Energy Proceedings
Vol 39, 2024
ISSN 2004-2965

Feasibility study of CO_2 sequestration by high quality foam at the late development stage of high water-cut reservoirs

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ABSTRACT

In order to store CO_2 efficiently and safely, the innovative approach of storing CO_2 in the water cut reservoirs entering the later stage of heavy oil development through high quality foam was proposed. Due to the high apparent viscosity of foam, the heterogeneity of reservoir was regulated, the CO_2 mobility was controlled, and the CO_2 storage efficiency was increased. In this paper, the influence of foam quality and reservoir permeability on CO_2 storage efficiency and oil recovery was researched through sandpack model experiment. In addition, in order to truly simulate the water-cut reservoir, the three-dimensional model was designed. The variation laws of gas saturation, mobility reduction coefficient, and CO_2 storage water consumption with the foam quality were summarized. The experimental results indicated that when the foam quality was 85%, the gas saturation of the water-cut reservoir was the highest, reached 75.36%, reflecting the high CO_2 storage efficiency and the mobility control ability. Moreover, the water consumption for CO_2 storage also dropped to the lowest, reached 43.88 g·mol^{-1}, representing the high quality foam has good CO_2 storage ability.

Keywords: Carbon Utilization, Carbon Storage, High quality foam, water-cut reservoir, oil recovery

NONMENCLATURE

Abbreviations	
3D	Three-dimensional
AOS	Sodium alpha-olefin Sulfonate
PV	Pore volume
MRC	Mobility reduction coefficient
Symbols	
q_l	Liquid flow, mL·min^{-1}
f_g	Quality of foam, %
q_g	Gas flow, mL·min^{-1}
q_s	Foaming agent flow, mL·min^{-1}
q_f	Foam flow, mL·min^{-1}
S_g	Gas saturation, %
W_i	Initial weight of the model after saturation with oil, g
W_f	Weight of the model after CO_2 foam flooding, g
ρ_{oil}	Density of oil sample, g·cm^{-3}
ρ_{CO2}	Density of CO_2, g·cm^{-3}
V_p	Pore volume of the model, cm^3
ΔP	Pressure gradient of model, MPa·m^{-1}
Δp_f	Pressure difference of model during CO_2 foam flooding, MPa
L	The length of the sandpack model, m
M	Mobility of foam, 1×10^{-3}μm^2·(mPa·s)$^{-1}$
k	Permeability of the model, 1×10^{-3}μm^2
μ_{app}	Apparent viscosity of foam, mPa·s
r	Radius of the sandpack model, m
A	Cross sectional area, mm^2

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

1. INTRODUCTION

CO_2 geological sequestration is a very promising method. Comparing the capacity of different formation types, high water-cut reservoirs in the later stage of heavy oil development has obvious advantages. Although storing CO_2 in high water-cut reservoir is safe, directly injected CO_2 cannot effectively utilize underground space, resulting in very low CO_2 storage efficiency[1-3]. Due to the low viscosity and high fluidity of CO_2, the injected CO_2 migrated along the top of the formation under gravity, resulting in very low sweep efficiency. Since the middle of the 20th century, foam has been used in oil and gas development as a clean, environmentally friendly and efficient displacement fluid[4-6]. Foam has a strong plugging effect on the high permeability channel, while it has a good sweep effect on the low permeability channel. Foam has high apparent viscosity, reducing the flow of gas in the formation. Therefore, foam has the potential to promote CO_2 storage[7].

The CO_2 foam was generated when CO_2 mixed with surfactant, and the flow of CO_2 was control by CO_2 foam. CO_2 foam has many advantages, such as effectively reducing CO_2 mobility by more than 50%, promoting the CO_2 sweep in low-permeability reservoirs, delaying the time node of gas channeling, and achieving the effect of improving oil recovery and CO_2 storage capacity[8]. Heller[9] found that the CO_2 flow was controlled by foam through a series of experiments. Raza[10] illustrated that CO_2 and surfactant solution were injected simultaneously to generate and stabilize foam, so as to reduce the fluidity of CO_2. Kovscek[11] based on the characteristics that foam can turn fluid in heterogeneous formations, through a series of experiments, concluded that foam can effectively reduce the flow capacity of gas in high permeability formation, and make the gas in high permeability formations turn to areas that were not affected in low permeability formations.

