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Recovery Potential and Mechanism Investigation of the Supercritical CO_2 EOR in the Bakken Tight Formation

Sai Wang, Juan Han, Yanbo Wang, Kegang Ling, Bao Jia, University of North Dakota;
Hongsheng Wang, Virginia Tech;
Yifu Long, Missouri University of Science and Technology

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Abstract

The low recovery of oil from the tight liquid-rich formations is still a main challenge for the tight reservoir. Thus, in order to break the chains and remove the obstacle such as the low recovery factor in the Bakken tight formation, even though the horizontal drilling and hydraulic fracturing technologies were already well applied in this field, the supercritical CO_2 flooding was proposed as an immense potential recovery method for the production improvement.

In this research, we conducted a series of CO_2 flooding experiments under various injection pressure (2500psi, 2800psi, 3000psi, 3500psi), to investigate the recovery potential of the core sample from Bakken tight formation. Also, the NMR analysis was processed of the core samples flooded with CO_2 agent under the above injection pressure variables. The result comparison demonstrates that, with the supercritical CO_2 injection pressure increase, the recovery factor gets incremental trend from 8.8% up to 33% recovery. Also, the macro pore and natural fracture system were proved to contribute more on the recovery potential. After reaching the miscible phase between the CO_2 and oil in the sample, the hydrocarbon existed in the micro pores start the contribution to the recovery potential. Thus, The CO_2 was identified as a potential recovery agent and the supercritical CO_2 EOR method was proposed as the potential recovery technology due to the high recovery factor obtained in the immiscible and miscible processes.

Introduction

The Bakken formation is currently one of the largest unconventional reservoirs in the world. According to the US Geological Survey in 2013, the oil and gas system has 7.4 billion barrels of recoverable reserves[1,2]. However, the primary recovery of the Bakken reservoir is still less than 10% even though the advanced technologies such as horizontal well and hydraulic fracturing applied[3]. Compared to its rich and dense oil reserves, Bakken reservoir development and enhanced oil recovery technology has great potential, thus the gas injection has become a domestic and foreign scholar actively explored content. Improving oil recovery is the constant pursuit of oil and gas field development[4,5]. The technology of enhancing oil recovery by gas injection brings new development methods for fulfilling this purpose. Carbon dioxide is a good candidate for the type of gas injection. Carbon dioxide injected into the formation can affect the properties of crude oil and improve oil recovery[6]. In tight Bakken reservoirs with extremely low permeability, carbon dioxide injection to develop tight oils may be the most effective method for enhanced oil recovery[7]. Previous studies have shown that the factors that contribute to the improvement of oil recovery during the contact between carbon dioxide and tight oil include reducing the viscosity of crude oil, improving the fluidity ratio of crude oil to water, reducing the interfacial tension between oil and water, volume expansion of crude oil, and light components extraction, molecular diffusion, dissolved gas flooding, mixed phase effects, and improved formation permeability, etc[8,9]. At the same time, a large amount of carbon dioxide injected into the ground can alleviate the greenhouses effect that are currently plaguing the world.

In recent years, the use of carbon dioxide to develop tight oil has been supported by many American researchers and scholars. They evaluated and analyzed the CO_2 enhanced oil recovery of tight oil injection from the perspective of experiments and numerical simulations. In terms of experiments, the tight oil core displacement experiments conducted by Gamadi[10] mainly showed that, the enhanced oil recovery factor can be improved by ranging from 33% to 85%. In terms of numerical simulation, Sorensen[11] have found that by injecting carbon dioxide, the oil production can be increased by 43% to 58% by establishing various numerical simulation models. However, the numerical models used by the above scholars in the research process generally establish a homogeneous model that assigns the same value to the mesh porosity and permeability, or a heterogeneous model that assigns different values to different small-layer porosity and permeability. The above model does not meet the actual characteristics of the Bakken reservoir, so the simulation results are often too idealistic. In terms of the choice of injection medium, carbon dioxide can be mixed with dense oil under lower pressure conditions compared with other injection gases. Carbon dioxide is easier to prepare as a relatively stable gas, and there are quite abundant carbon dioxide gas reservoirs in the ground which is easy and economical to obtain. Considering the impact of current greenhouse gases on the global climate, the environmental benefits of using carbon dioxide as an injection medium are self-evident.

