance of water-based fracturing fluids and supercritical CO_2 in three types of representative reservoirs (sandstone, conglomerate, and shale) was investigated. The results showed that there are differences in fracture initiation pressures in different rocks, but the fracture initiation pressure of supercritical CO_2 is lower than that of water regardless of the rock type. In sandstone reservoirs, supercritical CO_2 induced more complex fractures than water, resulting in branching fractures. In conglomerate reservoirs, hydraulic fractures pass through the conglomerate and are flatter, whereas supercritical CO_2 fractures pass through or around the conglomerate, and thus the fractures are more tortuous. Gravel stopped the fracture extension in both conditions. In shale reservoirs, supercritical CO_2 can communicate natural fractures more effectively than water, thereby increasing the effective transformation volume. The study provides theoretical guidance for reservoir adaptation of supercritical CO_2 fracturing.

Key words: *hydraulic fracturing, supercritical CO_2, initiation pressure, fracture pattern*

Introduction

Unconventional oil and gas reservoirs have dense rocks with extremely low porosity and permeability, requiring hydraulic fracturing to construct oil and gas seepage pathways for commercial development. Water-based fracturing fluids are widely used to crush the reservoir and carry the proppant to form highly conductive fractures. However, there are some shortcomings of water-based fracturing fluids in the application process. Water swells clay minerals and softens the fracture surface, which embeds the proppant and reduces the hydraulic conductivity [1-3]. The water required for hydraulic fracturing wells is measured in tens of thousands of cubic meters, which consumes a large amount of water resources, while the return fluid will pollute the environment.

Supercritical CO_2 attracts attention with its unique physical and chemical properties. It has an extremely low viscosity and a density close to that of water. Supercritical CO_2 replacing water as a fracturing fluid will avoid clay expansion, reduce fracture initiation pressure,

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and create a complex fracture network in the reservoir [4-6]. Injected CO_2 increases formation pressure and benefits production. In addition, CO_2 can displace adsorbed methane and improve recovery while allowing for carbon sequestration [7]. Numerous experimental and numerical simulation studies have been carried out on CO_2 flow in wells and fractures, fracture initiation and propagation, and proppant transportation [8-12]. Yang *et al.* [13] used CT to reconstruct the fracture in three dimensions and clarified that supercritical CO_2 produces more complex fractures under smaller differential stress. Zhou *et al.* [14] investigated the temperature effect caused by injected CO_2, and the results showed that the reduction of effective stress caused by thermal tensile stress and pore pressure is the main reason for the reduction of fracture pressure and the formation of fracture network in supercritical CO_2 fracturing and that the increase of temperature difference between reservoir and injected CO_2 is favorable for fracturing. Wang *et al.* [15] established a wellbore flow model for supercritical CO_2 fracturing return flow and found that reducing the discharge volume and increasing the tubing size can effectively keep the wellbore temperature high and reduce the risk of CO_2 hydrate formation. Zheng *et al.* [16] investigated the effect of pump injection schedule on proppant transportation in supercritical CO_2 fracturing by CFD-DEM method and found that injecting high density proppant first followed by low density proppant and lowering the initial temperature can improve the performance of supercritical CO_2 carrying proppant.

Nevertheless, the formation adaptability of CO_2 fracturing technology is still unclear. To address this issue, water, and CO_2 fracturing experiments were carried out on three typical reservoir rocks (sandstone, limestone, and conglomerate) in this paper. Characteristics of injection pressure variations were analyzed. The differences between the fracture morphology of water and CO_2 fracturing were compared. The results of the study are a guide to understanding the effectiveness of CO_2 fracturing in reservoirs with different lithologies.