There were many factors influencing foam seepage in the formation[12-14]. In order to explore the influence of foam on gas flow and CO_2 storage. In this paper, sandpack model experiments and 3D simulation reservoir model experiments were designed. The variation laws of gas saturation, CO_2 mobility, CO_2 mobility reduction coefficient and CO_2 storage water consumption under different quality foam were researched. The innovative method of high quality foam for CO_2 storage in high water cut reservoirs at the later stage of heavy oil development was obtained.

2. EXPERIMENT MATERIAL AND APPARATUS

2.1 Material

The oil sample with a density of 0.937 g/cm^3 and a viscosity of 646 mPa·s at 50°C was used in the experiments. The CO_2 with a purity＞99.99% was used to generate foam. The AOS selected as the foaming agent with a purity＞99.8%. The concentration of foaming agent used in the experiments was 0.1 wt%, 0.3 wt% and 0.5 wt%, respectively, to form CO_2 foam with different quality. The experimental water was self-made deionized water with a resistivity of 18.25 MΩ·cm. The material used to make the high permeability sandpack model was 80-100 mesh quartz, and to make the low permeability sandpack model was 160-200 mesh quartz.

2.2 Apparatus

The experimental procedures were shown in Fig.1 and Fig.2. The experimental apparatus mainly included 100DX ISCO high-precision pump (with accuracy of 0.003 mL, and with pressure resistance of 2 MPa), pressure gauge (with pressure resistance of 10 MPa), SLA5850S gas flowmeter (with accuracy of 0.01 mL·min^{-1}, and with flow resistance of 50 mL·min^{-1}), container (with volume of 3 L, with temperature resistance of 50 MPa, and with temperature resistance of 120 °C), foam generator, balance, measuring cylinder, and beaker.

The size of the sandpack model was Φ 1.5 cm × 60 cm. The left side of the model was the injection end, and the right side was the production end. The 3D simulation reservoir model was a stainless steel cube with a size of 400 mm × 400 mm × 150 mm. Injection well was distributed at the center of the model, with displacement fluid injected from the bottom of the model. Production

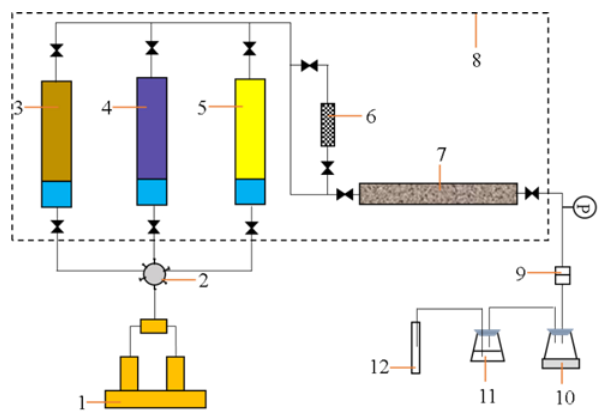
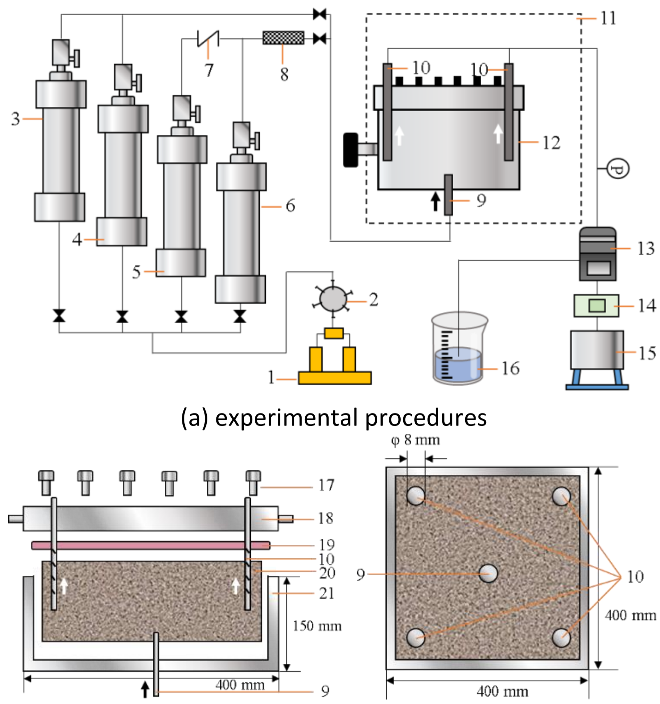


Fig. 1. Diagram of sandpack model experiment(1-ISCO pump; 2-Six port valve; 3-Oil; 4-Foaming agent; 5-CO_2; 6-Foam generator; 7-Sandpack model; 8-Incubator; 9-Back pressure valve; 10-Balance; 11-Wild mouth bottle; 12-Measuring cylinder)

wells were distributed at the corner, and fluid were produced from the top of the model.



