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Characterization of CO_2 Sequestration and Enhanced Oil Recovery in Near-depleted Edge-Bottom Water Reservoirs

Zhi Liu[1,2], Jianchun Xu[1,2*]

1 Key Laboratory of Unconventional Oil & Gas Development(China University of Petroleum(East China)), Ministry of Education, Qingdao 266580, PR China

2 School of Petroleum Engineering, China University of Petroleum(East China), Qingdao 266580, PR China
(*Corresponding Author: 20170048@upc.edu.cn)

ABSTRACT

Geological sequestration sites for CO_2 include depleted oil and gas reservoirs, deep aquifers, coal seams and deep-sea strata, etc. Among them, near-depleted oil and gas reservoirs are ideal sites for long-term CO_2 storage due to complete and safe trap closure and clear understanding. As the production of typical edge-bottom water reservoirs entered the high water cut stage, it becomed more difficult to further increase the recovery rate in conventional water drive development. We investigated the control factors of the CO_2 enhanced oil recovery and storage. Firstly, the typical characteristics of the reservoir were extracted to establish a conceptual model for numerical simulation and fit the reservoir production dynamics. We have studied the modes of CO_2 enhanced oil recovery (EOR), including water drive, gas drive, gas-top drive, water alternating gas (WAG) and bi-directional drive. The highest recovery was obtained with 39.04% for the bi-directional drive. Different injection pressures were then tested, combined with recovery and storage, we controlled the injection pressure close to the initial reservoir pressure at 14,000 kPa. Secondly, we have analysed the characteristics of the storage stage, including reservoir pressure maintenance and injection rates. It was assumed that the reservoir fracture pressure was 1.4 times the initial pressure, beyond which the CO2 would leak. The maximum storage weight obtained in this case is 25.683 million tonnes. Meanwhile, the slower the injection rate, the more CO_2 can be stored. We proposed a production scheme for near-depleted edge-bottom water reservoirs and analyzed the main parameters for CO_2 storage, providing some guidance for the siting and development of similar reservoirs.

Keywords: CO_2 storage; CO_2-EOR; Near-depleted edge-bottom water reservoir; Numerical simulation

NONMENCLATURE

Abbreviations	
CCUS	CO_2 capture, utilization and storage
EOR	Enhanced oil recovery
WAG	Water alternating gas
Symbols	
bbl/d	Barrel per day

1. INTRODUCTION

The concentration of CO_2 in the atmosphere has increased over the last few decades due to the burning of fossil fuels[1]. Many countries are increasingly focusing on CO_2 capture, utilization and storage(CCUS) to mitigate climate change[2]. There is great potential for injecting CO_2 into reservoirs to enhance recovery and storage[3,4]. The Sleipner CO_2 injection project is the world's first industrial offshore CO_2 capture and storage project, injecting more than 16 million tonnes of CO_2 in the 20 years since 1996[5]. The Weyburn project in Canada went through a series of water-driven developments before maintaining production at 15,000 bbls/d in 1990. This was followed by the injection of CO_2, which increased production up to 25,000 bbl/d. It has been a very successful field and research project[6]. The In Salah project in Algeria is an industrial-scale CO_2 storage project that has been in operation since 2004. Over the lifetime of the project, up to 17 million tonnes of CO_2 is planned to be stored. Monitoring of the injection has proven that there are no CO_2 leaks from the

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project[7]. In addition, there are a growing number of CO_2 storage facilities around the world.

In addition to the projects already underway, many researchers have been working on CO_2 enhanced oil recovery (EOR) and storage. Ampomah et al.[8] presented an optimization methodology for CO_2 enhanced oil recovery in partially depleted reservoirs. An optimization approach consisting of a proxy or surrogate model was constructed with a polynomial response surface method.The prediction outcome suggested robustness and reliability of the genetic algorithm for optimizing both oil recovery and CO_2 storage. Bachu et al.[9] devoloped a methodology for the identification and screening of oil reservoirs that are suitable for CO_2 flooding and for estimating their CO_2 sequestration capacity at depletion, as well as under enhanced oil recovery. Liang et al.[10] aimed at assessing the potential of CO_2 EOR and storage in three large oil fields based on the data of 183 mature oil reservoirs in the Shengli Oilfield area. They also analysed the reservoirs that are suitable for future CO_2-EOR and storage respectively. Rezk et al.[11] conducted a series of core flooding experiments at reservoir conditions using horizontal and vertical systems. The ultimate recovery factor was significantly improved by increasing the CO_2 injection rate.

