Evaluation and Optimization of Gas Volume on CO_2 Huff and Puff By Multiple Horizontal Wells in Fault-Block Reservoirs with Edge Aquifers

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Abstract

Problems like small sweeping volume, short stimulating period and poor producing performance challenge the effectiveness of single horizontal well CO_2 huff 'n' puff in the fault-block reservoirs with edge water. The effect of CO_2 volume on multiple horizontal wells CO_2 huff 'n' puff has been studied in this paper to investigates the feasibility of CO_2 huff 'n' puff by horizontal well group. Studies on both isothermal property of CO_2 and the CO_2-crude oil properties under reservoir conditions offer the possible basis for this work. A 3D edge water model with three horizontal wells, which was designed and produced according to geological data, was used to simulate the process of CO_2 huff 'n' puff by horizontal well group. Subsequently, experiments were carried to investigate the impact of CO2 volume on water control and oil stimulation. Results show the CO_2 isothermal compressibility under certain pressure make it possible to inject gas with relatively low energy loss and to enlarge sweeping volume. Meanwhile, with more CO_2 mole composition in the crude oil, the mixture intends to be more flowable. Consequently, as the gas volume increases from 0.07PV to 0.13PV, the comprehensive water cut rate drop from 0.72% to 5.93%, and both oil and gas production increase accordingly. However, the gas use ratio dwindles as the volume exceeds 0.13PV.

Introduction

There is around 50%-60% original oil in place remained after the primary and secondary oil recoveries. The ever-increasing demand for crude oil has inspired the innovative technologies to stimulate hydrocarbon productions. Therefore, enhanced oil recovery (EOR) methods, involving the injection of CO_2, N_2, hydrocarbon gases, or chemicals into oil reservoirs, becomes increasingly important in petroleum industry. Among the EOR methods, CO_2 EOR has gained more momentum since CO_2 injection can effectively improve the oil recovery factor and reduce greenhouse gas emissions to some extent[1-4].

The oil recovery can be enhanced by CO_2 injection through different processes, like displacing oil left in the unswept areas by water displacement. In addition, considerable oil production can be enhanced through series of micro mechanisms, covering oil expansion, viscosity reduction, capillary effect mitigation due to CO_2-crude oil interfacial tension (IFT)[5-7], light hydrocarbons extraction[8], permeability alteration[9-10], mass transfer through diffusion and dispersion. Oil mobility can be drastically improved due to the significant reduction in oil viscosity once mixed with the injected CO_2[11,12]. Oil expansion due to CO_2 dissolution can enhance oil recovery by stripping oil drops off the grain surface and increasing oil volume over the residual saturation, contributing the formation of continuous oil phase[7]. Reduction in residual oil saturation can also be achieved by the extraction of light hydrocarbons upon exposing the oil to a sufficient CO_2-rich gas[8]. However, the extraction mechanism is susceptible to hydrocarbon compositions in the crude oil. Therefore, heavy crude oils are less affected by this mechanism compared to light crude oils[13]. The contribution of each aforementioned mechanism to oil recovery is governed by the pressure, temperature, and CO_2 solubility.

According to the reservoir characteristics of a domestic edge water effect, using the self-designed edge water action level well group , physical model for edge water reservoirs horizontal well group and the physical simulation experiment, study the effect of injection volume on symmetry stimulation effect and optimize it, combined with the nature of the reservoir under the condition of high temperature and high pressure CO2 and its interaction with formation crude features, analysis of gas injection for horizontal well group raised the influence degree of the effect of oil water control in CO2 stimulation, for the effect of injection volume optimization and analysis to provide basic data and theoretical basis

Experiment materials and process

The crude oil used in the experiment was obtained from a fault-block reservoir in the Jidong Oilfield, is the mixture of reservoir crude oil with kerosene. And the oil viscosity is 189mPa·s under the reservoir condition(60 ℃, 16.4 MPa). Brine of the edge aquifers was collected from the production well with a salinity of 1572mg/L, $NaHCO_3$ type. The CO_2 gas was from the Jinggao Gas limited company with a purity of 99.9%.

