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A quick evaluation model for CO_2 flooding and sequestration

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Abstract: CO_2 flooding not only triggers an increase in oil production, but also reduces the amount of CO_2 released to the atmosphere (by storing it permanently in the formations). It is one of the best ways to use and store CO_2. This paper firstly selects the key factors after analyzing the factors influencing the CO_2 storage potential in the formations and oil recovery, and then introduces a series of dimensionless variables to describe reservoir characteristics. All influencing factors with varying values are calculated through a Box-Behnken experimental design. The results are interpreted by a response surface method, and then a quick screening model is obtained to evaluate the oil recovery and CO_2 storage potential for an oil reservoir. Based on the evaluation model, sensitivity analysis of each factor is carried out. Finally, research on CO_2 sequestration and flooding in a typical reservoir indicates that the evaluation model fits well with the numerical simulation, which proves that the evaluation model can provide criteria for screening attractive candidate reservoirs for CO_2 sequestration and flooding.

Key words: Evaluation model, enhanced oil recovery, CO_2 sequestration, Box-Behnken design, response surface method

1 Introduction

Due to the deterioration of the environment caused by global warming, China has to face even greater environmental challenges than before (Duan et al, 2004; Zeng et al, 2004). Effectively control and reduction of CO_2 emissions has become a hot topic, which urgently needs to be studied in depth (Qiang et al, 2006). Storing CO_2 permanently in deep strata by injecting it into reservoirs has been considered as a promising method (Bachu, 2000; Bachu and Stewart 2002; Bachu et al, 2007; Stevens et al, 2001; Winter, 2001; Li and Dong, 2006; Bradshaw et al, 2007). Firstly, the existence of natural CO_2 gas reservoirs proves that favorable geological structures can store CO_2 for a long time. Moreover, CO_2 flooding can improve oil recovery and then obtain greater economic benefits (Li et al, 2000; Xiong et al, 2001; Espie, 2003). When evaluating the suitability of reservoirs for CO_2 sequestration and flooding, the oil recovery and CO_2 utilization coefficient of the reservoir need to be used to make a wise decision. The oil recovery (expressed by R, fraction) is defined as the ratio between the oil production and the initial oil in place in the reservoir, and the CO_2 utilization coefficient (expressed by R_{CO_2}, t/m^3) is the ratio of the net injection amount of CO_2 to the volume of the oil produced (Bachu, 2003; Hendriks et al, 2004; Jiang and Shen, 2008; Shen et al, 2009). If the CO_2 utilization coefficient is known, it is convenient and useful for evaluating the potential of CO_2 sequestration.

There are many factors influencing CO_2 sequestration and oil displacement efficiency (Kovseek, 2003; Mo and Akervol, 2005; Wang et al, 2008; Zhang and Yang, 2008; Yao and Li, 2009). It is difficult to identify attractive candidate reservoirs for CO_2 flooding and sequestration. Therefore, it is necessary to establish an objective function considering a number of factors. A Box-Behnken design is used to evaluate the non-linear relationship between the objective function and factors (Ferreira et al, 2007). Moreover, compared with other methods for evaluating the non-linear relationship between objective function and factors, the Box-Behnken design is more efficient and requires only a few experiments to study the factors influencing CO_2 sequestration and flooding in complex reservoirs. A response surface method (Gao et al, 2004), which takes full advantage of mathematics and statistics, can be used to establish the functional relationship between the independent variables and objective values in complex experiments influenced by many factors. Wood et al (2006) introduced such dimensionless parameters as the effective aspect ratio, dip angle group, CO_2-oil mobility ratio, and buoyancy number to carry out a useful attempt in selecting attractive candidate reservoirs for CO_2 sequestration and flooding. They did not take into account the effect of reservoir heterogeneity. However, CO_2 sequestration and oil displacement efficiency is significantly influenced by reservoir heterogeneity.

In this paper, after analyzing all key factors affecting CO_2

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flooding and sequestration, we introduces such dimensionless parameters as the homogeneity coefficient, effective aspect ratio, CO_2-oil mobility ratio, buoyancy number, initial oil saturation, position parameters of high-permeability layers, injection pressure parameter, producing pressure parameter, reservoir pressure parameter and relative water body size to systematically characterize properties of CO_2 sequestration and oil displacement efficiency. Based on the Box-Behnken experimental design and the interpretative results from the response surface method, we derive a mathematical model for evaluating quickly carbon dioxide sequestration and displacement efficiency, which can provide criteria for identifying the attractive candidate reservoirs for CO_2 storage and oil displacement.