In summary, CO_2-EOR has been applied widely, but enhanced recovery in near-depleted reservoirs followed by storage in the depleted stage still requires comprehensive research. The paper is organized as follows. First, we built a conceptual model based on data from typical edge-bottom water reservoirs. Then we analysed the EOR models and the effect of injection pressure on recovery. Finally we investigate the effect of reservoir pressure maintenance and injection rate on storage.

2. METHODS AND NUMERICAL MODELS

2.1 Mechanisms of CO_2-EOR and storage

We conducted a numerical simulation in a near-depleted edge-bottom water reservoir. Near-depleted reservoirs can use CO_2 flooding to further enhanced recovery, while strong edge-bottom water reservoirs are also ideal site for CO_2 storage. We have mainly considered the following mechanisms for CO_2-EOR and storage:

(1) Mechanism of CO_2-EOR

The CO_2 injected into the reservoir is able to sufficiently swell and decrease the viscosity of the crude oil. The residual oil can be removed from the porous medium either by direct contact with the CO_2 or by water diffusion. Potential applications for injecting CO_2 into near-depleted reservoirs also include enhanced recovery through simple reservoir repressurisation[12].

(2) Mechanism of CO_2 storage

CO_2 storage mechanisms in reservoirs include gaseous based storage, liquid form based storage and hydrodynamic storage. Owing to the caprocks and structural traps, gaseous or supercritical CO_2 cannot easily migrate to the ground in the formation to be stored for a long time. The CO_2 storage mechanism in edge-bottom water reservoirs is mainly carried out by dissolution of the injected CO_2, a method with good stability[13]. Due to the low mineralisation of the reservoir, mineralised storage is not considered in our study.

2.2 Reservoir descriptions

In this study we have attempted to develop a numerical model that has the typical characteristics of the selected edge-bottom water reservoir. The CMG numerical simulation software was developed by the Canadian Computer Modelling Group ltd. and is capable of simulating the transport, physicochemical processes of oil, gas and water in the subsurface under a variety of complex geological conditions. All our simulations are carried out by CMG-GEM simulator.

We have developed a reservoir grid of 30 × 23 × 12, with a size of 1,200 m × 920 m × 200 m and a stratigraphic dip of 9°. Fig. 1 shows the distribution of the initial water saturation of the reservoir. The other model input parameters are shown in Table 1.

We selected typical edge-bottom water reservoir characteristics to develop a conceptual model. The reservoir has a porosity of 0.3 and a permeability of 800 mD. The top depth is 1,400 m, the oil layer is 100 m thick and the bottom is a water layer with another 20 times of edge water. The reservoir has an initial pressure of 14,000 kPa and an initial temperature of 55 ℃.

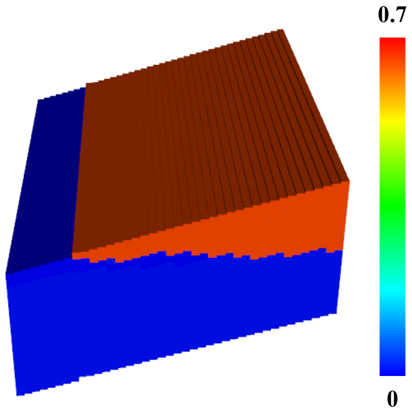

Fig. 1. Distribution of the initial water saturation of the reservoir

Table 1. Model Input Parameters for the Reservoir

Parameter	Value	Unit
Top of reservoir	1400	M
Reservoir temp	55	℃
Reservoir pressure	14000	kPa
Initial water saturation	0.35	
Compressibility	5.8e-7	1/kPa
Permeability	800	mD
Porosity	0.3	
Oil thickness	100	m

The reservoir was developed from 1980 and in 1985 it began to be explored by water flooding, with a production history up to 2015. At the end of the simulated production, the water cut of the produced fluid was 90.5% and the oil recovery was 31%. Reservoir pressure changed to 12,000 kPa. We are working on a study of enhanced recovery and storage in this field by CO_2.