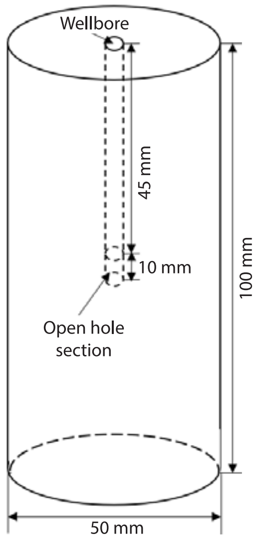

Figure 1. Schematic diagram of open hole completion

Materials

To compare the differences between water and CO_2 fracturing in reservoirs with different lithologies, three rocks were selected for this paper. Sandstone and limestone were drilled from natural out crops extracted from the Ordos Basin. The conglomerate outcrops collapsed after weathering, making it difficult to drill the sample. Therefore, artificial conglomerates cemented with concrete and gravel were taken. A hole with a depth of 55 mm was drilled in the center of a Ø50 mm × 100 mm cylindrical sample as a wellbore to inject the fracturing fluid. At the same time, the bottom of the borehole is reserved for a 10 mm open hole section, as shown in fig. 1. The experimental scheme is shown in tab. 1.

Apparatus

The fracturing device used is shown in fig. 2, which can carry out fracturing experiments with a variety of fluids, including water, carbon dioxide, and nitrogen.

The supercritical CO_2 injection device was used by a pneumatic booster pump to pressurize the low pressure CO_2 and store it in a high pressure tank. The CO_2 is heated by a water bath to bring it to a supercritical state. A maximum pressure of 100 MPa is available. The water injection unit provides water injection at a constant rate or pressure by ISCO pumps. The core holder of the

Table 1. Experimental design

Number	Rock type	Fluid type	Temperature [°C]	$\sigma_v \times \sigma_r$ [MPa]	Injection rate [mL per minute]
#1	Sandstone	Water	40	5 × 15	40
#2		CO_2			
#3	Limestone	Water			
#4		CO_2			
#5	Conglomerate	Water			
#6		CO_2			

confining pressure loading device can contain samples of Ø50 mm × 100 mm, and axial and radial stresses of up to 80 MPa could be applied through the hydraulic pump.

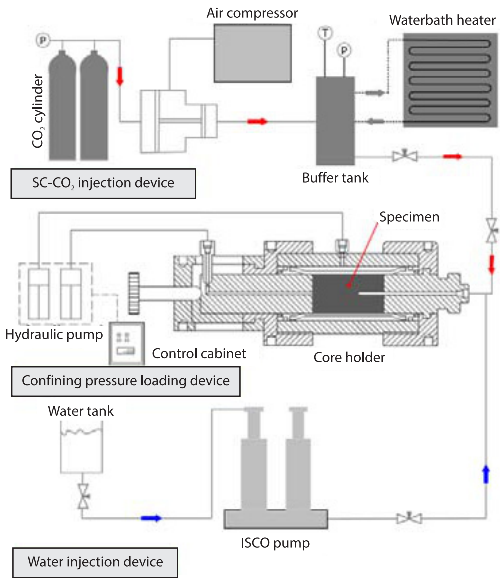

Figure 2. Schematic diagram of the fracturing experimental set-up [10]

Fracturing evolution characteristics

Figure 3 demonstrates the pressure-time profiles of water- and CO_2-induced fractures in different rocks. The pressure reached the peak value and then decreased rapidly. The trends of the curves indicated that all three rocks showed strong brittleness during the fluid-driven damage. The pressure profiles have similar characteristics regardless of the rock type. The pressure profile of CO_2 has a smaller slope at the beginning of injection compared to water. The pressure curves have similar characteristics regardless of the rock. The pressure curve of CO_2 has a smaller slope at the early stage of injection compared to water. This is because CO_2 is more strongly compressible than water,

