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Study on the Mechanism of Carbon Dioxide Miscible Fracturing Fluid Huff and Puff in Enhanced Oil Recovery

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Abstract: Carbon dioxide (CO_2) miscible fracturing huff-and-puff technology now plays a pivotal role in enhancing crude oil recovery rates, particularly in reservoirs with challenging physical properties, strong water sensitivity, high injection pressure, and complex water-injection dynamics. In this study, the oil-increasing mechanism and huff-and-puff effect of CO_2 miscible fracturing fluid are investigated through a comprehensive experimental approach. Specifically, experiments on PVT gas injection expansion, minimum miscible pressure, and CO_2 miscible fracturing fluid huff and puff are conducted on the G fault block reservoir of the J Oilfield. The experimental findings demonstrate that injecting CO_2 into reservoirs leads to an expansion in oil volume, a reduction in viscosity, and an increase in saturation pressure. Crude oil extraction is further enhanced by the addition of solubilizers and viscosity reducers. The use of solubilizers not only increases oil recovery rates but also reduces the minimum miscible pressure required for effective CO_2 dispersion. We also found that shut-in times, permeability, and the huff-and-puff method used all have considerable impacts on huff-and-puff recovery rates. This study offers valuable technical insights, supporting the application of CO_2 miscible fracturing huff-and-puff technology to enhance oil recovery rates in low-permeability reservoirs.

Keywords: CO_2 miscible fracturing fluid; huff and puff; minimum miscible pressure; enhanced oil recovery; low-permeability reservoir

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1. Introduction

As the exploration and development of conventional oil and gas resources continue to advance, unconventional resources such as those with low permeability and dense characteristics have become a focus of attention. For unconventional reservoirs, which may have poor physical properties, small pore throats, and severe heterogeneity, water injection and hydraulic fracturing may be used as development methods. However, the water flooding process often faces challenges due to the strong water sensitivity of the reservoirs and poor connectivity of pore throats. This results in high injection pressures and difficulties in water injection, leading in turn to the ineffective replenishment of formation energy and poor water flooding outcomes [1]. Moreover, the use of fracturing fluids in hydraulic fracturing can potentially damage reservoirs, thus compromising the fracturing results [2].

The injection of CO_2 into reservoirs is now considered one of the most effective methods for enhancing oil recovery. CO_2 can diffuse through fractures into the matrix, increase formation pressure, expand the volume of crude oil, reduce its viscosity, extract lighter components, and condense, while also mitigating greenhouse gas emissions through the sequestration and utilization of CO_2 [3–7]. Particularly under miscible conditions, the reduction in interfacial tension significantly enhances oil displacement efficiency. However, the use of CO_2 in miscible flooding involves challenges such as high miscibility pressure and the risk of gas breakthrough [8], for which CO_2 huff and puff is an effective mitigation technique [9,10]. In addition, CO_2 has the ability to fracture rocks and form complex fracture networks. CO_2 fracturing, as an emerging non-aqueous fracturing technology, has been widely applied in unconventional reservoirs. Field statistics indicate that CO_2 fracturing can significantly enhance oil recovery compared with conventional hydraulic fracturing, as injected CO_2 can penetrate tiny pore throats that water-based fracturing fluids cannot, so that core permeability is significantly improved [11].

The CO_2 miscible fracturing huff-and-puff technique, due to its unique mechanism and notable effects, has garnered attention as a promising means of enhancing oil recovery. This technique involves injecting CO_2 under high pressure into a reservoir to replenish formation energy and fracture the formation, while solubilizers and viscosity reducers are simultaneously injected. During the soaking process, CO_2 and solubilizers in the fractures fully contact the crude oil in the matrix to achieve miscibility, and the addition of viscosity reducers reduces the flow resistance caused by high pour points and the wax content of the crude oil, thereby enhancing the flow properties of the miscible crude oil during production and improving the mobilization of ultra-low-permeability reservoirs [12]. Compared to conventional CO_2 fracturing fluids, the injection of high-pressure liquid CO_2 is more conducive to the mixing, dissolution, and displacement of crude oil, resulting in more complex fracture expansion and better diversion effects [2]. The addition to CO_2 fracturing fluids of additives such as surfactants, viscosity reducers, and cosolvents can lower the minimum miscibility pressure and enhance miscibility. By such means, the limitations of CO_2 oil displacement may be addressed, with potentially significant benefits for future development [13].