The CO_2 huff and puff by multiple horizontal wells schematically shown in **Figure 1** was utilized in the experiments. A radius core holder specifically designed to the 3D model size with an inner diameter of 45cm diameter and depth of 10cm was used as a radius core holder for the CO_2 huff and puff experiments (left of **Figure 1**). This special core holder could sustain pressures up to 20MPa and temperature to 120℃. There are two high-pressure pumps (Model 100DX, Teledyne Technologies) working separately to pressurize the CO_2 (1 in **Figure 1 right**) and control the flow rate of the edge aquifer (4 in **Figure 1.b**). Pressures in the radius core holder were measured using pressure transducers (JYB-KO-H, Beijing ColliHigh sensing technology co., LTD). The produced gas and liquid were separated and measured by gas flowmeters (LF420-S, Laifeng Scientific Technology co., LTD) and graduated test tube.

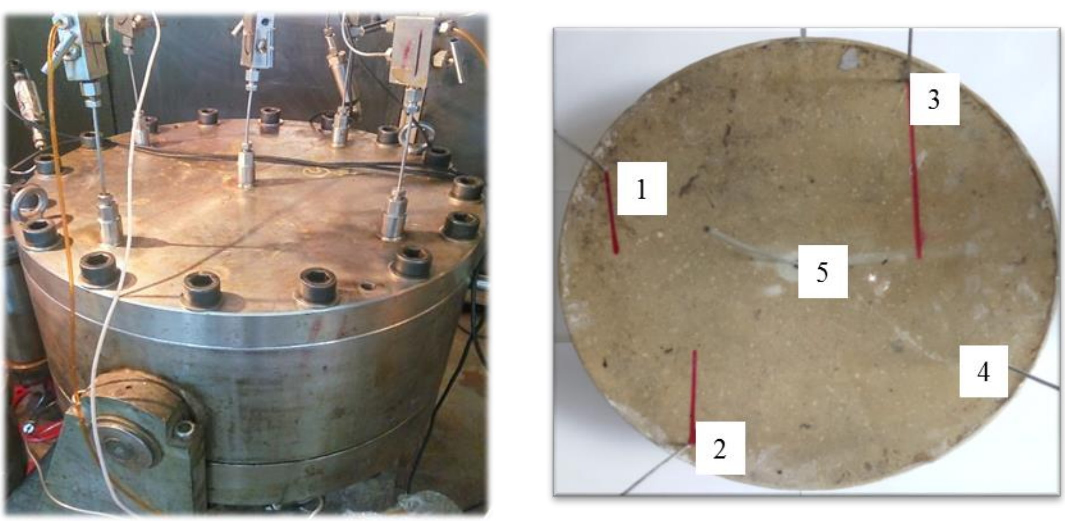

Figure 1 Radius Coreholder (left) and 3D model (right) for CO_2 huff and puff by multiple horizontal wells (red lines indicates the horizontal length and orientation of horizontal wells)

Experiments of CO_2 huff and puff by multiple horizontal wells of CO_2 volumes were performed in the laboratory using the experimental apparatus. The experimental procedures were as follows:

(1) Each 3D model was made from outcrop sand with 5 wells pre-buried according to the distribution patterns in Fig.1. The 3D model was evacuated for more than 4 h before saturated with brine, and the pore volumes and permeabilities were measured.

(2) The initial oil saturations and irreducible water saturations were calculated by the crude oil at a rate of 0.1 mL/min until the water production ceased. And the model was aged 48h at 60℃.

(3) Edge water flooding was initiated at back pressure of 7.5 MPa till the water-cut of one well reaches 98%, and the water flooding recovery was calculated.

(4) The high-pressure pump was initiated to inject CO_2 till the pressure in Well 5 was 3MPa, 5MPa, 7.5MPa and 10MPa.

(5) The soak time last 24h before all the horizontal wells recovered to production under 1 MPa BPR, and so did the edge aquifer flood. When water-cut of one horizontal well reaches 98%, flooding work ceased.