(b) 3D simulation model (c) Well distribution

Fig. 2 Diagram of 3D simulation reservoir model experiment (1-ISCO pump; 2-Six port valve; 3-Water; 4-Oil; 5-CO_2; 6-Foaming agent; 7-Check valve; 8-Foam generator; 9-Injection well; 10-Production well; 11-Incubator; 12-3D model; 13-Gas liquid separator; 14-Gas flowmeter; 15-CO_2 metering; 16-Beaker; 17-Steel bolts; 18-The upper steel plate; 19-Gasket; 20-Simulation of the reservoir; 21-The lower steel plate)

2.3 Experimental procedure

2.3.1 Sandpack model experiment

(1) In the preparations of the sandpack model, firstly, 80 mesh quartz sand and 100 mesh quartz sand were mixed in a volume ratio of 3:1, and the mixed sand was filled into the model cavity to make the high permeability model. 160 mesh quartz sand and 200 mesh quartz sand were prepared to make the low permeability model according to the same steps. After the air tightness test, the sealed model was connected with the vacuum pump to maintain the vacuuming for 24 h. After that, the water was injected into the model at a rate of 0.5 $mL\cdot min^{-1}$, and the porosity and permeability of sandpack model were measured. Then, oil saturation was carried out by injecting oil into the model at a rate of 0.2 $mL\cdot min^{-1}$. When the model outlet produces oil stably for 10 min, the oil saturation was completed.

(2) The concentration of foaming agent was set as 0.3 wt%. CO_2 foam with quality of 50%, 65% and 80% was prepared by injecting CO_2 and foaming agent with injection concentration ratio of 1:1, 2:1, 4:1 into the foam generator.

(3) The CO_2 foam flooding with different foam quality was conducted in the sandpack model. The experiment temperature was set at 65 °C, and the CO_2 foam injection rate was 2 $mL\cdot min^{-1}$. The oil recovery and the volume of CO_2 storage was recorded in the process of displacement. When the water saturation of produced liquid reached 98%, the experiment was finished.

(4) The quality of foam and permeability of sandpack model were changed, respectively. The CO_2 foam flooding experiments were conducted according to repeat steps (1) to (3).

2.3.2 simulated reservoir model experiment

(1) The preparation process of the 3D simulation reservoir model was consistent with step (1) recorded in section 2.3.1. Injected oil into 3D simulation reservoir model at an injection rate of 20 $mL\cdot min^{-1}$. The oil was injected from the injection well, and the saturation oil process was completed when the production well produced uniform oil flow.

(2) In order to simulate the high water-cut reservoir in the later stage of heavy oil displacement, after saturated oil, water flooding was first carried out. When the water saturation of produced fluid reached 89%, it was deemed that the model had entered the later stage of development with high water-cut, and the CO_2 foam flooding was conducted.

(3) In the process of CO_2 foam flooding, the CO_2 foam with different quality was injected into the 3D simulation reservoir model at an injection rate of 18 $mL\cdot min^{-1}$. When the water saturation in the production fluid of the four production wells exceeded 98%, the experiment was stopped.

(3) The gas saturation of produced liquid, apparent viscosity of produced oil, water consumption for CO_2 storage, and mobility reduction coefficient in the process of CO_2 foam flooding were recorded, respectively. Then, the quality of CO_2 foam was changed and repeated steps (1) - (3).

3. RESULT AND DISCUSSION

3.1 Effect of different foam quality and sandpack model permeability on CO_2 storage efficiency

The oil displacement experiment parameters of sandpack model under different foam quality were reflected in Table 1.

The sandpack model experiments with different permeability were conducted. The permeability

Table. 1 Parameters of sandpack model experiments

(a. Parameters of sandpack model)

NO.	Porosity / (%)	Permeability / ($1\times10^{-3}\mu m^2$)
1	25.81	418.33
2	25.99	525.75
3	26.12	648.61
4	39.69	978.89
5	40.05	1154.76
6	39.54	865.74

(b. Injection parameters of CO_2 foam)