In recent years, a number of scholars have focused on the use of CO_2 miscibility and CO_2 huff-and-puff techniques to enhance oil recovery. The work of Cai et al. [14] revealed that CO_2 miscibility facilitates the displacement of oil in micropores, resulting in a final recovery rate approximately twice that of immiscible displacement, with higher residual CO_2 in miscible flooding primarily due to its dissolution in crude oil. N. Kumar et al. [15] reported that the main mechanisms through which CO_2 and crude oil miscibility enhance recovery rates include promoting expansion in crude oil volume, reducing interfacial tension, lowering crude oil viscosity and density, inducing hydrocarbon evaporation or condensation, altering rock wettability, and enabling CO_2 dissolution in water to achieve CO_2 sequestration. Lv et al. [16] used nuclear magnetic resonance and physical simulation to conduct experiments on CO_2 huff and puff and surfactant-assisted CO_2 huff and puff. Their results suggested that the use of surfactants in assisting CO_2 huff and puff can further enhance recovery rates. This is because the presence of surfactants reduces oil–gas interfacial tension, which improves the injection and diffusion capabilities of CO_2, increases the amount of CO_2 dissolved in the oil, enhances the CO_2 sweep and oil displacement efficiency in tight reservoirs, significantly improves the mobilization of crude oil in micropores, and achieves better CO_2 sequestration. Wang et al. [17] found that in low-permeability reservoirs, adjuvants can effectively promote the realization of CO_2 and crude oil miscible flooding under injection pressures lower than the minimum miscibility pressure (MMP) and that miscible flooding significantly reduces oil saturation in the core. Research by Li et al. [18] demonstrated that the use of surfactants can effectively reduce the minimum miscibility pressure and improve the solubility of CO_2 in crude oil.

The development of low-permeability tight oil reservoirs is commonly accompanied by fracturing, in which the initial contact of the injected CO_2 occurs with fractures. The impact of these fractures on CO_2 huff and puff cannot be overlooked. Alharthy et al. [19] proposed a simulation model that takes fractures into account and studied the CO_2 huff-and-puff process in the Bakken formation. They concluded that the contact area between

CO_2 and crude oil is crucial for enhancing recovery rates. Wei et al. [20] arrived at similar conclusions through laboratory testing. Bai et al. [21] examined the recovery rate evaluation of fractured core samples under varying permeabilities and found that fractures can reduce the sensitivity of recovery rates to matrix permeability, with oil recovery occurring primarily from larger pores. Yang et al. [22] pointed out that fractures significantly influence the migration of crude oil, noting that in a negative convection state, the oil recovery from medium pores in fractured samples was 2.88 times higher than that obtained from non-fractured samples.

The studies mentioned above focused primarily on the impact of a single factor. There has been little comprehensive research on the multifactorial effects of fractures, mixed-phase injections, and the use of chemical additives in the CO_2 huff and puff technique. Neither has there been any direct investigation of the CO_2 miscible fracturing huff-and-puff technology. In the G block of the J Oilfield, the crude oil exhibits low viscosity and a high wax content. The sand bodies in this block are developed in a ribbon-like pattern, with an overburden permeability which is mostly less than 0.1 mD. The G block is also characterized by very large pores, fine throats, poor connectivity, and high starting pressure, so that conventional water injection involves difficulties which make effective displacement a challenging task. This leads to injection incapacity and extraction inefficiency, complicating energy replenishment. In this block, an initial pilot experiment using CO_2 miscible fracturing huff and puff in a well resulted in significantly increased production; however, the mechanisms by which the CO_2 miscible fracturing huff-and-puff technique enhances recovery rates remain unclear, and further implementation in this area requires additional in-depth studies, such as those described in this paper.

For the study reported here, we conducted PVT experiments, minimum miscibility pressure tests, and CO_2 huff-and-puff experiments on the low-permeability reservoirs of the G block in the J Oilfield. We systematically analyzed the mechanisms of action of the CO_2 miscible fracturing fluid huff-and-puff technology. Our results reveal the potential application mechanisms of this method for enhancing recovery rates and provide technical support for the further application of this technology in similar reservoirs.

2. Experiment

2.1. Experimental Materials

① Oil sample: The crude oil utilized originated from the wellhead of the G fault block reservoir within the J Oilfield. Specifically, we employed a high-temperature, high-pressure sampler to separate the oil and water. Representative live oil samples were then established at 113.8 °C and 33 MPa by recombining the oil and gas samples according to the formation gas components and the production gas–oil ratio. The components of the gas were as follows: CH_4 66.78%, C_2H_6 12.57%, C_3H_8 10.14%, C_4H_{10} 3.51%, CO_2 5.01%, and N_2 1.99%. Notably, the gas-to-oil ratio of this simulated crude oil stood at 91.2 m^3/m^3.

② Gas injected: CO_2 gas with a purity of 99.999% was used.

③ Fracturing fluid additives: The solubilizers and viscosity reducers employed belonged to the fracturing fluid series additives that are routinely used on site within the target reservoir. These additives were developed by the Oil Production Technology Research Institute of the Great Wall Drilling Engineering Technology Research Institute based on the fluid properties and reservoir characteristics of the G fault block within the J Oilfield. The concentration dosage for these additives was set to 10%.

④ Slim tube: A slim tube with a length of 15 m and a diameter of 4.4 mm was used; this exhibited a permeability of 5800 mD and possessed a pore volume of 84.2 mL.

⑤ Water: The water employed in this study was sourced directly from the target oil reservoir site. Prior to the experimentation, it underwent filtration using a 0.45 μm filter membrane, facilitated through a sand core funnel.

⑥ Core: The core specimens utilized consisted of natural rock samples generously supplied by J OilField, China. These cores exhibited a permeability range spanning from 4 to 40 mD, and their additional properties are shown in Table 1.