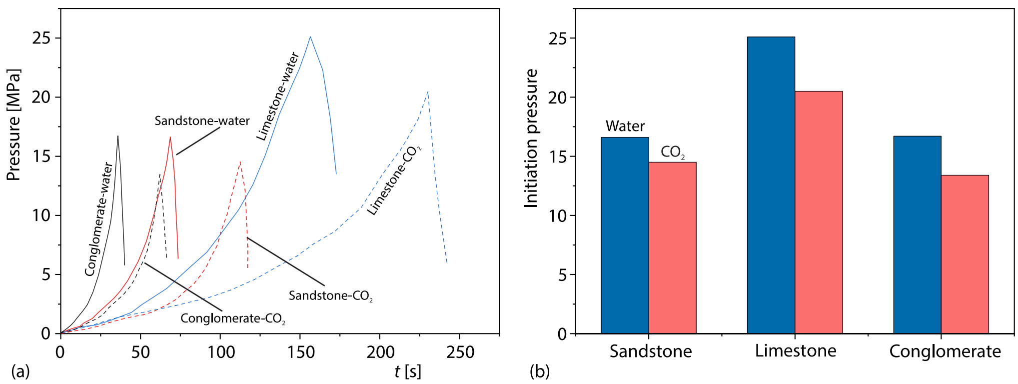

Figure 3. Injection pressure profile (a) and initiation pressure (b)

and the pressurization process needs to compress the CO_2 first, so the initial pressurization rate is slower. As a result, CO_2-induced rocks take longer to fracture than water. This also allowed sufficient time for CO_2 to spread through the pores of the rock, increasing the pore pressure and reducing the effective stress.

The CO_2 fracturing has a lower initiation pressure than water in all three rocks. During the fracturing process, the surface tension of the fluid is directly related to whether it can enter the crack tip [17, 18]. In the process of fracture propagation, supercritical CO_2, which has a lower viscosity and almost zero surface tension, has less flow resistance inside the fracture and could reach the fracture tip. As shown in fig. 4, supercritical CO_2 has a smaller fluid lag zone at the crack tip, which reduces the net pressure required for crack propagation [19].

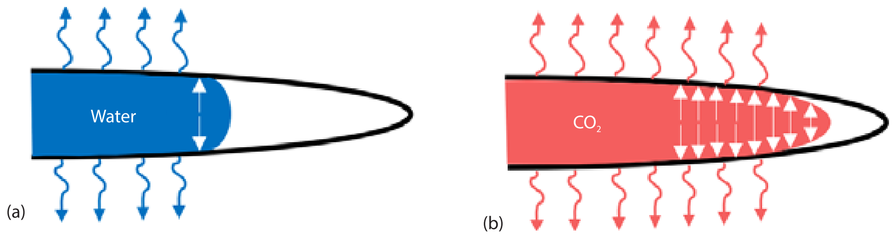

Figure 4. Schematic diagram of crack tips for different fluids; (a) water and (b) CO_2

Since the rock samples in the experiment were small, crack initiation and extension occurred almost at the same time, and the peak of the pressure curve was assumed to be the initiation pressure, as shown in fig. 3(b). The fracture initiation pressures for CO_2 fracturing in sandstone, chert, and conglomerate were decreased by 2.6 MPa, 4.6 MPa, and 3.1 MPa, respectively. In limestone with high initiation pressure, the effect of CO_2 fracturing in reducing initiation pressure is more significant.

Fracture morphology

The fracture morphology of water and CO_2 fracturing in different rocks is shown in fig. 5. It can be visualized that hydraulic fracturing produced only one main fracture and CO_2 fracturing induced a more complex fracture.

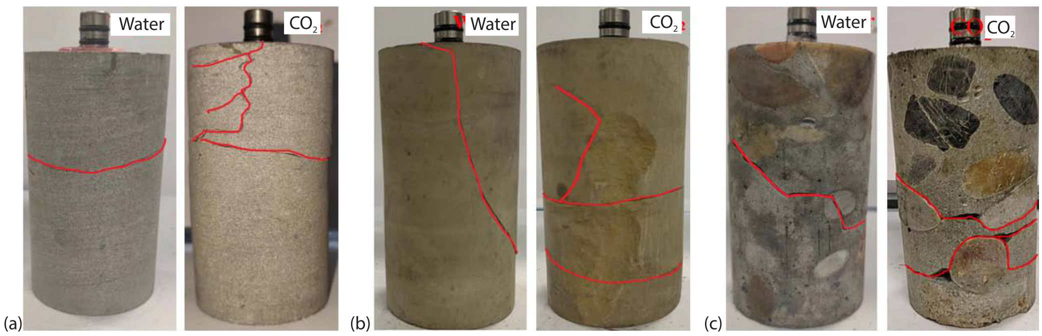

Figure 5. Fracture morphology of water and CO_2 fracturing in different rocks; (a) sandstone, (b) limestone, and (c) conglomerate