Table 1 Radius model parameters of CO_2 huff and puff cases

Experiment NO.	Pressure, MPa	bulk volume, cm^3	pore volume, cm^3	porosity, %	oil saturation, %
1	3	5652	842	14.89	65.32
2	5	5652	839	14.84	66.61
3	7.5	5652	810	14.33	64.56
4	10	5652	845	14.95	68.69

As introduced in the previous section, the CO_2 volume can be calculated by the density changes in a constant volume cylinder with a movable piston before and after injection at the constant temperature. CO_2 equation of state (EOS) in the density form is below,

$$PM_{CO_2} = z\rho_{CO_2}RT \tag{1}$$

The density difference before and after CO_2 can be described,

$$\Delta\rho=\rho_1 - \rho_2=\left(\frac{P_1}{z_1}-\frac{P_2}{z_2}\right)\frac{M_{CO_2}}{RT} \tag{2}$$

The cylinder volume is 1000 cm^3 under this experiment condition, then the mass of the injected CO_2 can be calculated. Additionally, the volume under standard and experimental condition can be calculated by the CO_2 EOS in mass form (Eq. 3). Tab.3 summarized the gas injection volume under

$$PV = z\frac{m_{CO_2}}{M_{CO_2}}RT \tag{3}$$

Table 2 CO_2 injection volumes under different conditions by EOS calculation

Experiment NO.	Pressure, MPa	CO_2 mass, g	volume, PV (333.15K, injection pressure)	volume, PV (2933.15K, 0.1MPa)
1	3	3.294	0.07	2.1987
2	5	8.420	0.10	5.1233
3	7.5	18.030	0.13	9.7194
4	10	33.431	0.14	13.8035

Results and discussion

CO_2 compressibility under experimental conditions

Since the gas volume was measured according to the pressure value within the radius model. Under the reservoir condition, CO_2 was squeezed into the target zone by surface compressor, and gas compressibility coefficient was the key parameter to assess the injectivity and efficiency.CO_2 isothermal compressibility under different injecting pressure was evaluated (**Figure 2**). CO_2 compressibility decreased drastically with the elevating pressure and increased slightly near 8.5MPa. Namely, CO_2 was least compressed at pressure ranges of 6.5-8.5MPa at which CO_2 phase transformed from gas to supercritical state. During the injection process, CO_2 was easily compressed at gas phase, consuming large portion of energy to compress gas rather than to pump into the formation. Therefore, elevating injection pressure would achieve an economical energy efficiency for an expanded seeping volume.

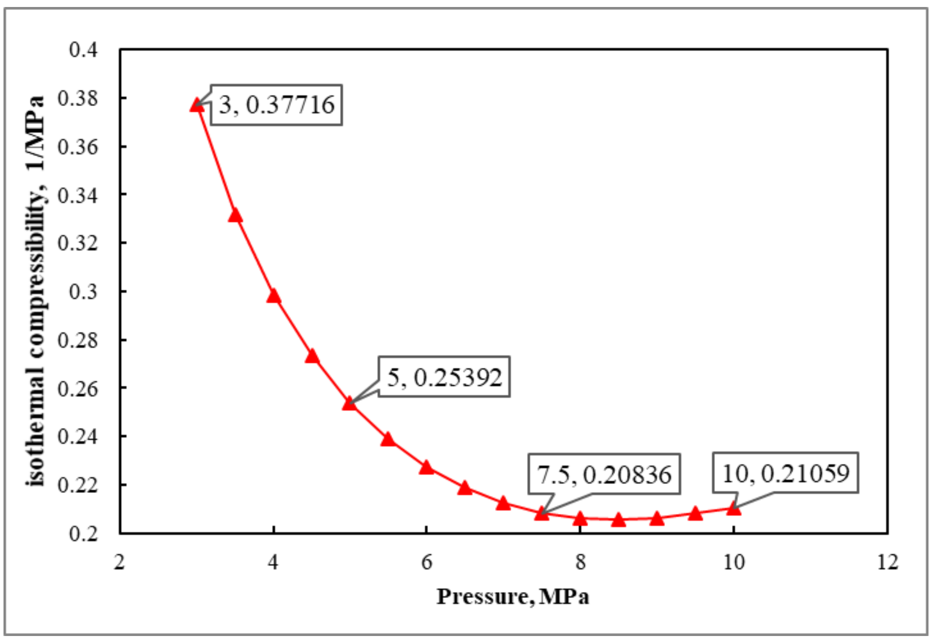

Figure 2 CO_2 isothermal compressibility coefficient curve under experimental condition (333.15K)

