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Analysis of the influence of CO_2 pre-injection during hydraulic fracturing on enhanced oil recovery in shale reservoirs

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1 Introduction

Hydraulic fracturing was first developed in North America, resulting in a multi-stage horizontal well and multi-layer vertical well volume fracturing technology, and has been commonly used in reservoir reconstruction. However, hydraulic fracturing will cause a lot of waste of water resources, and the treatment of flowback fluids requires high cost (Wang et al., 2012; Lu et al., 2016; Rao et al., 2021). Supercritical CO_2 has attracted much attention due to its high mobility and low intermolecular interaction. Using CO_2 fracturing can effectively avoid the above problems by show more effectively increase the reservoir pressure and reduce the damage to the reservoir (King, 1983; Bryant and Monger, 1988; Yost et al., 1993; Xie and Hou, 2009). However, CO_2 fracturing needs a large number of supercritical CO_2, which is expensive and not easily accessible.

Since the first application of CO_2 fracturing technology in the United States in the 1980s, CO_2 fracturing technology has entered a stage of rapid development (Gupta and Bobier, 1998; Wei et al., 2019; Chen et al., 2020). A large number of CO_2 pre-injection experiments during hydraulic fracturing have been carried out, and field applications have been carried out in oilfields, which have achieved good results in increasing production (Liu et al., 2014; Zhou et al., 2019). In 1990, CO_2 sand fracturing, N_2 foam fracturing and N_2 fracturing were carried out in 15 gas wells in Kentucky, United States. The production data show that the cumulative gas production of CO_2 sand fracturing wells in 37 months is 2 times that of N_2 fracturing wells and 5 times that of N_2 foam fracturing wells. In 2014, an oil well in Oklahoma was fractured by CO_2. The daily oil production after fracturing was 2.7 t, and the oil production increased to 3.3 t/d after 1 month. CO_2 fracturing technology has been applied in 25 wells of tight oil reservoir, and the average daily production of single well is 1.7 t higher than that of adjacent wells. But up to now, there is still a lack of discussion on the mechanisms of CO_2 pre-injection to increase reservoir energy and production. Therefore, this paper aimed at investigating the interaction between pre-injected CO_2 and the reservoir fluid/rock/energy, providing reference for further confirming the mechanism of enhancing production and improving the fracturing effect.

2 Effect of CO_2 on rocks and fluids in reservoirs

The study on the interaction of injected CO_2 with reservoir rocks and fluids is of great significance for fracturing and reservoir reconstruction using CO_2. The influence of injected CO_2 on reservoirs is mainly reflected in four aspects, namely, improving physical properties of matrix, influence on fluid, improving stimulation effect and increasing reservoir pressure.

2.1 Effect of CO_2 on reservoir rocks

The improvement of reservoir properties by CO_2 is mainly reflected in the influence of porosity and permeability of rock, the change of reservoir wettability, plugging removal, and inhibition of clay expansion.

2.1.1 Changes of porosity and permeability

On the one hand, when the CO_2 dissolution mechanism dominates, the porosity and permeability of rock will increase with the injection of CO_2. When rocks and reservoir water contact with CO_2, CO_2 aqueous solution will produce new pores or broaden primary pores in the dissolution of organic matter or minerals, and the dissolution will increase with the increase of temperature and immersion time (Ross et al., 1981; Pokrovsky et al., 2005). Zou et al. (2021) conducted an experiment on the change of pore structure of shale reservoirs after immersion in CO_2 aqueous solution for 24 h under simulated reservoir temperature/pressure conditions (80°C, 20 MPa), and the rock matrix sample was soaked for 24 h. A large number of dissolved pores appeared, the porosity