3. RESULTS AND DISCUSSION

3.1 Analysis of CO_2-EOR in near-depleted edge-bottom water reservoir

3.1.1 Injection modes

For high water cut reservoirs, we first investigated different injection modes to obtain the maximum recovery rate. Fig. 2 shows the quantitative characterisation of the recovery after 10 years for different injection modes, including water drive, gas drive, gas-cap drive, water alternating gas (WAG) injection and bi-directional drive with the injection of gas at the top and water at the bottom. The 5 modes maintain the same injection pressure of 16,800 kPa for 10 years. And Fig. 3 shows the distribution of oil saturation for the five different injection modes.

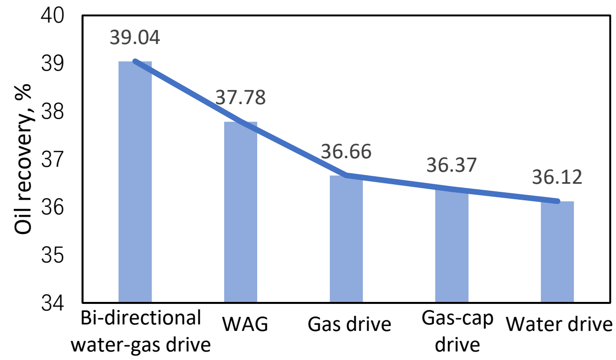

Fig. 2. Total recovery for different injection modes

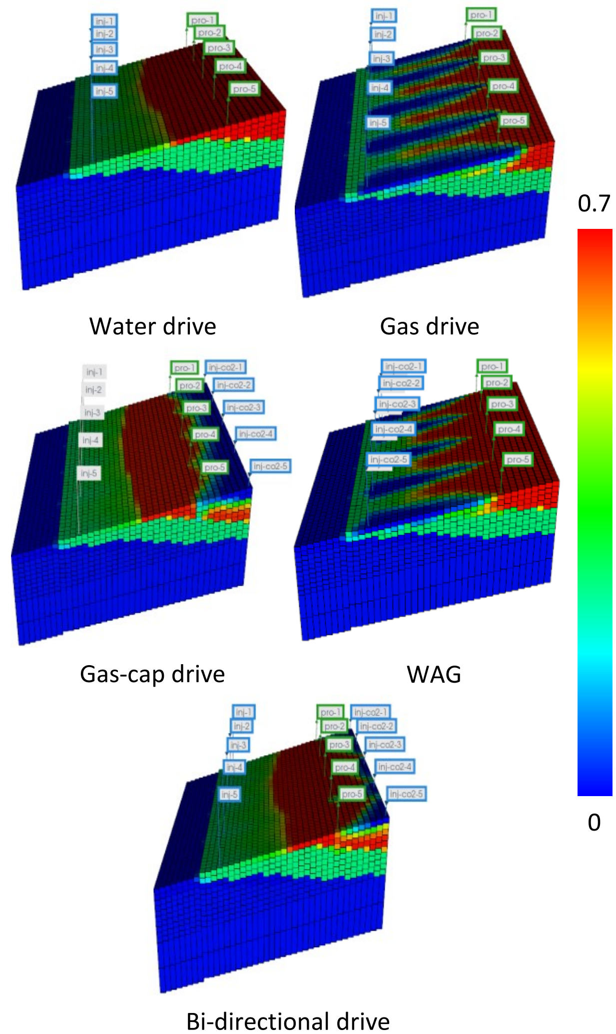

Fig. 3. Distribution of oil saturation in 2025

As expected, water drives, as a method of enhanced recovery, had the lowest recovery rates at 36.12% in the high water-cut reservoir. Therefore it is essential to change the injection mode to improve the recovery rate. The injection modes that were more effective than water drive were gas-cap drive and gas drive. Gas flooding performed better in improvement of the microscopic sweeping efficiency. However, due to the significant density and viscosity differences between oil and gas, continuous gas injection typically exhibited poor volumetric sweeping efficiency because of instability and gravity separation at the fluid leading front. The distribution of the oil saturation showed that gas injected either from the top or the bottom will move along the cap. CO_2 transport in the subsurface tended to form dominant channels, resulting in smaller swept areas. The water alternating gas injection had enhanced recovery substantially at 37.78%. During the WAG process, a significant increase in swept volume could be observed and the fluctuating pressure was able to push more gas into the smaller pores and expel the oil. The water phase reduced the relative permeability of the reservoir gas and improved the overall sweeping efficiency. Of all the EOR methods, the bi-directional drive achieved the best performance at a recovery of 39.04%. By injecting gas at the top and water at the bottom, the pressure was applied in both directions to keep the oil layer in the middle. We could see that water flooding and gas injection stabilised the fluid front interface. The bi-directional drive had the most stable oil layer and was able to maintain long-term production.