Table 1. Core basic parameters and corresponding experimental settings.

Core	Length (cm)	Diameter (cm)	Permeability (mD)	Porosity (%)	Injection Medium	Shut-In Time	Huff-and-Puff Mode
1-1	9.454	2.523	39.42	19.72	CO_2 + solubilizer	6	Same well
1-2	9.835	2.525	38.58	19.27		12	
1-3	9.637	2.521	39.15	19.31		24	
1-4	9.646	2.523	38.97	18.96		48	
2-1	9.832	2.520	11.85	17.02	CO_2	12	Same well
2-2	9.994	2.521	11.25	17.25	CO_2 + solubilizer		
2-3	9.705	2.522	11.48	17.31			
2-4	9.924	2.523	12.07	17.59			Different well
3-1	9.841	2.532	4.54	12.72			Same well

2.2. Experimental Design

The experimental temperature was set to 113.8 °C, the pressure was 33 MPa, and the fracturing pressure was 55 MPa. Notably, these values align with those observed in the formation reservoir.

2.2.1. Experiment on Gas Injection Expansion

To investigate the impacts of CO_2 and fracturing fluid additives on the high-pressure physical properties of crude oil and to clarify the oil-increasing mechanism of the CO_2 miscible fracturing fluid, experiments were conducted on the high-pressure physical properties of crude oil and gas injection expansion. As illustrated in Figure 1, a PVT experimental device was used in conjunction with a high-temperature and high-pressure formation fluid viscometer. The industry standard GB/T 26981-2020 "Analysis Method for Reservoir Fluid Physical Properties" [23] was employed as a reference. The experimental procedure may be stated as follows:

① Add a specified quantity of simulated crude oil into the PVT cylinder. Then, elevate the temperature and pressure to match the reservoir conditions. Precisely measure the resulting oil sample volume. Following this, perform degassing experiments to ascertain both the gas–oil ratio and the volume coefficient of the oil.

② Employ the stepwise pressure reduction method to establish the p–V relationship for the oil sample. At each stable pressure reduction stage, record the corresponding sample volume values. These data points collectively form the p–V relationship curve. The inflection point on this curve corresponds to the bubble point pressure.

③ First, compute the required quantity of injected gas (ranging from 10 mol% to 60 mol%) for each stage, considering the composition of the original oil sample. Then, introduce CO_2 gas into the PVT cylinder and pressurize it beyond the bubble point pressure. Agitate the sample thoroughly to achieve fluid uniformity. Next, execute the procedures outlined in ② to establish the corresponding p–V relationship curve. Calculate the essential properties, including the saturation pressure, density, and volume coefficient. Finally, employ a high-temperature and high-pressure formation fluid viscometer to measure viscosity.

④ Following the gas injection experiment, reintroduce a specific quantity of simulated crude oil into the PVT cylinder after meticulously cleaning the latter. Additionally, incorporate 0.1 PV of fracturing fluid additives. Subsequently, replicate the procedures outlined in steps ① to ③. Observe and quantify the alterations in the high-pressure physical properties of the oil as well as the characteristic behavior of gas injection expansion.

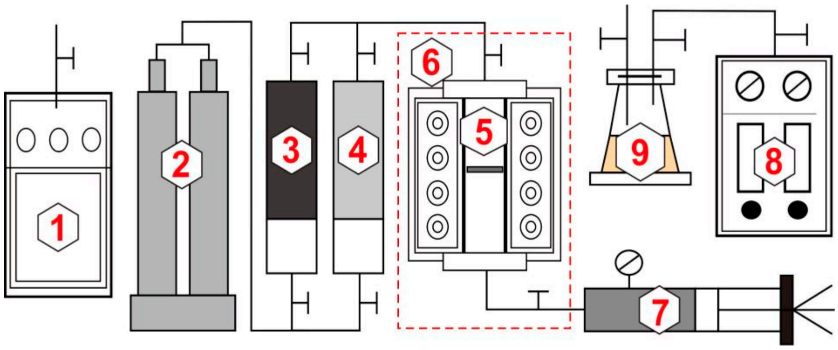

Figure 1. Schematic diagram of the PVT experimental device: (1) chromatograph; (2) ISCO pump; (3) oil; (4) CO_2; (5) PVT visualization tube; (6) temperate box; (7) high-pressure pump; (8) gas meter; (9) gas–liquid separator.

2.2.2. Experiment on Minimum Miscibility Pressure

To investigate the miscible conditions of the target reservoir and assess the impact of fracturing fluid additives on miscible pressure, we conducted minimum miscible pressure (MMP) experiments using a thin tube experimental device. These experiments adhered to the industry standard outlined in SY/T 6573-2016: "Mesurement Method for Minimum Miscibility Pressure by Slim Tube Test" [24]. The schematic representation of the experimental setup is presented in Figure 2. The experimental procedure may be stated as follows:

① Saturate the slim tube with dead oil under experimental temperature and pressure and accurately measure the pore volume (volume entering the pump).
② Displace dead oil within the thin tube with live oil until the produced gas–oil ratio at the outlet end matches that of the simulated oil.
③ Displace the live oil with CO_2 gas at a constant rate and continue the injection process until 1.2 PV of gas is injected. Throughout this phase, record the amount of crude oil produced for every 0.1 PV of CO_2 injected. Subsequently, calculate the corresponding degree of oil reserve recovery. Plot the relationship between the degree of reserve recovery and the amount of CO_2 injected.
④ Evaluate both the degree of reserve recovery and final recovery efficiency after changing the pressure and repeating the above steps. Specifically, the set experimental pressure should cover no fewer than three points when the final recovery efficiency is greater than 90% or less than 90%. Finally, plot the relationship between recovery efficiency and pressure. For trend lines of scatter points greater than and less than a 90% recovery efficiency, the pressure corresponding to the intersection is the MMP.