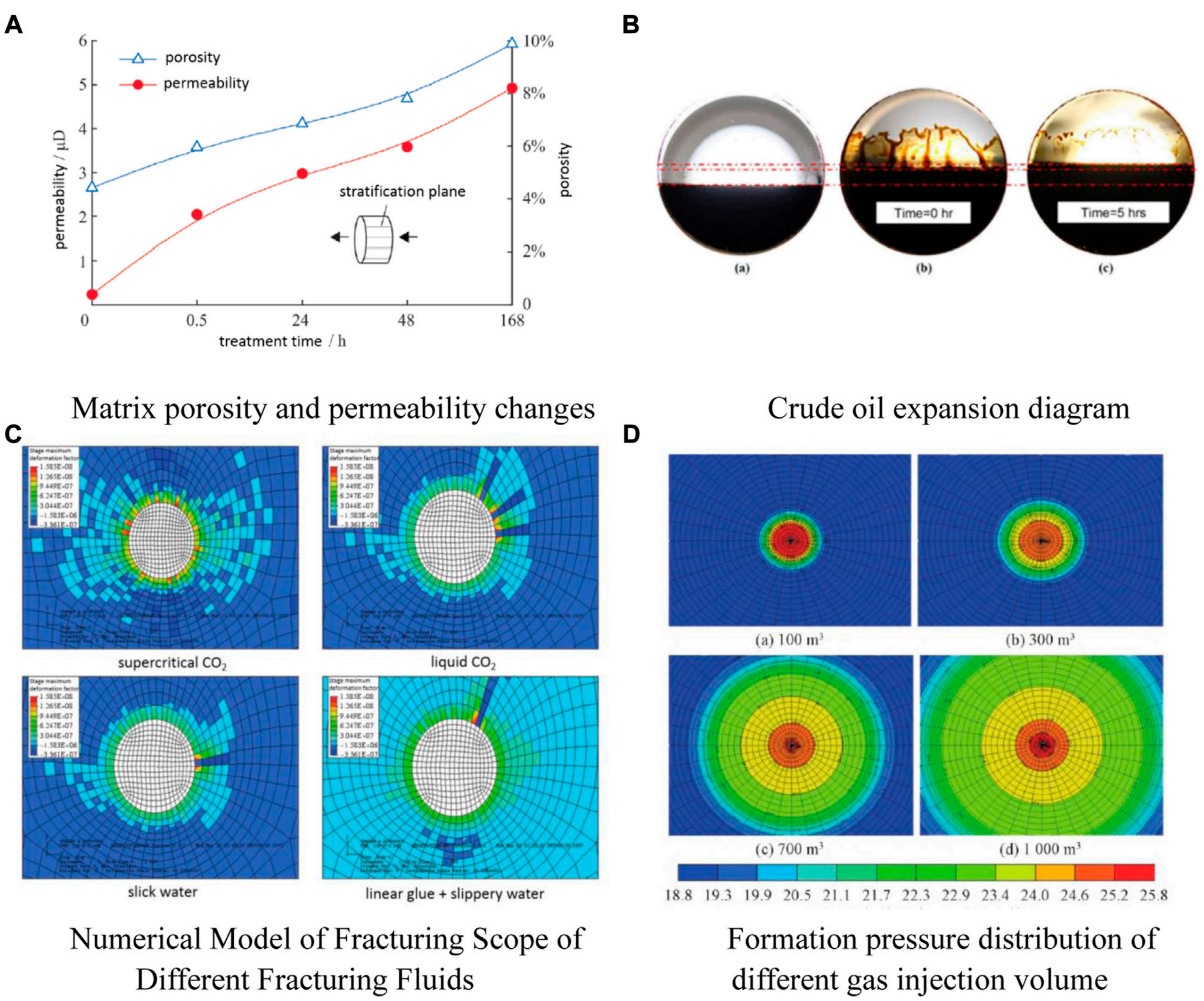

FIGURE 1
Effect of CO_2 injection.

was increased by 6.9%, and the permeability was increased from 0.23 μD to 2.98 μD. Experiments have proven that CO_2 can greatly increase the porosity and permeability, which is beneficial to increase production after fracturing.

On the other hand, when CO_2 adsorption expansion is dominant, CO_2 injection will reduce rock porosity and permeability. The interaction of CO_2, brine, and rock will form mineral crystals, which grow and precipitate in pores (Xu et al., 2005; Lahann et al., 2013). An experimental study by Kumar et al. (2015) showed that the adsorption of CO_2 in micropores may cause adsorption-induced swelling, thereby closing existing natural fractures and reducing fluid flow capacity. The change of pore structure is significantly affected by CO_2, and it is necessary to conduct targeted research on shale in practical applications.