2 Analysis of factors affecting CO_2 flooding and sequestration

2.1 Evaluation indices for CO_2 flooding and sequestration

In the process of CO_2 injection to the reservoir, the oil recovery and CO_2 sequestration capacity are important. Consequently, the oil recovery (R) and CO_2 utilization coefficient (R_{co_2}) are introduced to characterize CO_2 flooding and sequestration, which can be expressed as follows:

$$R = \frac{N_p}{N} \times 100\% \tag{1}$$

$$R_{CO_2} = \frac{\rho_{CO_2} Q_{CO_2\text{-s}}}{NR} \tag{2}$$

with

$$Q_{CO_2\text{-S}} = N_{iCO_2} - N_{pCO_2} \tag{3}$$

$$\begin{aligned} N_{pCO_2} &= \int_0^{t_{shut}} Q_0 F_{CO_2\text{-o}}\, dt \\ &= \int_{t_{breakthrough}}^{t_{shut}} Q_0 F_{CO_2\text{-o}}\, dt \\ &= \int_{t_{breakthrough}}^{t_{shut}} Q_0 (F_{CO_2\text{+g-o}} - F_{go})\, dt \end{aligned} \tag{4}$$

$$N_{iCO_2} = \int_0^{t_{stop}} v_{CO_2}\, dt \tag{5}$$

where R is the oil recovery, fraction; N_p is the cumulative oil production, 10^4 m^3; N is the initial oil in place, 10^4 m^3; $Q_{CO_2\text{-s}}$ is the amount of CO_2 stored in the reservoir, $10^4 m^3$; N_{iCO_2} is the cumulative volume of CO_2 injected, $10^4 m^3$; N_{pCO_2} is the cumulative volume of CO_2 produced, 10^4 m^3; v_{CO_2} is the CO_2 injection rate, $10^4 m^3/a$; Q_0 is the oil production rate, $10^4 m^3/a$; F_{go} is the ratio of gas to oil in the hydrocarbons produced, m^3/m^3; $F_{CO_2\text{-o}}$ is the ratio of CO_2 produced to oil, m^3/m^3; $F_{CO_2\text{+g-o}}$ is the ratio of the volume of CO_2 and hydrocarbon gas produced to the volume of oil, m^3/m^3; $t_{breakthrough}$ is the CO_2 breakthrough time, a; t_{shut} is the production time required when the $F_{CO_2\text{-o}}$ of the production well reaches the controlling gas-oil ratio, which is defined as the maximum gas-oil ratio for normal operation; t_{stop} is the cumulative time of gas injection, a; R_{CO_2} is the CO_2 utilization coefficient, t/m^3; ρ_{CO_2} is the density of CO_2 under standard conditions, t/m^3.

2.2 Numerical calculation of CO_2 flooding and sequestration

Taking a typical reservoir as a research example, we established a three-dimensional geological model and calculated the CO_2 utilization coefficient and oil recovery under different reservoir conditions. We considered such main factors as thickness, permeability, vertical/horizontal permeability ratio, reservoir heterogeneity (areal heterogeneity and sedimentary rhythm), crude oil composition, fluid viscosity ratio, buoyancy (buoyancy is the ratio of the gravity forces to the viscous forces in a reservoir), diffusion, development mode, and the size of natural water bodies. Based on the initial parameters of the typical reservoirs, we changed the magnitude of above parameters, and calculated CO_2 utilization coefficient and oil recovery. Fig. 1 shows the numerical simulation of CO_2 sequestration and oil displacement.