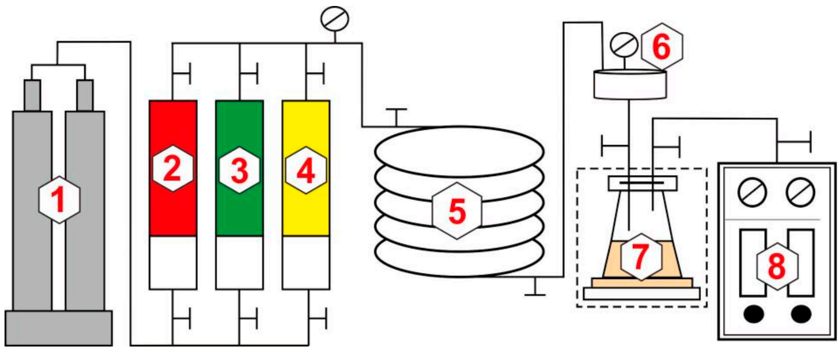

Figure 2. Schematic diagram of the minimum miscibility pressure experimental device: (1) ISCO pump; (2) live oil; (3) dead oil; (4) CO_2; (5) slim tube; (6) back-pressure valve; (7) gas–liquid separator; (8) gas meter.

2.2.3. Experiment on CO_2 Miscible Fracturing Huff and Puff

To investigate the huff-and-puff effect of CO_2 miscible fracturing, we conducted CO_2 miscible fracturing huff-and-puff experiments using a core displacement device. The experimental device is schematically shown in Figure 3, and the experimental steps may be stated as follows:

① Evacuate and pressurize the core to achieve formation water saturation. Next, prepare the core by introducing bound water using a gas-driving method. Determine the core's irreducible water saturation through weight measurements before and after gas driving.

② Create a single-through fracture by splitting the core, thus mimicking the fracturing characteristics of the reservoir. Subsequently, load the core into the core holder and saturate it with dead oil.

③ Displace the dead oil with live oil until the gas–oil ratio at the outlet matches that of the live oil, and then perform aging.

④ Inject 0.1 PV of the fracturing fluid additive at a low flow rate and formation temperature. Then, displace the oil continuously with CO_2 until the pressure reaches 55 MPa. Shut in the well after closing the valve and reopen it after the specified shut-in time. Gradually reduce the pressure by adjusting the back-pressure valve. Throughout this process, record the oil and gas production to evaluate recovery efficiency.

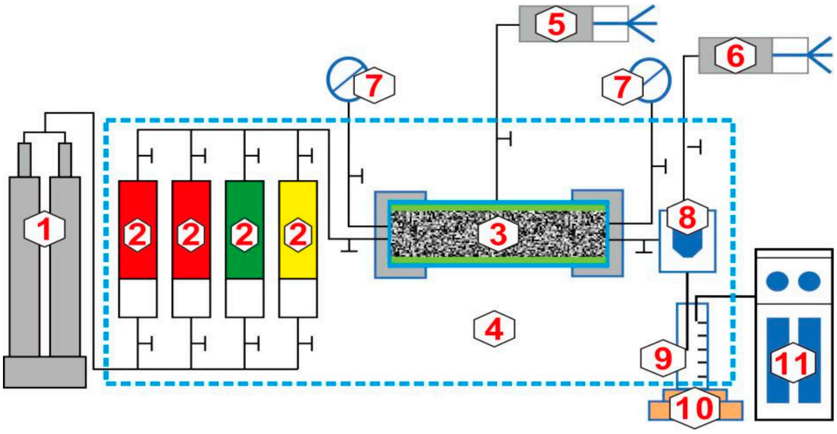

Figure 3. Diagram of CO_2 miscible throughput experimental device: (1) ISCO pump; (2) live oil/dead oil/formation water/CO_2; (3) core holder; (4) constant temperature oven; (5) surrounding-pressure pump; (6) back-pressure pump; (7) pressure sensor; (8) back-pressure valve; (9) gas–liquid separator; (10) electronic balance; (11) gas meter.