2.1.2 Change of wettability

CO_2 can change reservoir wettability (Chiquet et al., 2005; Zhang et al., 2018). The injection of CO_2 will form carbonate in the reservoir, and the acid reacts with the minerals in the reservoir to generate new minerals, thereby changing the wettability of the solid wall of the liquid phase. The strong hydrophilicity of the reservoir is conducive to improving the injectivity of subsequent water flooding, and thus improving the recovery efficiency. Yao et al. (2017) proved that after injection of CO_2 into the reservoir, the wetting contact angle decreased and the hydrophilicity of the reservoir increased.

2.1.3 Deblocking and inhibiting clay swelling

In shale reservoirs, the reduction of the pH value of reservoir water can inhibit the expansion of clay. In carbonatite and sandstone, partial plugging can be relieved to restore oil well production. In the experiments by Zhang et al. (2020), the aqueous solution was slightly acidic owing to CO_2 dissolution, and the formation water dissolved CO_2 and interacted with the formation matrix to relieve plugging and inhibit clay swelling.

2.2 Effect of CO_2 on fluid

The influence of CO_2 on fluid is mainly reflected in the influence of extraction rate, density, expansion, gas solubility, surface tension, and irreducible water saturation.

2.2.1 Effect on mass transfer of oil

CO_2 enhances the extraction capacity of crude oil (Ding et al., 2019). It is difficult for CO_2 to get miscible with crude oil at first contact, so pre-injection of CO_2 can achieve multi-contact with oil, and the extraction effect of CO_2 on crude oil is continuously enriched to realize the miscibility. CO_2 has strong extraction ability for C2-C5 components of crude oil, but weak extraction ability for heavy components and methane. Liu et al. (2021) determined the extraction rate of crude oil by CO_2 at different pressures. Results show that CO_2 density was positively correlated with pressure. When the pressure reaches 40 MPa, the extraction rate can reach 85.2%. The experiment showed that CO_2 significantly enhanced the extraction rate of crude oil, as shown in Figure 1A.

2.2.2 Effect on oil density

Dissolving CO_2 in crude oil will increase the density of crude oil. With the increase of CO_2 content, more supercritical CO_2 contacts with crude oil, and the density of crude oil increases with the increase of CO_2 content (Abedini and Torabi, 2014). Su et al. (2021) injected 45% mole fraction of CO_2 into crude oil in the oil expansion experiment, and the oil density was increased by 8.78% from 0.7341 to 0.7986 g/cm^3 at 20 MPa.

2.2.3 Effect on oil expansion

CO_2 has a high expansion effect on crude oil. The specific volume, reservoir volume factor and compressibility coefficient of crude oil increase after CO_2 injection, which increases the compressibility of crude oil and further improves the productivity of oil wells (Nobakht et al., 2008), as shown in Figure 1B. Su et al. (2021) conducted crude oil expansion experiment, and found that when the mole fraction of CO_2 in crude oil was increased from 0 to 0.45%, the specific volume, reservoir volume factor, and compressibility coefficient of crude oil were increased by 2.53, 30.06, and 41.54%, respectively. Zhang et al. (2020) injected CO_2 into crude oil, and the expansion coefficient of crude oil increased from 1.00 to 1.19 after adding 45% CO_2. The above experiments have demonstrated that CO_2 can significantly enhance the elastic energy of reservoir.

2.2.4 Effect on gas solubility

The injection of CO_2 can effectively improve the gas solubility of crude oil. The higher the viscosity of crude oil is, the more obvious the viscosity reduction effect will be. Lower viscosity can increase its mobility, which is conducive to the production of crude oil. Shi and Zhao (2020) found that the average dissolved gas-oil ratio of the oil samples increased from 13.5 to 18.05, an increase of 4.52, accounting for 33.41% of the dissolved gas-oil ratio of total oil samples. The data show that CO_2 injection into crude oil can effectively enhance the gas solubility of crude oil and improve the gas solubility of crude oil.