NO.	Foam quality / (%)	CO_2 injection rate / ($mL\cdot min^{-1}$)	Foaming agent injection rate / ($mL\cdot min^{-1}$)
1	50	1.00	1.00
2	65	1.50	0.75
3	80	1.60	0.40
4	50	1.00	1.00
5	65	1.50	0.75
6	50	1.00	1.00

modified from 418.33 × 10^{-3} μm² to 1154.76 × 10^{-3} μm², which covering both high permeability and low permeability. The quality of foam was changed from 50% to 80%. Foam quality was defined as the ratio of gas flow rate to the foam flow rate under certain pressure and temperature, as shown in equation (1). The high quality foam was generally defined as foam quality ⩾ 80%[15]. The foam quality was calculated according to the injection rate of CO_2 and foaming agent, as exhibited in Table 1.

$$f_g = \frac{q_g}{q_g + q_s} \times 100\% = \frac{q_g}{q_f} \times 100\% \qquad (1)$$

3.1.1 Influence of foam quality on CO_2 storage

The CO_2 storage efficiency was measured by calculating the average gas saturation in the sandpack model during CO_2 foam flooding. The calculation formula for the average gas saturation was shown in equation (2).

$$S_g = \frac{W_i - W_f}{(\rho_{oil} - \rho_{CO2})V_p} \times 100\% \qquad (2)$$

The curve of gas saturation of sandpack model under different foam quality was declared in Fig.3.

The variation of gas saturation in the sandpack model under different foam quality was generally the same. With the injection of CO_2 foam, the curve of gas saturation first rise sharply, then slowed down, and finally reached a stable level. As demonstrated in the Fig.3, with the increase of foam quality, the time node for the sharp rise of gas saturation was advanced, and the efficiency of CO_2 storage increased. When the quality of foam reached 80%, the gas saturation of the sandpack model was the highest, reaching 81.86%. However, the time node for the sharp rise of gas saturation was no longer significantly advanced. This phenomenon indicated that with the increase of the foam quality, the CO_2 content in the foam was increased. The flow capacity of gas in the sandpack model was stronger than that of liquid, leading to the time node of the sharp rise of gas saturation advanced[16].

In conclusion, when the foam quality was 80%, the

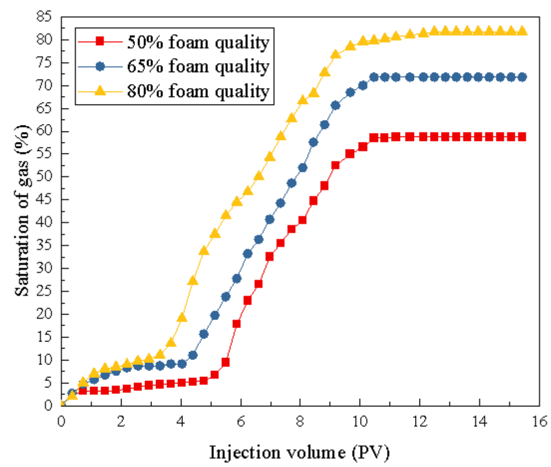


Fig. 3 Curve of gas saturation with PV injections in CO_2 foam flooding experiment under different foam quality

gas saturation in the sandpack model increased rapidly and reaches the maximum, the CO_2 storage efficiency was maximized, and the CO_2 was swept rapidly in the sandpack model. Therefore, the foam quality of 80% was regarded as the optimal foam quality for CO_2 storage.

In order to study the mechanism of gas saturation increased by CO_2 foam, the pressure gradient curve with foam quality in CO_2 foam flooding experiment under different PV injections was studied, as shown in Fig.4. The calculation method for pressure gradient was the pressure difference between the injection end and production end of the sandpack model divided by the length of the sandpack model, as reflected in equation (3):

$$\Delta P = \frac{\Delta p_f}{L} \qquad (3)$$

As clarified in Fig.4, with the foam quality increased from 50% to 80%, the pressure gradient was 2.63MPa·m^{-1}, 2.87 MPa·m^{-1}, and 3.26 MPa·m^{-1}, respectively. The flow resistance was influenced by foam quality. Specifically, with the increase of foam quality, the stability of foam increased, and the liquid discharge rate decreased, leading to the apparent viscosity of foam increased with the increase of foam quality. When the injection volume of CO_2 foam increased from 0 PV to 3 PV, the pressure gradient of sandpack model increased slowly under different foam quality. When the injection volume of CO_2 foam increased from 3 PV to 11 PV, the pressure gradient of sandpack model increased rapidly, with a significant trend. When the injection volume of CO_2 foam increased from 11 PV to 15 PV, the pressure gradient of sandpack model remained stable. When the foam quality was 80%, the pressure gradient reached the maximum value, which was 3.26 $MPa \cdot m^{-1}$.