Nuclear magnetic resonance (NMR) is a phenomenon in which some nuclear nucleus with a spin magnetic moment absorbs electromagnetic waves of a specific frequency under an external magnetic field, thereby changing the energy state[12]. The nuclear magnetic resonance technology is widely applied in petroleum exploration and development field recently[13]. Through nuclear magnetic resonance testing of rock samples, the physical properties and fluid parameters of the formation such as reservoir permeability, porosity, oil saturation, percentage of movable fluid and mobile water saturation can be quickly obtained, which is benefit for the division, evaluation and identification of the effective reservoirs.

After the fluid (oil or water) is contained in the pores of the tight shale reservoir, the force between the fluid molecules and the surface of the pore solids is generated, and the strength of the force is related to the pore size, morphology, mineral composition, surface properties, fluid type and viscosity, etc. When performing nuclear magnetic resonance measurement on a core sample containing fluid (oil or water), the obtained T_2 spectrum indicates the pore size distribution inside the core[14]. Within the T_2 plot, the abscissa indicates the T_2 relaxation time, and the ordinate indicates the fluid component occupancy share of different T_2 relaxation times in the core. The T_2 relaxation time is characterized by the strength of the surface of the fluid molecule and the pore solid. The fluid in the tiny pore is strongly affected by the surface of the pore solid. The T_2 relaxation time of the fluid is small, and the fluid is in a restrained or immobile state. It is called a restraint fluid or a non-movable fluid[15]. The fluid in the larger pores is weakly affected by the surface of the pore solid, the T_2 relaxation time of the fluid is large, and the fluid is in a free or movable state, called a free fluid or a movable fluid. Given the T_2 cutoff at the T_2 spectrum, the fluid in the right pore of the T_2 cutoff is a movable fluid, and the fluid in the left pore is a non-movable fluid, Through using the magnitude and distribution characteristics of the T_2 relaxation time in the nuclear magnetic resonance T_2 spectrum of the fluid in the rock sample, the state of the fluid in the pore can be analyzed.

In this research, we investigated the recovery potential of the supercritical CO_2 flooding process varied with different pressure range, which lead to the immiscible and miscible phase. The recovery factor was obtained and analysis. In order to verify the results got for the flooding process, the NMR T_2 spectrum were applied and interpreted in detail. Both of those two methods provides the strong support to the essential potential of the CO_2 EOR process.

Experimental Design

The rock samples from Middle Bakken formation (well file:16089) were obtained from the Core Laboratory at UND for the purpose of core flooding experiment analysis. The core plugs were cleaned using solvent in order to elute the organic materials in the pore and then settled into a vacuum oven over 72 hours for the purpose of drying out completely. Then, the cylindrical Bakken core plug was covered with copper sheeting in order to both form a gas-tight seal on the cylindrical wall of the sample and to apply radial confining pressure. The core plugs were evacuated and saturated with the crude oil from Middle Bakken for 15 days. In this procedure, the core plugs were evacuated for 2 hours and 3000 psi over burden pressure (OBP) was applied before starting the evacuation process. Then, the crude oil was injected at the specified low flow rate until the oil was visible at the outlet of the injection system. Keeping the oil injection operation dynamically for at least 15 days for fully saturated the core samples. In between, the core samples was released out and weighed several times and finally stop the oil injection process until the weight of the core sample reach the constant value. All the weight values, include the dry weights of all samples, the weight with the copper sheeting and the post-saturated weight of the core samples were recorded accurately, in order to obtain the accurate initial oil saturation.