2.2.5 Effect on oil-water surface tension

CO_2 can reduce the oil-water interfacial tension and reduce the viscosity of crude oil. CO_2 was injected into the reservoir in advance and CO_2 was contacted with crude oil many times, which improved the physical properties of crude oil, enhanced the mobility of crude oil and finally reached the miscibility. This will greatly reduce crude oil viscosity, improve displacement efficiency and increase production. The high-pressure PVT experiments conducted by Yang et al. (2009) showed that when the oil-water mixed solution was saturated with CO_2, the interfacial tension can be reduced by about 33%. Reducing the surface tension can reduce the adhesion work that needs to be overcome to strip oil from the rock surface, making the oil adhered to the rock surface and pores easier to be extracted.

2.2.6 Effect on irreducible water saturation

Injecting CO_2 increases irreducible water saturation (Liu et al., 2020). With the injection of CO_2, the dissolved gas volume of reservoir water increase. Some of the irreducible water that occupies the oil flow channel becomes mobile water, which makes the oil flow out and thus improves the recovery efficiency. Zhao et al. (2011) conducted the reservoir water injection CO_2 expansion experiment, and found that when the injection pressure was 27 MPa, irreducible water saturation increased from 36.3 to 41.11%.

2.3 Improving stimulated effect

Improving stimulated effect by CO_2 is mainly reflected in reducing initiation pressure and increasing fracture complexity.

2.3.1 Reducing initiation pressure

Supercritical CO_2 can reduce the rupture pressure of rocks. Since supercritical CO_2 has good diffusion and permeability, supercritical CO_2 fracturing reduces the effective stress of surrounding rock by increasing pore pressure, which makes the initiation pressure lower than hydraulic fracturing (Tudor et al., 1994; Ito, 2008; Zou et al., 2018; Deng et al., 2022), as shown in Figure 1C. Ding et al. (2018) analyzed the fracturing mechanism of supercritical CO_2 fracturing based on the rock fracture criterion of linear elastic model. The calculated data indicated that the rupture pressure by using supercritical CO_2 was reduced by 75.5%. Wang et al. (2019) experimentally demonstrated that the initiation pressure of supercritical CO_2 fracturing rock is 15% lower than that of liquid CO_2 under the same conditions, which is about half of that of hydraulic fracturing.

2.3.2 Increasing fracture complexity

Supercritical CO_2 has the effect of slippage and diffusion, which makes its liquidity have certain nonlinear characteristics. CO_2 can enter the tiny pores and fracture tips that water and fracturing fluid cannot enter during the propagation, promoting the opening of natural weak surface and increasing the complexity of fractures (Zou et al., 2018; Sheng et al., 2019; Tudor et al., 1994; Ito, 2008). Su et al. (2019) combined with physical simulation and numerical simulation, and found that the volume strain increment produced by supercritical CO_2 fracturing is higher than that of hydraulic fracturing, the fracture conplexity and fracture surface roughness after fracturing are also larger, and the fracture morphology is more complex (Zhou et al., 2016).

2.4 Enhancing reservoir pressure

Injection of CO_2 can effectively increase reservoir pressure, which is conducive to production. CO_2 has strong injection, good diffusion, strong production-increasing effect, wide range of pressure spread. Equal velocity injection of liquid carbon dioxide and water, the pressure-increasing effect of CO_2 injection is twice that of water injection (Singh, 2018; Xiao, 2018). Zhang et al. (2020) found that with the increase of CO_2 injection rate, the radius of miscible zone increased gradually. Due to the rapid propagation of CO_2 pressure, the reservoir pressure increases rapidly, as shown in Figure 1D, and the pressure can be maintained above 29 MPa in the reservoir near the wellbore.

3 Conclusion and foresight

CO_2 pre-injection during hydraulic fracturing can affect the physical properties of the reservoir, increase the porosity and permeability of the rock and improve the wettability of the reservoir, which is conducive to improving the subsequent water flooding injection capacity. CO_2 injection enhances the flow capacity of crude oil by using the effect of CO_2 injection on the fluid, making it easier for crude oil to be recovered. It also reduces initiation pressure, increases fracture complexity and increases formation pressure. Combined with water-based fracturing fluid, the fractures were further propagated and effectively supported.

At present, the mechanism of CO_2 pre-injection during hydraulic fracturing on reservoir has not been comprehensive considered in the fracture propagation simulation and production dynamic simulation. In the future, all of the mechanism should be considered for the accuracy and efficiency of experimental and theory research.

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Conflict of interest

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