3. Experimental Results and Analysis

3.1. Mechanism of Oil Production Increase

3.1.1. Interaction between CO_2 and Crude Oil

In this experimental study, we investigated the impacts of CO_2 and CO_2 miscible fracturing fluid on the properties of crude oil. The results are presented in Figure 4. It can be seen from the figure that the saturation pressure, volume coefficient, and density of crude oil all increase as the amount of injected CO_2 increases. Specifically, when the CO_2 injection amount rises from 0 to 60 mol%, the saturation pressure increases from 25.2 MPa to 47.49 MPa, the volume coefficient increases from 1.3915 to 2.0630, and the crude oil density increases from 0.7435 g/cm^3 to 0.7966 g/cm^3. However, with the same increase in injected CO_2, the viscosity of crude oil decreases from 0.402 mPa·s to 0.269 mPa·s. This is due to the fact that as the CO_2 content increases, the saturation pressure of crude oil also increases. This compression of the oil results in more CO_2 dissolving under high pressure, which in turn reduces the viscosity of the crude oil and improves its flowability. In addition, the density of CO_2 is higher than that of crude oil under a high saturation pressure. Consequently, the more CO_2 that dissolved in crude oil, the higher the density of that oil will be [25]. The higher the CO_2 content, the greater the increase in saturation pressure and density. The above results indicate that CO_2 plays a pivotal role in expanding and reducing the viscosity of crude oil, thereby facilitating its solubilization, expansion, and displacement.

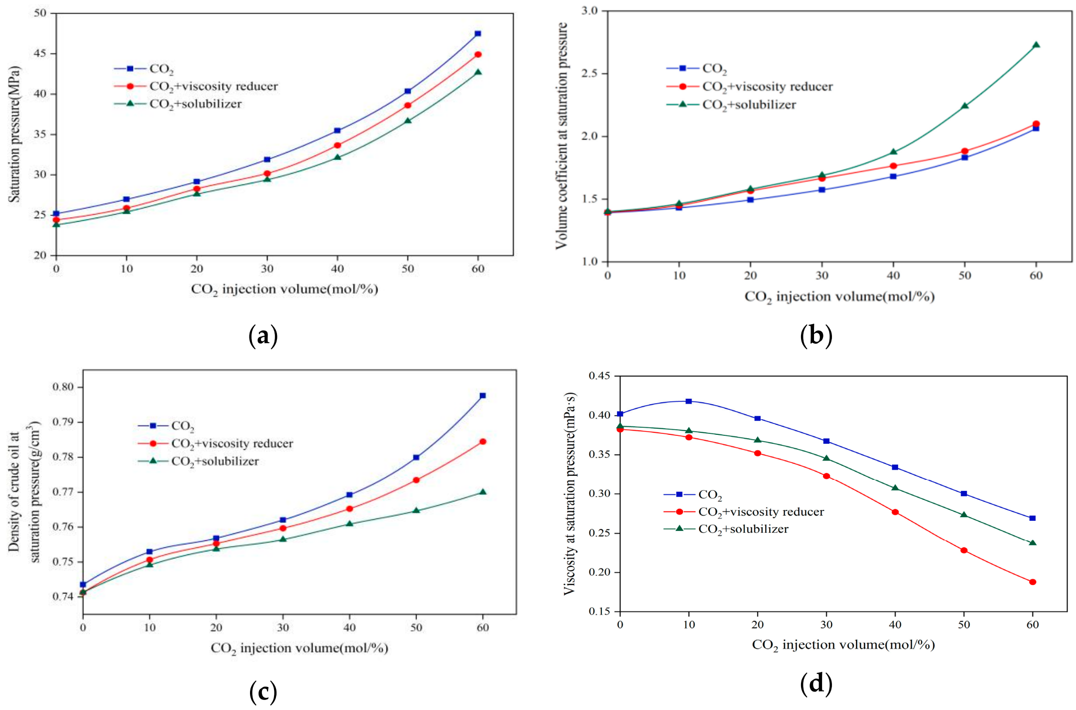

Figure 4. (**a**) The relationship between saturation pressure and amounts of injected CO_2. Under saturation pressure, the changes in (**b**) volume coefficient, (**c**) density, and (**d**) viscosity of crude oil, with varying amounts of injected CO_2.

It can also be seen from Figure 4 that when a solubilizer or viscosity reducer is introduced and an equivalent amount of CO_2 is dissolved, the volume coefficient of the crude oil surpasses that of oil without additives. Simultaneously, the saturation pressure, density, and viscosity of the crude oil all decrease. In addition, as the amount of injected CO_2 increases, the corresponding increase or decrease in these properties becomes more pronounced. These results demonstrate that the additives effectively enhance CO_2 dissolution in crude oil. This phenomenon leads to increased oil expansion, greater elastic energy, reduced viscosity, and improved fluidity, thereby making it easier for the crude oil to be extracted. In the present study, we found that the use of solubilizers resulted in more significant changes in saturation pressure, the volume coefficient, and crude oil density compared with viscosity reducers, indicating that solubilizers have a better effect on crude oil and allow more oil to be produced.