The Vinci core flooding apparatus will be used for CO_2 flooding in this project (Fig. 1). The system can perform single and multiphase core flood studies at reservoir conditions. It allows the evaluation of critical parameters such as brine sensitivity, return permeability, critical flow velocity and various secondary and tertiary EOR methods, including water flooding, polymer injection, miscible and immiscible gas flooding, acid treatments and microbial flooding. Relative permeability at irreducible water saturation, residual oil saturation, displacement efficiency and incremental oil recovery after implementation of the EOR process, can be determined. The computer-controlled system is provided with a unique software that allows both manual and automated operation where all key components can be controlled including pumps, valves, video capturing and data acquisition. A test sequencer also permits automated elaborate test sequences. The core holder, air operated valves, produced fluid separator if selected and necessary plumbing are mounted in an isothermal convective air bath that has been designed to provide easy access to all main components. After the core plug is taken from core, it will be installed into the core holder and the overburden pressure will applied. Then the pump will supply the pressure source to maintain the constant CO_2 injection pressure through the core plug. The operating temperature will be set to assure that the CO_2 passing through core holder is in the super-critical phase or gas phase when the operating pressure is maintained at moderate to high pressure. The entire apparatus, except for the pumps, is contained in an air bath box to maintain a constant temperature throughout the experiment. The operation temperature was set as 40℃ (104°F) to make sure the CO_2 was under supercritical state. Fig. 2 shows the schematic diagram of the core flooding system. Through the CO_2 flooding process, under a series of injection pressure (2500psi, 2800psi, 3000psi, 3500psi), the final oil recovery vs. injected pore volume from the injection and production data and plots between injected super-critical CO_2 vs. oil recovery were generated.

Fig. 1 Vinci core-flood system to be used for CO_2 injection in Bakken shale samples

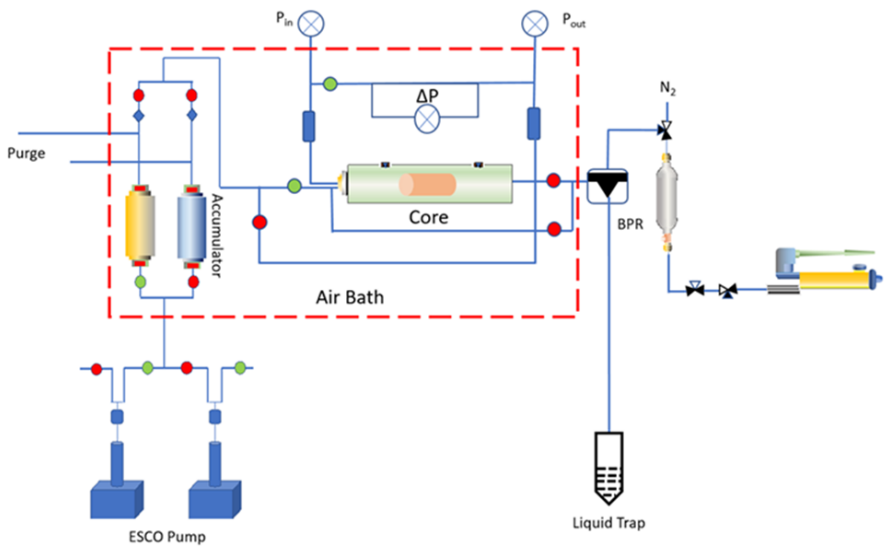

Fig. 2 Schematic diagram of the core flooding system[16].

It is critical to conduct the mechanisms investigation of the oil mobilization in the tight formation when the CO_2 enhanced oil recovery and carbon sequestration processed. After the core samples were flooded under the varied CO_2 injection pressure, the core was taken out from the core flooding system and conducted the NMR test immediately. In this work, the exposure behavior between the supercritical CO_2 and the core sample from Middle Bakken formation has been progressed experimentally by using nuclear magnetic resonance transverse relaxation time (NMR T_2) spectrum. Quantitative analysis of recovery at the pore scale was achieved. Effects of varies CO_2 injection pressure (2500psi, 2800psi, 3000psi, 3500 psi) on recovery performance have been investigated properly.