Oil properties alteration by CO2 solubility

The dissolution of CO_2 into crude oil caused oil expansion, mobility improvement and interfacial tension reduction, lowing the oil saturation in the formation. Under formation condition, oil volume expanded with the rise in CO_2 mole fraction. The volume increased 8% as the CO_2 mole fraction properties elevated to 30%. Therefore, the expansion of discontinuous oil droplets makes it possible to merge with the other isolated droplets, forming a continuous phase. Meanwhile, saturation pressure of the mixture increased to 9.38MPa, 2.13MPa higher than the original oil. The injection of CO_2 supplied the depleted formation energy. Consequently, gas oil ratio elevated to 35.5 A m^3/m^3 as large amount of gas dissolute as formation pressure depleted under saturation pressure, and “foamy oil” has a better mobility compared to the dead oil with lower viscosity, contributing oil flow into the wellbore.

Table 3 Oil properties mixed with different CO2 mole fractions

CO_2 mole fraction, %	B_o, dimensionless	P_b, MPa	GOR, m^3/m^3
0	1	7.189	0
5	1.0138	7.604	5.9
10	1.0277	7.995	11.8
20	1.0555	8.714	23.7
30	1.0835	9.389	35.5

CO_2 diffusion properties in crude oil

For CO_2 distribution in porous media, certain measured data were necessary to evaluate the CO_2 sweeping efficiency in the model. Pressure diffusion and molecular diffusion are the distinct mechanisms that affect the trend of CO_2 variation. Molecular diffusion is the tendency to mix due to concentration gradient. Pressure diffusion (gravitational segregation) the separation by pressure gradient. In our experiment, pressure was the indirect parameter to quantify the CO_2 injection volume, therefore, the two main mechanisms should not be neglected. Both CO_2 diffusion coefficient in the oil sample and CO_2 density under experimental condition various pressure were presented (**Figure 3**). Since the temperature was constant under experimental process, diffusion coefficient of CO_2 in the crude oil in various pressures condition was the key parameter to evaluate the CO_2 dispersion in the radius model during the soaking period. Results showed that the coefficient increased from $2.9927\times10^{-8}m^2/s$ to $4.8890\times10^{-8}m^2/s$, a near linear increase before the CO_2 critical state, and the tendency became debated after the critical point since the coefficient reduced to $4.7676\times10^{-8}m^2/s$ under 10 MPa condition. The round pot in Fig.2 depicted the tendency of CO_2density under experimental conditions. The oil and water densities are 0.837 $g/cm^3$and 1.15 g/cm^3 respectively. While the density of gaseous CO_2 is 0.0535 g/cm^3 at 3MPa, much lower than the formation liquids. The huge density gap leads to gravitational overlapping, contributing a gas distribution in the upper part of the model. When the difference narrows down to relatively high density like 0.1728g/cm^3 at 7.5MPa, the gas profile overrides the water swept area and expands oil by solution.