3.1.2 Injection pressure

Once a bi-directional injection had been determined, we investigated the effect of injection pressure on the oil recovery. The injection pressures were set at 12,600 kPa, 14,000 kPa, 15,400 kPa and 16,800 kPa respectively and Fig. 4 shows the recovery rates at different injection pressures.

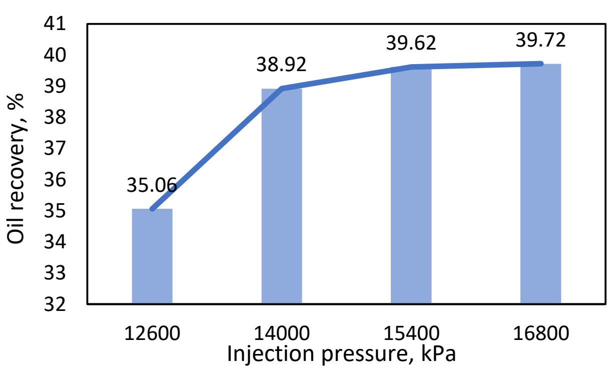

Fig. 4. Total recovery for different injection pressures

The maximum increase in recovery was 3.86% when the injection pressure was increased from 12,600 kPa to 14,000 kPa, increasing to 38.92%. At this point the pressure was restored to the initial reservoir pressure. The curve shows that increasing the pressure again will only increase the recovery by a small amount to 39.72%. The reason is that at higher pressures can also lead to produce more gas from the production wells, reducing crude oil production. Neither could it provide enough pressure difference for injection at the storage stage. Taking the EOR and storage stages together, keeping the injection pressure close to the initial reservoir pressure is the most effective.

3.2 Analysis of CO_2 storage in near-depleted edge-bottom water reservoir

3.2.1 Reservoir pressure maintenance

The efficiency of CO_2 storage should also be considered when the reservoir is in the depleted stage. Reservoir pressure is one of the most important parameters affecting CO_2 storage[14]. We studied the effect of reservoir pressure maintenance on CO_2 storage after 10 years of bi-directional injection in the reservoir.

We continue to inject gas for another 30 years and Fig. 5 shows the cumulative gas injection weight for different pressure maintenance from 1 time initial reservoir pressure to 1.4 times initial reservoir pressure.

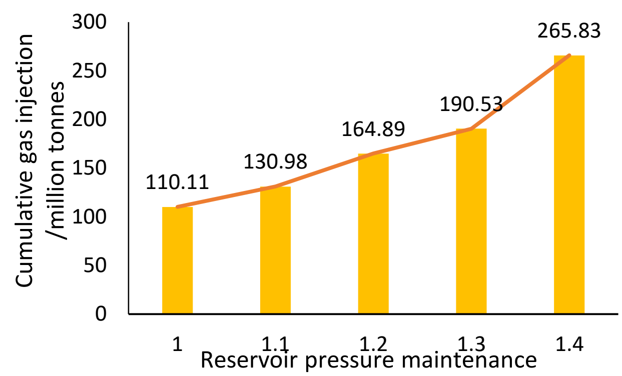

Fig. 5.Cumulative gas injection for different pressure maintenance

In terms of cumulative gas injection weight for different pressure maintenance, we can see that the pressure has a significant effect on storage. The storage weight to maintain the initial reservoir pressure was 110.11 million tonnes. And pressures maintenance from 1.1 times to 1.4 times the initial reservoir pressure, with cumulative storage weight was increased from 1.19 times to 2.41 times. The storage weight provided by increased pressure maintenance is increasing. This is because the increased pressure facilitates multiple mechanisms to promote storage. Physically, on the one hand, the increased pressure compresses the fluid, making the volume of injected CO_2 smaller. On the other hand, it also compresses the rock, allowing more space to store the CO_2. Moreover the solubility of CO_2 in fluids is also pressure dependent, with greater solubility at higher pressures also allowing more CO_2 to be injected into the reservoir.