Result and Discussion

Under variable super critical CO_2 injection pressure range (2500 psi, 2800psi, 3000psi, 3500psi), the recovery potential for the core plug with the incremental injection volume of supercritical CO_2 were demonstrated in Fig.3. Based on the observation, with 6 PV of CO_2 continuously injected, the pressure was a primary factor which may give the positive effect on the recovery potential of the CO_2 flooding process. With the pressure increase, the recovery factor of core was increase from 8.9% to around 34% dramatically with the CO_2 injection pressure varied from 2500psi to 3500psi, which can be proved to be more beneficial for release the limitation of the low recovery factor in the Bakken formation. Under 2500psi, with the continuous injection of CO_2, the recovery factor was increase quickly and then trend to increase slowly then almost achieve the balance, which means not too much oil will be recovered. The main reason for this curve trend is due to the immiscible flooding process dominant. Immiscible CO_2 flooding was capable of mobilizing oil in the rock with very low permeability (0.16 mD). The injection pressure of CO_2 is below the minimum miscible pressure(MMP), which is around 2780 psi for the Middle Bakken formation, thus the CO_2 cannot penetrate into the matrix and extract the oil from the small pore. In this immiscible flooding process, the natural fracture and large pore were believed to dominate the recovery potential. Another factor may affect the recovery potential is the ability of oil extraction by supercritical CO_2.

Back to the high pressure range(2800psi, 3000psi, 3500psi), which are above the minimum miscible pressure, the recovery potential curve can be divided into three stages: 1) Before the 2PV of Supercritical CO_2 injection, the recovery factors for all pressure variables were observed rapid growth. In this stage, the produced oil was mainly from the natural fracture and pores with large size. 2) between 2 PV and 3PV of supercritical CO_2 injection, the recovery factors keep the minute increase or reach a transient equilibrium. The main reason for this phenomenon happened is that the major portion of the hydrocarbon from the natural fracture and large pore was extracted and produced, and the sweeping power of the CO_2 agent is not enough to extract the residual oil inside of the fractures and large pores, thus the maximum recovery potential of those two structures were touched. Another reason for the production delay may due to the time spend for the supercritical CO_2 penetrate into the pores with small size and start to dissolve the light components of the oil then reach the miscible phase. 3) Stage 3 is observed from the 3.5PV of CO_2 injection to the end of the injection process. In this stage, under all the injection pressure variables, the recovery factors start to increase again. The reason for this incremental trend of recovery factor is mainly due to the meso pores and the micro pores start to dominate the oil production. After contacting with the CO_2 for a certain time , the hydrocarbon fluids start to be dissolved out and then achieve the miscible phase, thus the oil begin to be produced under the pressure push energy.

We should notice that 6PV of supercritical CO_2 injection is not the end of the recovery potential increment. While considering the economic factors, the injection amount of the CO_2 should be evaluated properly.

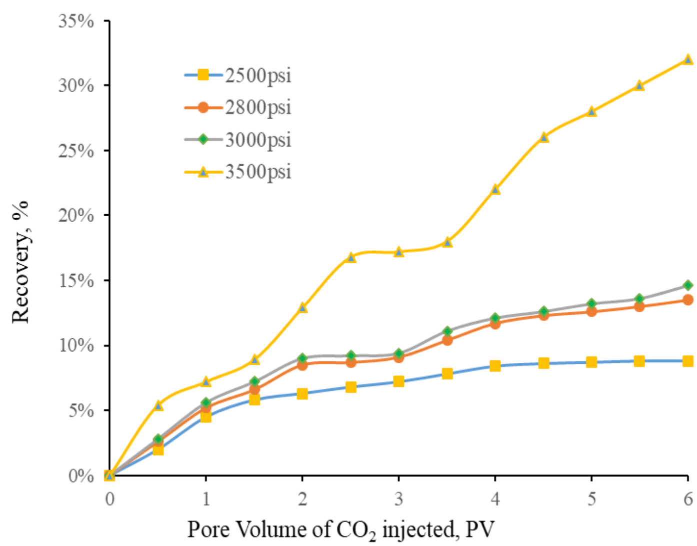

Fig. 3 Recovery potential vs. the PV of CO_2 injected, pressure range: 2500psi, 2800pis, 3000psi, 3500psi.

Fig. 4 reveals out a typical NMR T_2 spectrum of the sample from the Bakken formation. Generally, the integral area of the NMR T_2 spectra curve represents the pore fraction which hold the hydrocarbon, in other words, the oil saturation of the core sample. In the sample NMR T_2 spectra, two nanoid peak and a towering peak can be observed clearly. The towering peak can be converted and interpreted as the meso and macro pore distribution, the left weak peak stand for the micro pore existing. For the right peak in the T_2 spectrum, it is explained as the natural fracture appearance.