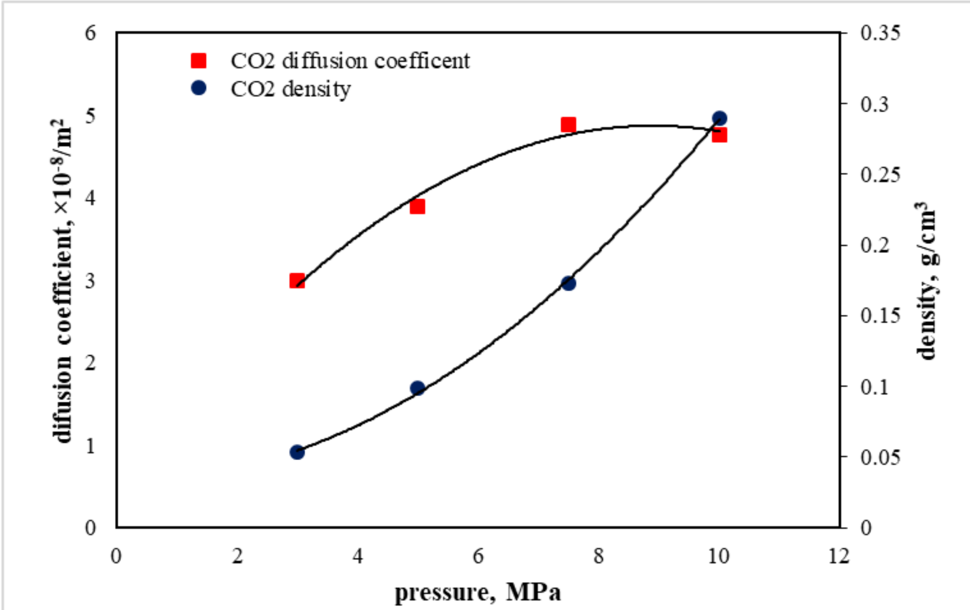

Figure 3 diffusion data of CO_2 under experimental condition
(diffusion coefficient were measured by pressure decay method and CO_2 density data were collected from NIST, a standard reference database)

Oil stimulation results and gas utility

Oil recovery results enhanced by CO_2 huff and puff were the comprehensive consequence of CO_2 oil interactions. **Figure 4** demonstrates the results of enhanced oil recovery by CO_2 huff and puff under different volumes. The stimulated oil increased in accordance with the enlarged CO_2 injection volume, as the overall oil recovery was 5.87% in 2.1987 SCPV and 22.36% in 13.8035 SCPV. More CO_2 meant a higher oil recovery. From the relation between oil stimulation and distance from edge aquifer in a single horizontal well, in the 2.1987 SCPV case, oil recovery in horizontal wells #1 and #2 was 2.60% and 2.02% respectively, higher than that in #3 which was only 1.25%, which was near the edge aquifer. And results of the other three experiments demonstrated the same oil recovery outcomes. For the horizontal well #3, which was located near the edge aquifer, much of the oil was flooded during the initial water flooding stage, then oil saturation was lower than the other two wells. Therefore, increasing gas injection volume can significantly increase the oil recovery. And the stimulation effect of CO_2 huff and puff mainly comes from horizontal wells with high oil saturation far away from the edge water.

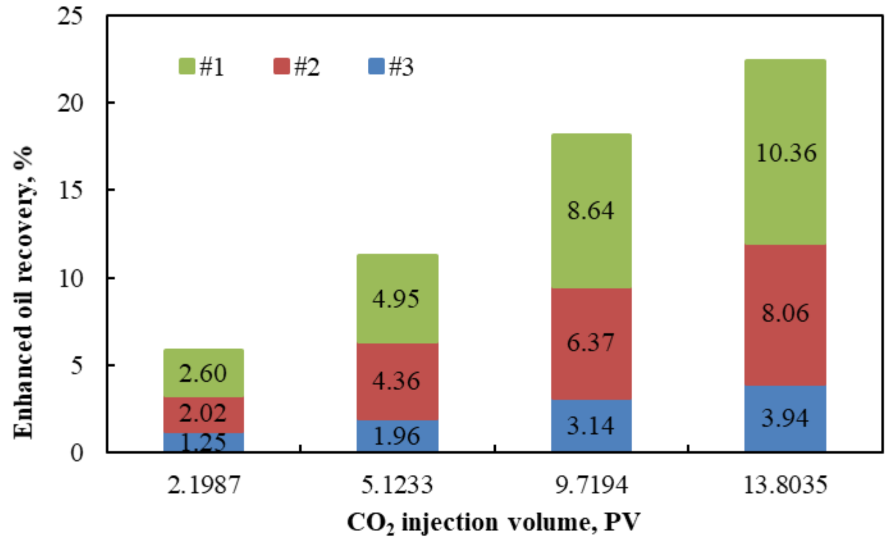

Figure 4 Enhanced oil recovery in single well of different CO_2 volumes
(gas volume in standard condition, corresponding to experimental condition 3MPa, 5MPa, 7.5MPa and 10MPa)