In the process of CO_2 foam flowed in the sandpack model, the flow state of foam was different due to the different quality of foam, resulting in different plugging effect in channel with high permeability and low permeability. The plugging ability of high quality foam was very conducive to the storage of CO_2 in deep water cut reservoirs.

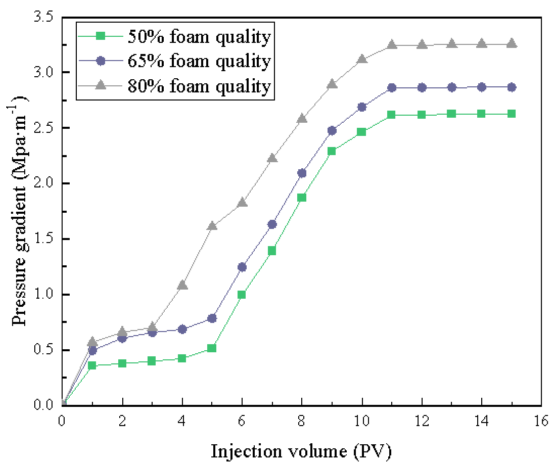


Fig. 4 Curve of pressure gradient with foam quality in CO_2 foam flooding experiment under different PV injections

3.1.2 Influence of sandpack model permeability on CO_2 storage and oil recovery

The research in section 3.1.1 manifested that the CO_2 storage capacity in the water cur reservoir was effectively improved. In addition to the foam quality, permeability of sandpack model was also an extremely important factor affecting the CO_2 storage capacity. The pore structure of the formation reflected by permeability, which can not only have a significant impact on the generation and aggregation of foam, but also affect the number and size of foam. When the permeability was too low, the large capillary force was generated, reducing the stability of foam. When the permeability was too high, the pore throat of formation was too large, reducing the plugging effect of foam. Therefore, selecting an appropriate formation permeability was important for improving CO_2 storage efficiency.

Oil recovery was an important indicator to reflect the improvement of oil displacement, and the gas saturation of sandpack model was the most intuitive indicator to measure CO_2 storage efficiency[17]. The curve of gas saturation during CO_2 foam flooding under different sandpack model permeability was shown in Fig.5.

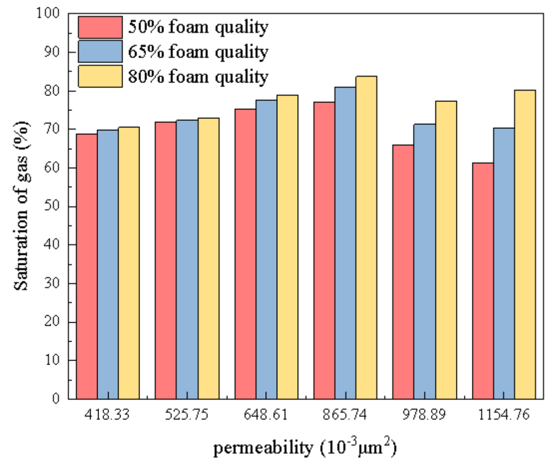


Fig. 5 Curve of pressure gradient with foam quality in CO_2 foam flooding experiment under different PV injections

As demonstrated in Fig.5, as the permeability increased, the gas saturation first increased and then decreased. In addition, with the increase of permeability, the improvement effect of high quality foam on gas saturation gradually increased, indicating that the high permeability channel was plugged by CO_2 foam. When the permeability was 865.74×10^{-3} μm^2 and the foam quality was 80%, the gas saturation increased to the maximum value, reaching 83.74%. When the permeability increased from 418.33×10^{-3} μm^2 to 865.74×10^{-3} μm^2, the permeability was low and the capillary force was large, causing the CO_2 foam to be in an unstable state, and the plugging effect of CO_2 foam was greatly weakened. As the permeability of the sandpack model increased, the CO_2 foam gradually stabilized, the mobility control ability increased, and the gas saturation increased. When the sandpack permeability increased from 865.74×10^{-3} μm^2 to 1154.76×10^{-3} μm^2, the capillary force decreased, the seepage resistance of CO_2 foam decreased, and the plugging effect of CO_2 foam decreased, leading to the decrease of gas saturation, which eventually reduced to 61.41%.

Comparing the gas saturation of sandpack model under different permeability, it was found that they all exceeded 60%, which fully proved that in high water cut reservoirs with medium and high permeability, the CO_2 was effectively stored by high quality foam, and the carbon neutrality was achieved.

The oil recovery under the influence of permeability was shown in Fig.6.