However, the pressure in a reservoir cannot be increased indefinitely and pressure management also needs to be considered[15]. Based on the stratigraphic characteristics, we have created a closed fracture in the cantre of the conceptual model. And the fracture will open when the pressure greater than 1.4 times the initial reservoir pressure. Fig. 6 shows the distribution of gas saturation of CO_2 leakage. When the reservoir pressure did not reach the fracture pressure, all the gas was preserved below the cap and no leakage occurred due to the shielding effect of the cap. When the pressure was greater than the fracture pressure, the gas injection process would be accompanied by gas leakage from the fracture. The gas leaked over a larger area as time went on. The increased pressure can also be associated with other stratigraphic influences, so the injection process should be carried out at a safe pressure.

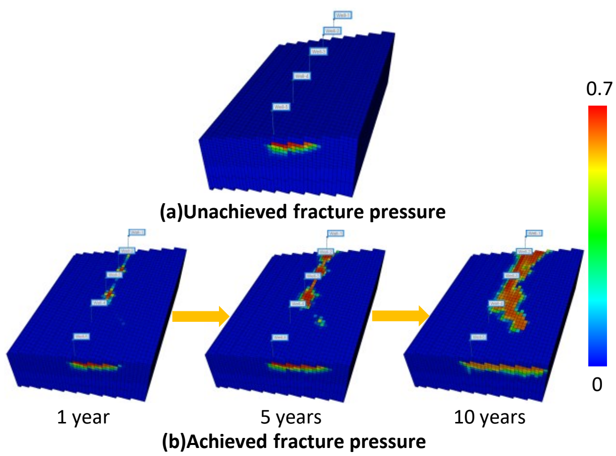

Fig. 6. Distribution of gas saturation of CO_2 leakage

3.2.2 Injection rates

In addition to pressure maintenance, the injection rate is also an important factor that affects the storage weight. The first 10 years of the injection stage was the EOR stage, followed by 8 years of simultaneous top and bottom gas injection. After a sufficiently large gas top was formed, gas was only injected from the bottom. We set the injection rates at 75,000 m^3/d, 150,000 m^3/d, 22,500 m^3/d and 30,000 m^3/d respectively. Fig. 7 shows the variation of the storage weight at different injection rates.

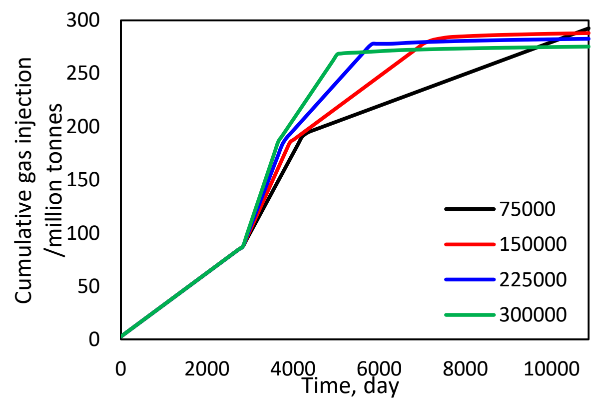

Fig. 7. Curves of storage weight at different injection rates

Based on the curves, we can see that the higher the injection rate, the earlier the upper limit of storage weight was reached. The cumulative storage weight for an injection rate of 300,000 m^3/d was 285.24 million tonnes. We continued to decrease the injection rate, the later it reached the reservoir storage limit. Keeping the injection for a longer period of time facilitated pressure diffusion and CO_2 dissolution, therefore maximising the final storage weight. Even we could observe that when the injection rate was 75,000 m3/d, the cumulative injection for 30 years was a maximum of 292.42 million tonnes, which did not yet reach the upper limit of the reservoir.

4. CONCLUSIONS

In this study, numerical simulations were used to investigate the CO_2-EOR and storage in near-depleted edge-bottom water reservoirs.

Firstly we selected the characteristics of a typical near-depleted edge-bottom water reservoir to build a conceptual model and match the history.

Secondly, in the CO_2-EOR stage, maintaining the same injection pressure, we compared each of the five EOR methods, including water drive, gas drive, gas-cap drive, WAG and bi-directional drive. The bi-directional drive has the highest recovery rate of 39.04%. Then we analysed the effect of injection pressure. As it was important to achieve the maximum possible recovery and to increase the storage weight, keeping the injection pressure close to the initial reservoir pressure gave the best result.

Lastly, there is the analysis of CO_2 sequestration. The most influential injection factor was reservoir pressure maintenance. The higher the pressure, the more the reservoir was stored. However, increasing the injection pressure should take into account safety. Finally the effect of injection rate on storage is also analysed. Large injection rates achieved the upper storage limit more quickly, but with less cumulative storage. Smaller rates were able to store more CO_2.

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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