From the aspects of the enhanced oil recovery and gas utility (**Figure 5**), result of 9.37 scPV was 6.87% higher than that of 5.21PV, only 4.21% lower than that of 13.08 PV. Hence, the oil increase became less significant after 7.5MPa injection volume, and enlarging CO_2 injection volume would not stimulate oil drastically. Since small gas volume means light mass, the gas utility ratio, increased oil mass per 1g CO_2, decreased with the rising CO_2 volume. However, the gas utility ratio corresponding to 0.13PV under 7.5 MPa turned less obvious. In addition, free gas from production curves in Fig.3 also explained the shrank oil stimulation by unit mass CO_2 since the accumulated gas volume surged to 8000 cm^3 in 13.80 scPV.

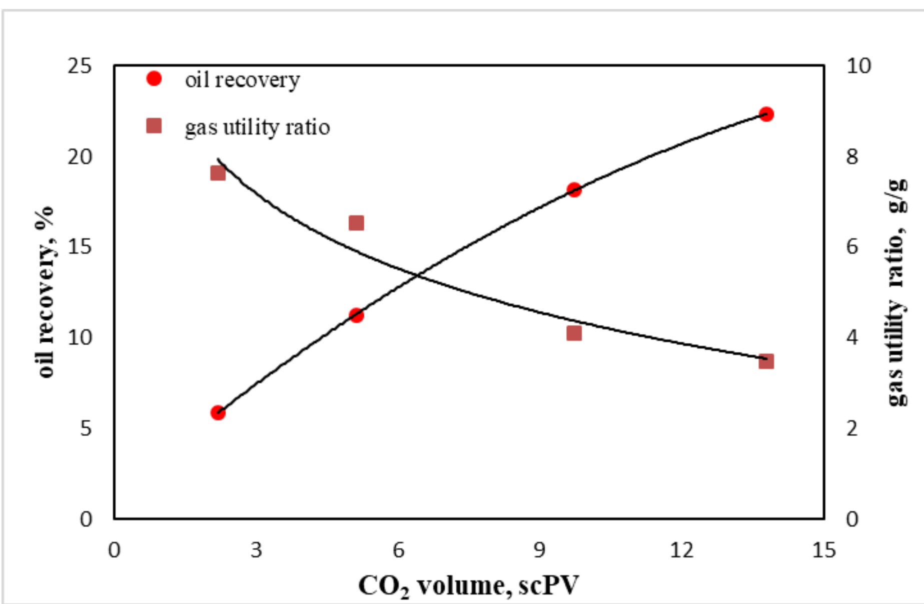

Figure 5 Overall enhanced oil recovery and gas utility ratio of different CO_2 volumes
(gas volume in standard condition, corresponding to experimental condition 3MPa, 5MPa, 7.5MPa and 10MPa)

Conclusion

From the results of injection volume optimization of CO_2 huff and puff from three horizontal wells in the radius model. Several conclusions has been reached as follows:

(1) The CO_2 huff and puff in the fault-block reservoir model with edge aquifer proved to be effective in water cresting control and oil stimulation. As injection volume of CO_2 was elevated, both the reduced water cut and enhanced oil production were observed, with substantial increase in free gas production. The injection volume needs to be optimized to alleviate the contradiction among water control, oil enhancement and high gas production.

(2) Based on the properties of CO_2 gas and CO_2-formation crude oil under high pressure conditions, the isothermal compression coefficient of CO_2 is the lowest under the experiment condition (60℃, 7.5MPa), corresponding to 9.72PV injection volume. The CO_2 gas can be squeezed into the formation, and the fluidity of crude oil increases with significant expansion with elevated CO_2 mole fraction.

(3) Under the experimental conditions of this study, results of water control and oil stimulation in 0.13 PV CO_2 was much better than that of 0.10PV, and similar to that of 0.14PV with much less gas production. And the optimal injection volume of CO_2 huff and puff in horizontal well group was 0.13PV.

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