3.1.2. Minimum Miscibility Pressure

Crude oil and CO_2 achieve miscibility under the condition that the reservoir injection pressure surpasses the minimum miscibility pressure. This process results in a reduction in the surface tension of the miscible oil, thereby enhancing the efficiency of oil recovery. For the present study, a minimum miscibility pressure experiment was conducted to determine the miscibility conditions for the CO_2 miscible fracturing fluid. The results are illustrated in Figure 5. It can be seen from the figure that the minimum miscibility pressure for crude oil and CO_2 in the absence of a solubilizer is 27.76 MPa. This indicates that miscibility can be attained by injecting CO_2 under the formation pressure of the reservoir (33 MPa). In contrast, after the injection of 0.1 PV solubilizer, the minimum miscibility pressure decreases to 23.73 MPa, representing a reduction of 14.52% compared with the previous value. This reduction can be attributed to the solubilizer's ability to decrease the interfacial tension between CO_2 and crude oil, thereby facilitating the dissolution of more CO_2 into the crude oil.

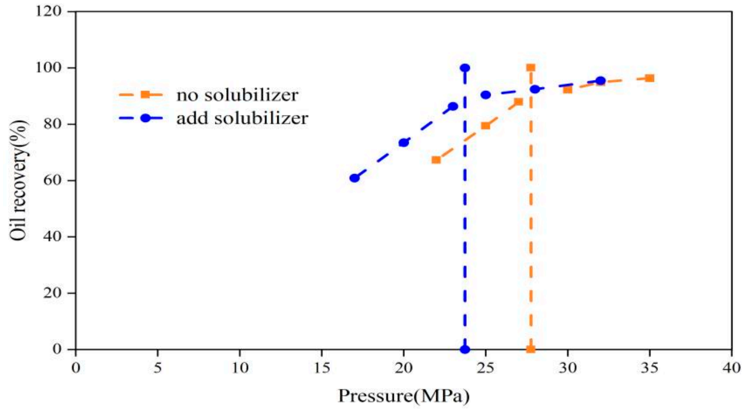

Figure 5. Results of experiment on minimum miscibility pressure between crude oil and CO_2.

3.2. Effect of Huff and Puff

3.2.1. Impact of Fracturing Fluid Additives

Huff-and-puff experiments involving CO_2, CO_2 + solubilizer, and CO_2 + viscosity reducer were conducted on cores 2-1, 2-2, and 2-3, respectively. These experiments were conducted under identical well-soaking durations of 12 h. The results are presented in Figures 6 and 7. It can be seen from Figure 6 that for cores exhibiting the same permeability level, a combination of CO_2 and solubilizer yields the highest recovery rate, at 48.27%. The use of CO_2 and a viscosity reducer, or CO_2 alone, results in recovery rates which are marginally lower, at 43.80% and 38.22%, respectively. The injection of solubilizer slugs increases the recovery rate of huff and puff by 10.05% compared with the use of CO_2 alone. The injection of the solubilizer allows more CO_2 in the fractures to be dissolved in the matrix crude oil. This expands the volume and reduces the viscosity of the crude oil, allowing more crude oil to be extracted into the fractures under the swelling effect during extraction.

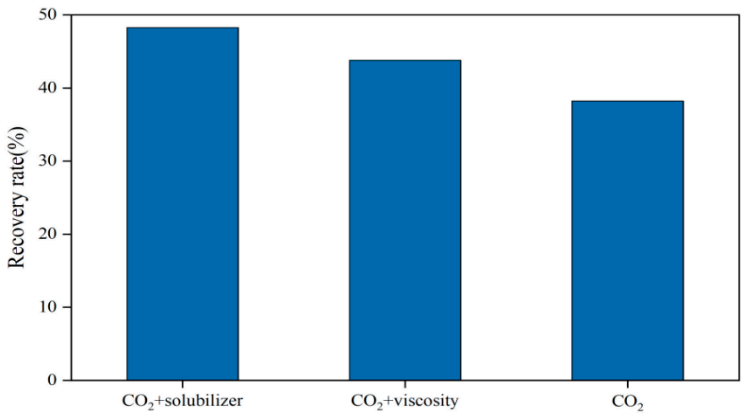

Figure 6. Effects on recovery efficiency results of adding different additives.

Figure 7 illustrates a positive correlation between the decreases in average pressure and the increases in the stage recovery rates. Notably, a pressure range of 35–25 MPa yields a marginally higher stage recovery rate compared with a range of 25–15 MPa. This is because CO_2 and crude oil reaches a miscible state at 35–25 MPa, and any further reduction in pressure causes resistance due to large amounts of degassing, resulting in a slight reduction in the stage recovery rate in the 25–15 MPa range. However, continued pressure reduction causes gathering of the separated gas to produce a gas-driving effect, thereby promoting the flow of crude oil. Consequently, stage recovery efficiency rises again within the 15–2 MPa range.

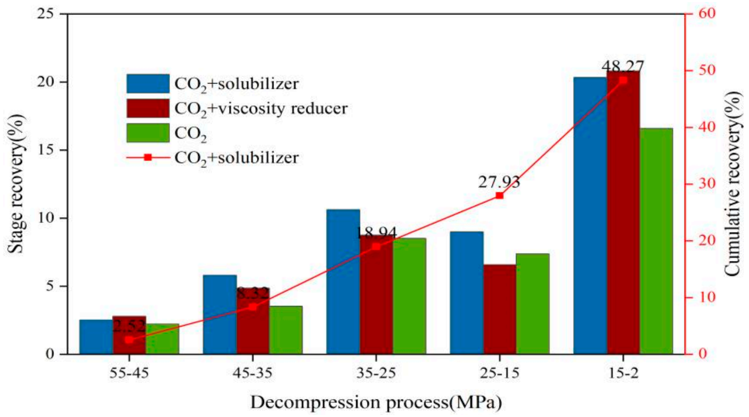

Figure 7. Effects on stage recovery of adding different additives in decompression process.