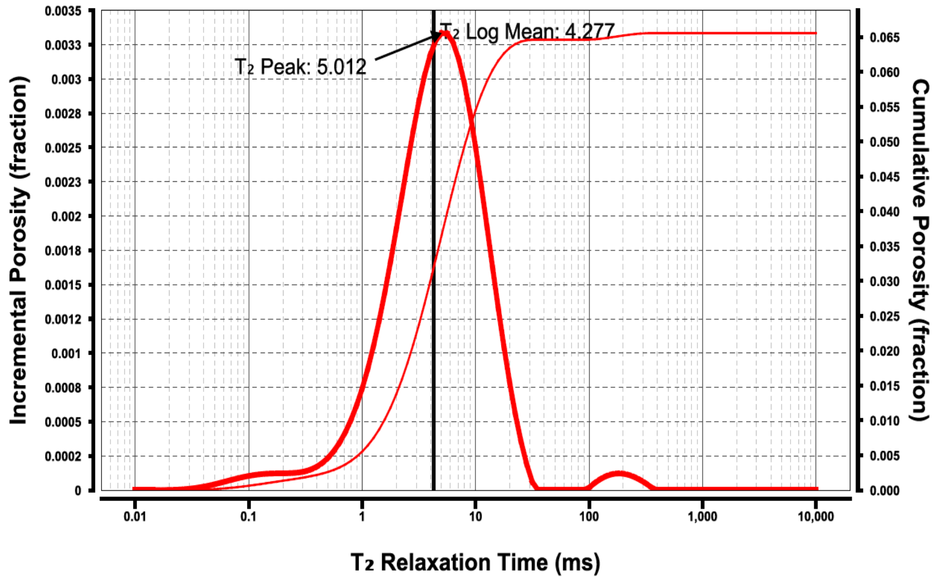

Fig. 4 Typical T_2 spectrum of the Middle Bakken Formation.

In order to interpret the NMR T_2 spectrum intuitively, the correlation conversion of NMR T_2 relaxation time and pore throat radius obtained for the N_2 gas adsorption were generated and applied[17].

T_2 can be rewritten as equation (1).

$$T_2 = Cr \tag{1}$$

Where,

C = 1/ (ρ Fs), and C is a constant conversion coefficient (ms/μ m).

Conversion coefficient C that scales relaxation time T_2 into average pore throat radius r is determined by a method mentioned by Saidian and Prasad[18]. Through this method, the conversion coefficient C of the Bakken formation is calculated to be 2.78 ms/μm.

Fig. 5 illustrates the NMR T_2 spectra of CO_2 flooding experiment under different CO_2 injection pressure. It can be stated that the hydrocarbon in all pores can be mobilized with the CO_2 flooding pressure increase. Note that the reduction of the incremental porosity(y axis) of the pores with radius larger than 0.3μm is greater than that of pores with radius small than 0.3μm. Hence, the recovery potential of the former pores is more effective and larger than the small pore size. With the CO_2 injection, the oil existing in the pores with radius greater than 0.3μm start to diffuse to the surface of the tight matrix gradually.

Also, the towering peak of each CO_2 injection pressure variables trend to shift to the left slightly. The explanation is that the oil in the larger pore size will be recovered firstly while the hydrocarbon still remained in the smaller size pores, Thus the T_2 spectra signal which shows the total residual oil in the pores will drift to the left.

As mentioned above, the weak peak in the right side of the NMR T_2 spectra represent the recovery character of the natural fracture in the core sample. It can be seen that the left shit phenomenon also occurred during the supercritical flooding process. Also, the peak values were observed to be increased, especially under the pressure of 3500psi. It indicated that the oil in the micro pores flows to the fracture. Generally , the fracture system in the core was deemed as the main fluid flow channel. Before achieving the miscible phase, the hydrocarbon was storage in the micro pores and keep immoveable. With the CO_2 flooding pressure increase, the miscible phase will be realized and thus the oil in the micro pores will be diffused out and pushed forward to the void space which is easy to flow into. The permeability of the natural fractures in the core is larger than that of other void space, thus the natural fracture has the priority for the oil access, which mainly contribute to the peak value increase.