In sandstones, hydraulic fracturing produces a relatively simple fracture with only one main fracture perpendicular to the wellbore. In contrast, CO_2-induced fractures have complex geometries. The fractures produced branches and secondary fractures after fracture initiation at the bottom of the wellbore. Due to the presence of laminations in the sandstone, the fracture morphology is also influenced by the laminations. In limestones, hydraulic fracturing produced a main fracture that intersected the wellbore diagonally. The fracture was deflected along the axial stress after initiating from the bottom of the borehole. In addition the near wellbore, CO_2 fracturing produced a fracture in the lower portion of the rock sample and a partial collapse on the side of the sample.

The presence of conglomerates gives conglomerates a stronger heterogeneity than sandstones and limestones. The strength of the gravel, its content, its size, and cementation strength all affect the final patterns of the cracks [20, 21]. Four modes of fracture-gravel interaction exist: penetration, deflection, attraction, and termination [22]. Penetration and deflection occurred in hydraulic fracturing, and deflection and attraction occurred in CO_2 fracturing in this study. Fractures in conglomerates were significantly more tortuous than in sandstones and limestones. Most of the CO_2-induced fractures in conglomerates are deflections rather than penetrations. It is explained by the fact that CO_2 has a much lower viscosity and can enter the interface between the conglomerate and the matrix. It is easier to open the interface than to crush the matrix and gravel. Moreover, matrix collapse can be seen near the gravels in the CO_2-fractured rock samples. These disintegrated particles can act as proppants to form self-supporting fractures.

The lengths of water- and CO_2-induced fractures in three rocks were counted, as shown in fig. 6. The CO_2 fracturing forms multiple fractures, so the fracture lengths are significantly longer than those of hydraulic fracturing. The lengths of CO_2-induced fractures in sandstone, limestone, and conglomerate were 2.56, 1.86, and 2.15 times the lengths of those induced by water, respectively.

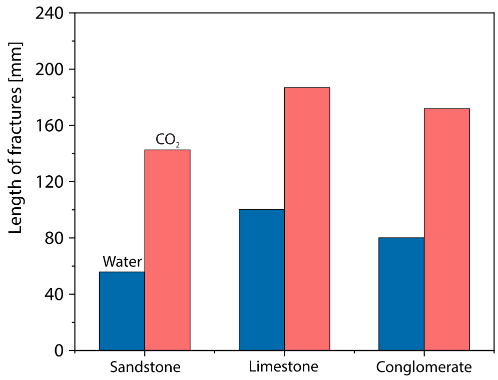

Figure 6. Length of fractures induced by water and CO_2 fracturing in different rocks

Conclusion

Several important conclusions can be drawn from the current experimental studies of hydraulic fracturing performed by injecting water and CO_2 into different rocks: CO_2 could reduce the initiation pressure of rock, and this effect is more pronounced in dense and stiff reservoirs. The initiation pressure of CO_2 fracturing in limestone was 4.6 MPa lower than that of water. For different rocks, CO_2 fracturing produces more tortuous fractures with more complex spatial patterns, which provide more efficient flow channels for oil and gas transportation. Enhancement of CO_2 fracturing in conglomerate reservoirs is more pronounced than in sandstones and limestones. In dense, hard, heterogeneous water-sensitive reservoirs, CO_2 is more preferred than water as a fracturing fluid. The results of the study provide a reference for the selection of fracturing fluids for reservoirs with different lithologies. In reservoirs with a high content of carbonate minerals, the dissolving effect of CO_2 on minerals cannot be neglected, which needs further study.

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