3.2.2. Impact of Shut-in Time

Cores 1-1, 1-2, 1-3, and 1-4 were used to carry out experiments on the huff-and-puff effect of CO_2 + solubilizer under varying shut-in times. It can be seen from Figure 8 that there is a positive correlation between the well shut-in time and the recovery rate for cores of identical permeability. However, beyond a well shut-in duration of 24 h, the efficiency of recovery plateaus, suggesting that the optimal well-soaking time has been achieved.

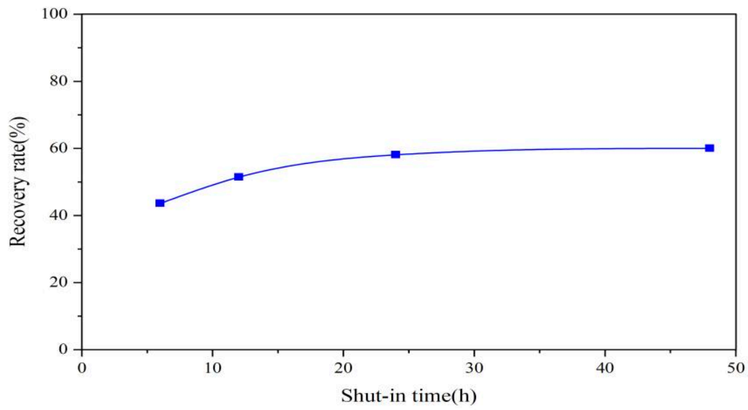

Figure 8. Relationship between huff-and-puff recovery efficiency and well shut-in time.

From Figure 9, it can be seen that the lower the blowout pressure, the more oil is produced, with the increase in huff-and-puff production being more obvious in the later stages of pressure drop. This phenomenon occurs because the crude oil produced in the initial stage mainly relies on the expansion effect caused by CO_2 dissolved in the crude oil. When the pressure drops below the saturation pressure, the dissolved CO_2 starts to separate from the oil, so that gas propels the crude oil during the discharge process. The figure also illustrates that at a pressure drop ranging from 15 to 2 MPa, the recovery rate exceeds 20% for varying durations of the well shut-in time. Particularly, the recovery rate is notably higher during this stage. Therefore, it is essential to control pressure drop production during production.

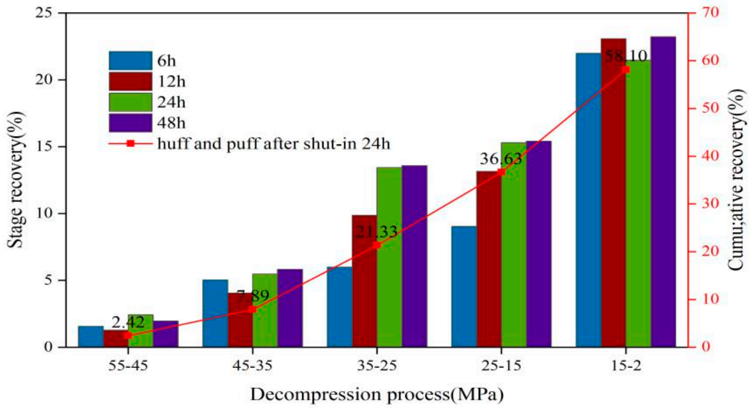

Figure 9. Huff-and-puff efficiency results under different discharge pressures.

3.2.3. Impact of Permeability

Cores with different matrix permeabilities (nos. 1-2, 2-2, and 3-1) were used to carry out experiments on the huff-and-puff effect of CO_2 + solubilizer under the same well shut-in time (12 h). In Figure 10, a positive correlation between the permeability and the recovery efficiency may be observed. The corresponding recovery rates for the three cores are 51.43%, 48.27%, and 24.59%, respectively. The recovery rate of the high-permeability core is 26.83% higher than that of the low-permeability core. Hence, the huff-and-puff effect of CO_2 miscible fracturing is enhanced with better physical properties of the reservoir and higher matrix permeability.

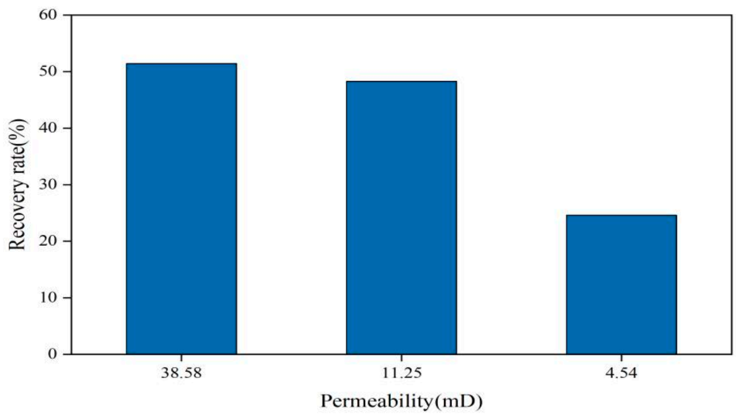

Figure 10. Huff-and-puff efficiency for cores with different permeabilities.