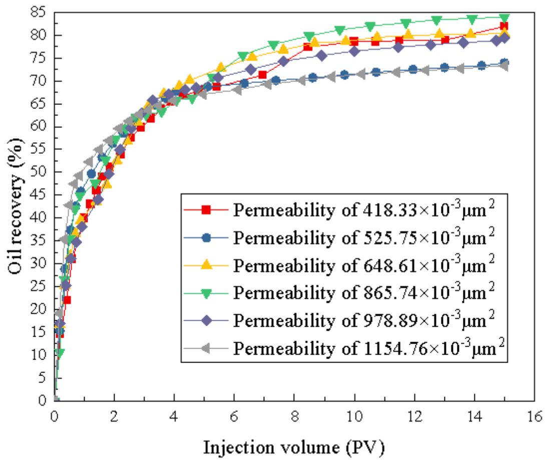


Fig. 6 Curve of oil recovery with the influence of permeability

The Fig.6 demonstrated that when the permeability was 865.74×10^{-3} μm^2, the oil recovery was the highest, reaching 83.94%. At the same time, the mobility control ability of CO_2 foam under this permeability was good, the swept volume of foam was high, and more residual oil was produced.

3.2 Study on real seepage process of CO_2 foam in 3D simulation reservoir model

In order to simulate real deep water cut reservoir, a 3D simulation reservoir model was developed. To explore the storage efficiency of CO_2 in oil reservoirs, in addition to quantifying changes in gas saturation, other parameter should also be researched. Among them, the mobility reduction coefficient reflected the mobility control ability of foam in the formation[19]. The water consumption for CO_2 storage reflected the water cost in the process of CO_2 storage[20]. Therefore, the study of gas saturation, mobility reduction coefficient, apparent viscosity and water consumption in the reservoir was of great significance for researching the CO_2 storage capacity improved by high quality foam.

3.2.1 Research on gas saturation change of high quality foam in 3D model

According to the result in Section 3.1, high quality CO_2 foam was more conducive to obtaining high gas saturation. Therefore, in the process of CO_2 foam flooding in 3D simulation reservoir model, foam with quality of 80% was selected for displacement. The gas saturation and oil recovery were shown in Fig.7.

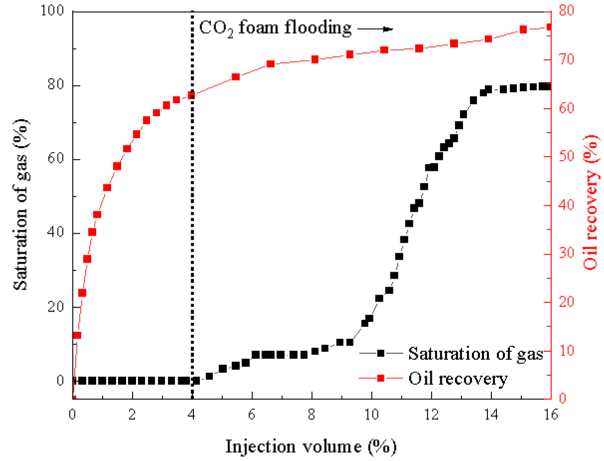


Fig. 7 Curve of oil recovery and saturate of gas in 3D simulated reservoir model experiment

In the experiment, the water flooding was first conducted. When the volume of injection fluid reached 4 PV, the CO_2 foam flooding was conducted. Fig.7 manifested that the plugging effect of CO_2 foam was good and the sweep range of foam was large. The oil recovery reached 79.68%, and the gas saturation was maintained at 76.76%, indicating a good CO_2 storage efficiency.

3.2.2 Research on mobility reduction coefficient during high quality foam flooding in 3D model

The mobility calculation was shown in equation (4):

$$M = \frac{k}{\mu_{\text{app}}} = \frac{(q_g + q_l)L}{\Delta p_f \pi r^2} \tag{4}$$

The change of foam mobility with fluid injection amount under different foam quality was exhibited in Fig.8.