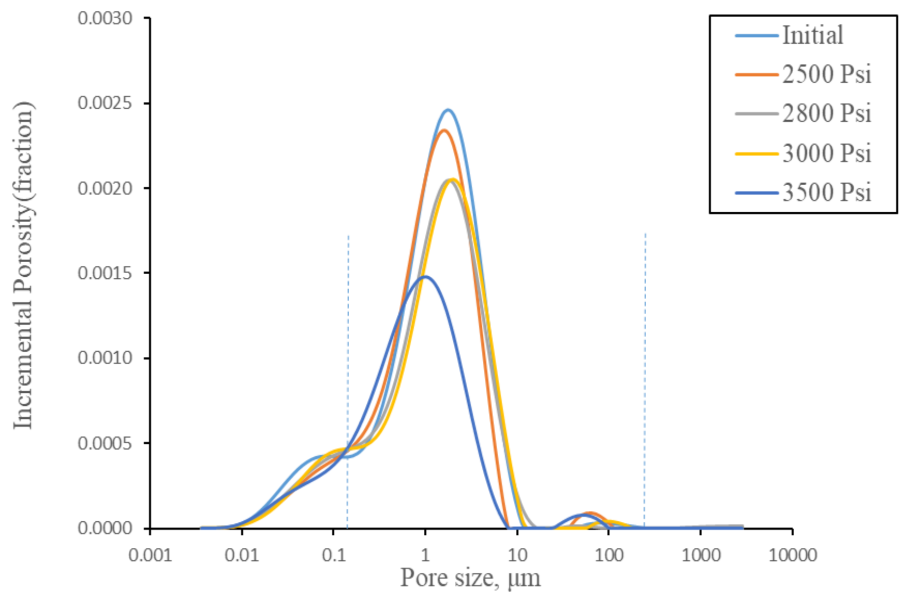

Fig. 5 NMR T_2 spectra of exposure experiment under different CO_2 injection pressure. Pressure range:2500psi, 2800psi, 3000psi, 3500psi

Table 1 Interpretation of the NMR T_2 Spectra

Initial oil saturation in the micro core	0.005187	Initial oil saturation in the macro pores and fracture		0.050784
	Pressure Range, psi			
	2500	**2800**	**3000**	**3500**
Residual oil saturation in the micro pores, fraction	0.004500	0.004238	0.004175	0.003881
Recovered oil volume from the micro pores by variable injection pressure	0.000687	0.000949	0.001012	0.001306
Recovery factor in the micro pore	0.132392	0.182911	0.195049	0.251765
Recovery factor in the total pore volume	0.012268	0.016950	0.018075	0.023330
Residual oil saturation in the macro pores and natural fractures, fraction	0.046223	0.044029	0.043873	0.032711
Recovered oil volume from the macro pores and fractures by variable injection pressure	0.004561	0.006756	0.006911	0.018073
Recovery factor in the macro pores and factures	0.089817	0.133028	0.136094	0.355881
Recovery factor in the total pore volume	0.081494	0.120701	0.123482	0.322902

Recoveries of oil in different pore size with CO_2 injection pressure variation are shown in Fig. 6. With the injection pressure increase, the recovery potential of the micro pore followed slowly increase trend. And the recovery factor from the micro pores was incremental from1.2% to 2.3% with the injection pressure increasing.

While in the macro pores and natural fractures, the recovery potential was observed to intend to effective augment with the CO_2 injection pressure increase. The recovery factor was identified as following an upward trend, which is from 8.9% to 35.6% with the supercritical CO_2 injection pressure increase.

Comparing the recovery potential from the micro pores and macro pores and natural fractures, the macro pores and natural fractures were proved to donate more contribution to the total recovery potential than that from the micro pores. The explanation may because of the different minimum mixture pressure between the two phases, the supercritical CO_2 and the oil fluid. In the macro pores and fractures with larger pore size, the MMP is relatively easy to achieve, which means the CO_2 phase and the oil phase are more comfortable to reach the miscible phase, thus the mixed fluid is easy to recovered. While in the micro pores whose pore throat is pretty small, the capillary pressure stayed in the high value. Hence the MMP is more difficulty to reach. Then the miscible phase is hard to achieve and further affect the recovery factor changed significantly.