3.2.4. Impact of Huff-and-Puff Patterns

In the experiments just described, the same-well huff-and-puff method was used. This method involves injecting CO_2 and fracturing fluid additives from the outlet end and performing depressurization mining from the outlet end after the well is shut in for a certain time. To examine the impact of the huff-and-puff method on recovery efficiency, core nos. 2-4 were employed to conduct different-well huff-and-puff experiments. This alternative method involved injecting CO_2 and fracturing fluid additives from the outlet end then mining from the inlet end after the well was shut in for a certain time. The additive used was a solubilizer, and the shut-in time was 12 h. The experimental results are plotted in Figure 11.

The results indicated that the huff-and-puff method significantly impacts the recovery efficiency, with better performance being obtained using the different-well method. Compared with the 48.27% recovery efficiency of the same-well huff-and-puff method, the different-well method exhibited an increase of 27.39%. The dissolution rate of injected CO_2 and additives mainly depends on the diffusion rate of CO_2 in crude oil, and this in turn is influenced by the concentration difference and the contact extent between CO_2 with crude oil. When using the injection well for production, a substantial quantity of CO_2 returns first when the pressure drops as the CO_2 accumulates at the bottom. Consequently, the originally saturated crude oil becomes difficult to produce due to large amounts of degassing. However, when producing from a production well, the injected CO2 can continuously drive the oil from the injection well to the production well. Moreover, by exploiting the dissolution and expansion capabilities of CO_2, the CO_2 around the injection well can serve the dual role of pressure maintenance and secondary displacement, thereby significantly increasing crude oil production.

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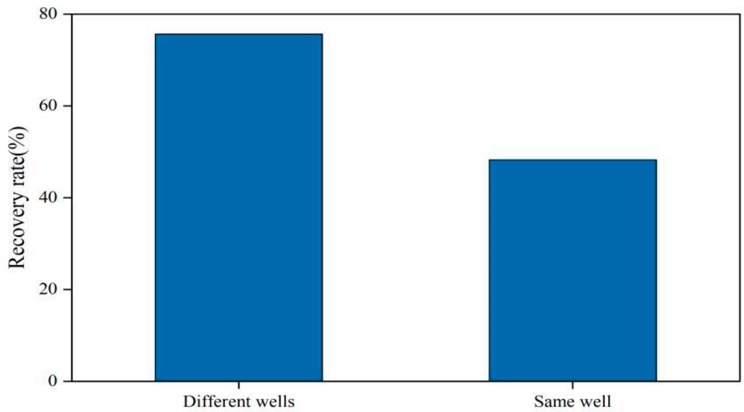

Figure 11. Effect of huff-and-puff method on recovery efficiency.

4. Conclusions

In the present study, to clarify the oil-increasing mechanism and huff-and-puff effect of CO_2 miscible fracturing fluid in the low-permeability reservoir of the G fault block in the J Oilfield, we carried out crude oil gas injection expansion experiments, minimum miscible pressure experiments, and CO_2 miscible fracturing fluid huff-and-puff experiments.

The experimental results proved that injecting CO_2 into crude oil to achieve a miscible state produced an expansion in crude oil volume, a reduction in viscosity, and an increase in elastic energy, all of which contributed significantly to improved rates of crude oil recovery. Furthermore, the introduction of fracturing fluid additives enabled CO_2 to be more easily dissolved in crude oil, with the solubilizer proving more effective than a viscosity reducer in this regard. The use of the solubilizer increased the oil recovery rate by an additional 10.05%, and also reduced the minimum miscibility pressure of CO_2 and crude oil from 27.76 MPa to 23.73 MPa. We also found that the recovery rate obtained using CO_2 miscible fracturing fluid huff and puff was better than that obtained using CO_2 huff and puff. The addition of the solubilizer and viscosity reducer increased recovery rates by 10.05% and 5.58%, respectively, compared with CO_2 huff and puff. Factors such as shut-in time, matrix permeability, and the huff-and-puff method used also significantly influenced the huff-and-puff effect. Specifically, we found that the recovery efficiency was proportional to well shut-in times, with the optimal such time being 24 h. In addition, we found that the recovery rate of high-permeability cores was 26.83% higher than that of low-permeability cores, and the recovery efficiency under the different-well stimulation was 27.39% higher than that under the same-well stimulation.

These findings reveal the potential application of CO_2 miscible fracturing fluid huff-and-puff technology in improving oil recovery and the mechanisms involved. They provide technical support for the application and implementation of this technology in low-permeability reservoirs, with a potential positive impact on the environment through the better storage and utilization of CO_2.

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