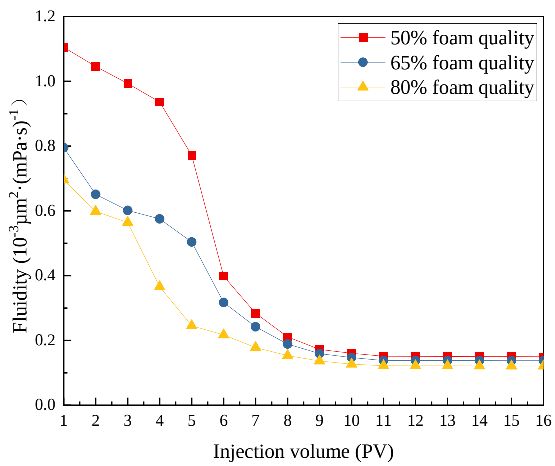


Fig. 8 Curve of fluidity under different foam quality

The mobility of foam presented a three-stage change of slow decline, rapid decline, and then slow decline. When the foam injection volume increased from 0 PV to

5 PV, the mobility of fluid decreased slightly, foam was constantly flowing into the model, and the plugging effect of foam was increased. When the foam injection volume increased from 5 PV to 10 PV, the mobility of fluid significantly decreased and gradually reached a stable state, and foam produced a good plugging effect in the model. When the foam injection volume increased from 10 PV to 16 PV, the mobility and the sweep range of fluid reached a stable state. The flow control effect was the best when the foam quality was 80%, and the fluid mobility decreased to 0.12×10^{-3} $\mu m^2\cdot(mPa\cdot s)^{-1}$. The appropriate capillary force and apparent viscosity in the pores were formed, resulting in the plugging effect and stability of foam was optimal.

During the calculation of mobility reduction coefficient, this factor was defined as the ratio of pressure difference between injection end and production end of 3D model, as shown in equation (5).

$$MRC = \frac{\Delta p_f}{\Delta p_w} = \frac{\dfrac{q_f \mu_{app} L}{kA}}{\dfrac{q_l \mu_w L}{kA}} = \frac{\mu_{app}}{\mu_w} \qquad (5)$$

The variation of mobility reduction coefficient with fluid injection volume under different foam quality was displayed in Fig.9.

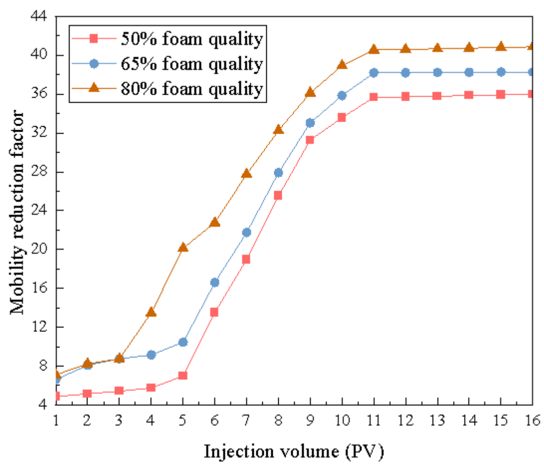


Fig. 9 Curve of mobility reduction factor with foam quality under different PV injections

The mobility reduction coefficient indicated the ability of foam flooding to generate resistance in the model. It was used to calculate the apparent viscosity of foam[21]. The apparent viscosity of foam affected by many factors, such as surfactant concentration, salinity, foam quality, pressure, temperature, shear rate and shear stress.

The apparent viscosity of CO_2 foam increased with the increase of model permeability. Moreover, the mobility difference under different model permeability decreased, basically in the same order of magnitude. This phenomenon was advantage to control the CO_2 mobility, improving CO_2 storage effect. With the foam quality increased from 50% to 80%, the mobility reduction coefficients were 35.95, 38.28 and 40.87 respectively.

3.2.3 Research on foam apparent viscosity during high quality foam flooding in 3D model

The formula for calculating foam apparent viscosity was shown in equation (6).

$$\mu_{app} = \mu_w MRC = \frac{\Delta p_f A k}{q_f L} \qquad (6)$$

Fig.10 illustrated the change curve of apparent viscosity of CO_2 foam with foam quality under different injected volume, and its trend was the same as the curve trend of mobility reduction coefficient.

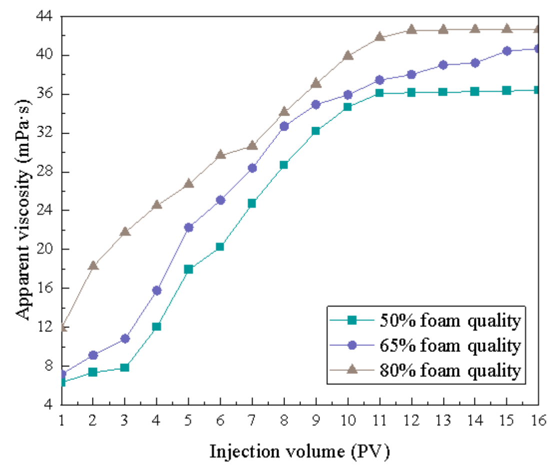


Fig. 10 Curve of apparent viscosity with foam quality under different PV injection conditions

When the injection volume increased from 1 PV to 11 PV, the apparent viscosity of foam with different quality increased rapidly and changed significantly. The foam was gradually swept in the model, and the plugging effect was reflected. When the injection volume increased from 11 PV to 15 PV, the apparent viscosity of foam remained stable. The maximum foam apparent viscosity reached 42.66 mPa·s. The apparent viscosity of foam increased as the quality of foam increased from 50% to 80%, indicating that foam has good mobility control ability, and has the ability to generate flow resistance in reservoir, which was benefit to CO_2 storage.