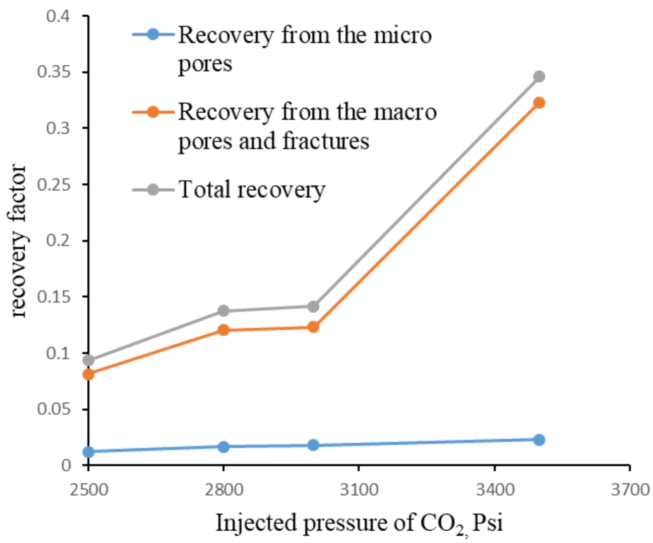

Fig. 6 Recovery weigh in different pore size. Pressure range:2500psi, 2800psi, 3000psi, 3500psi.

Fig. 7 represents the recovery potential obtained from the CO_2 flooding experiment and the NMR T_2 spectra for both of the cores. Compared with the recovery results between the flooding experiment and NMR T_2 spectra interpretation with carried injection pressure, the good match was obtain between the two curves, which demonstrated that the recovery results are reliable and accurate.

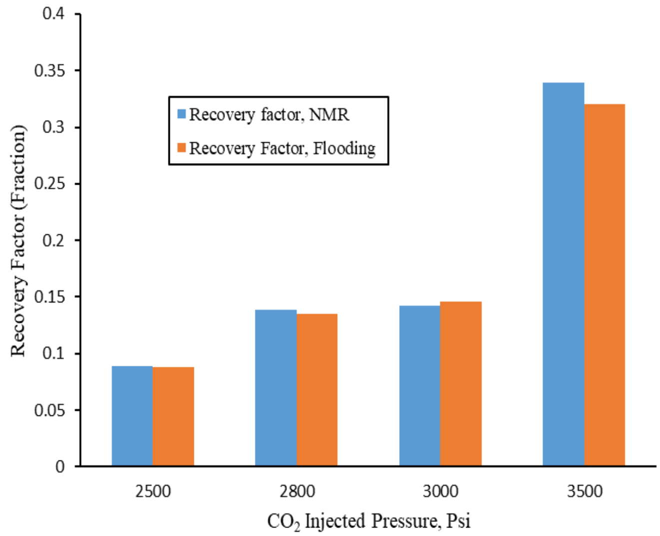

Fig. 7 Recovery factor comparison between NMR and flooding experiment. Pressure range: 2500 psi, 2800 psi, 3000 psi, 3500 psi.

Conclusions

Following conclusions can be drawn upon this study.

- A model coupling CO_2-water fractional flow in horizontal direction with CO_2-water segregation in vertical direction has been proposed. It can be used to simulate the performance of CO_2 sequestration in aquifer.
- The model indicates that CO_2 displacing water is not a piston-like displacement. CO_2 saturation at the displacement front is a function of fluid and rock properties. Behind the CO_2 front, CO_2 saturation increases gradually, and water saturation decreases accordingly until water saturation reaches irreducible water saturation.
- The propagation of CO_2 front is not linear to the injection time. its movement slows down as it moves away from injection well.
- For same radius, CO_2-water segregation causes higher CO_2 saturation at top of aquifer and low at the bottom of aquifer.
- Low vertical/horizontal permeability ratio can delay CO_2-water segregation, leads to a less severity of CO_2 overriding.

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