3.2.4 Research on water consumption of CO_2 storage by high quality foam in 3D model

The curve of gas saturation and water consumption for CO_2 storage during foam flooding with different quality was shown in Fig.11. The water consumption was defined as the amount of water required to store 1 mol of CO_2. The water consumption for CO_2 storage was calculated with the maximum gas saturation, and does not include the water in the surfactant solution during displacement, because the water in the surfactant can still generate foam with CO_2 in the later stage.

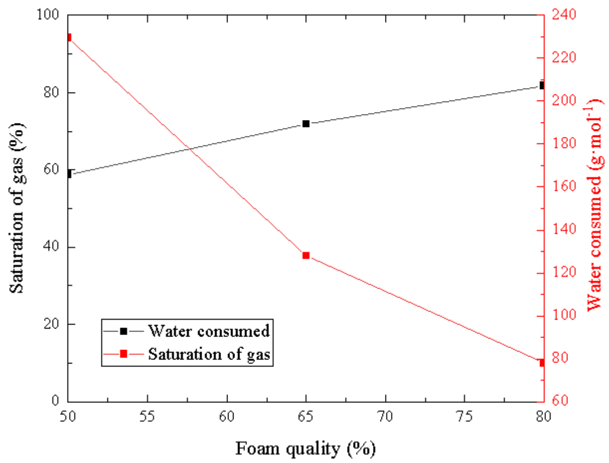


Fig. 11 Curve of water consumption for CO_2 storage and gas saturation of with foam quality

As the foam quality increased from 50% to 80%, the water consumption for CO_2 storage decreased to 229.41 $g\cdot mol^{-1}$, 128.02 $g\cdot mol^{-1}$ and 78.08 $g\cdot mol^{-1}$, respectively. With the foam quality increased, the proportion of CO2 in foam increased while the content of surfactant in foam continuously decreased, effectively reducing the water consumption for CO_2 storage. When the quality of foam was 80%, the gas saturation reached the peak, and the water consumption for CO_2 storage was at a low level. Therefore, 80% was determined as the best foam quality range. Under the action of high quality foam, the CO_2 storage efficiency was improved, the water consumption for CO_2 storage was significantly reduced, while achieving economic and environmental benefits.

4. CONCLUSIONS

(1) The result of sandpack model declared that the stability of high quality foam was strong, which was benefit to spreading in the formation. Under the action of high quality foam, the gas saturation increased to 81.86%, the pressure gradient reached to 3.26 $MPa\cdot m^{-1}$, Indicating the plugging ability of high quality foam was benefit to the storage of CO_2 in deep water cut reservoir. Additionally, the gas saturation under middle and high permeability sandpack model experiments were exceed 60%, which proved that the CO_2 was effectively stored in the water cut reservoir with middle and high permeability by the high quality foam.

(2) In the 3D simulation reservoir model experiment, as the fluid injection volume increased, the curve of gas saturation, mobility reduction coefficient, and apparent viscosity were reflected a slow upward process. When the quality of foam was 80%, the oil recovery increased to 79.68%, the gas saturation was maintained at 76.76%, the mobility reduction coefficient of fluid increased to 40.87, the apparent viscosity increased to 42.66 mPa·s. The experiment result represented that compared with pure CO_2 flooding, CO_2 foam flooding with high foam quality has good mobility control ability, which was conducive to CO_2 storage.

(3) With the increase of foam quality, the proportion of CO_2 in foam gradually increased, while the proportion of surfactant decreased, effectively reducing the water consumption for CO_2 storage. When the quality of foam was 80%, the gas saturation reached the peak, and the water consumption for CO_2 storage was at a low level, reaching 78.08 $g\cdot mol^{-1}$, achieving economic and environmental benefits.

ACKNOWLEDGEMENT

The authors appreciate the financial support of the National Nature Science Foundation of China (Grant No. U20B6003).

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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