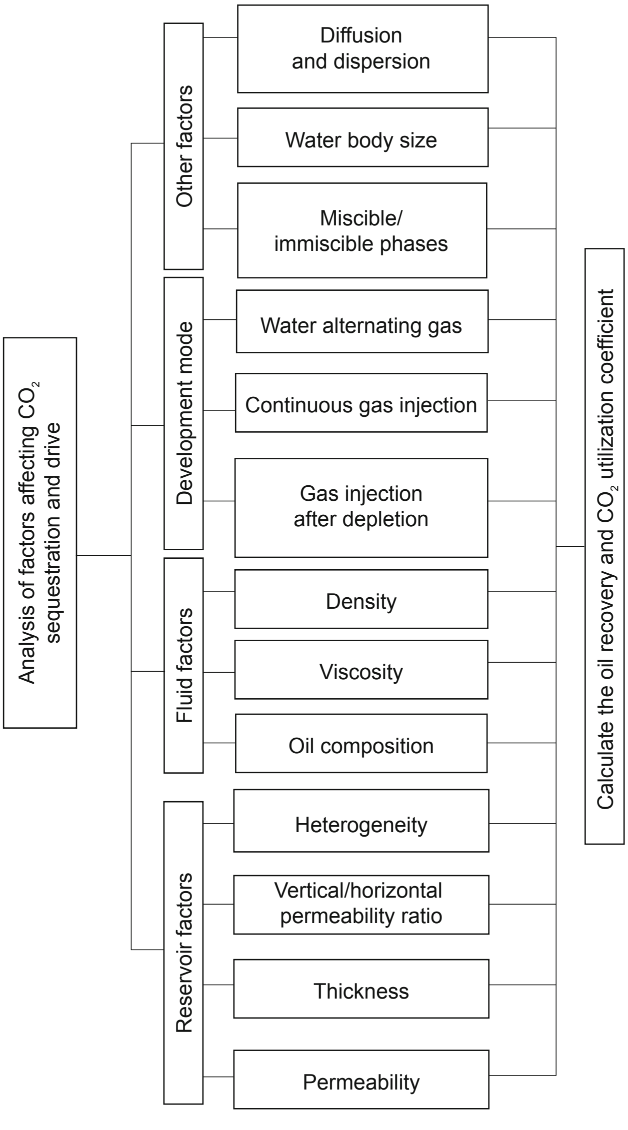

Fig. 1 Numerical simulation of CO_2 sequestration and oil displacement

2.3 Factors affecting CO_2 sequestration and flooding

The simulation results indicate that the key factors are formation heterogeneity, oil-CO_2 viscosity ratio, sedimentary rhythm, miscible/immiscible phases, and buoyancy/gravity; the minor ones are formation thickness, diffusion/dispersion, gas injection rate, and water body size (Yao and Li, 2009).

In short, there are many factors influencing CO_2 sequestration and oil displacement efficiency, which makes it difficult to evaluate the effect of CO_2 flooding and sequestration. Consequently, it is necessary to establish an evaluation model considering a number of factors.

3 Introduction of dimensionless groups to systematically scale reservoir properties

Based on the aforementioned analysis of main controlling factors for CO_2 utilization coefficient and oil recovery, ten factors were selected. They are the effective aspect ratio R_L, CO_2-oil mobility ratio M_g^o, buoyancy number N_g^o, initial oil saturation S_{oi}, reservoir heterogeneity, sedimentary rhythm, injection pressure parameter, producing pressure parameter, reservoir pressure parameter, and water body size. Previous studies provide positive and negative influencing relationships of all reservoir parameters, and a detailed description is given of how these parameters affect the CO_2 sequestration and oil displacement efficiency. According to the analysis of physics and mechanics, we determined the affiliation relationship between the related reservoir parameters and the above ten dimensionless groups. As to every group, on the base of dimensional analysis, influencing parameters were more obviously chosen for the dimensionless group. The most important principle of its combination was that making sure every positive and negative factor to oil recovery and CO_2 utilization coefficient lie separately on different sides of the fraction line. Similarly, other dimensionless groups were formed; all ten dimensionless groups were qualified to systematically scale reservoir properties. The concrete dimensionless groups are defined as follows:

The effective aspect ratio $R_L = \frac{L}{H}\sqrt{\frac{k_z}{k_h}}$ (R_L is related to cross-flow within the reservoir, which includes the length to height ratio and the vertical to horizontal permeability ratio)

CO_2-oil mobility ratio $M_g^o = \frac{k_{rg}^o m_o}{k_{ro}^o m_g}$

The buoyancy number $N_g^o = \frac{H \Delta \rho g \cos \alpha}{\Delta P}$

Initial oil saturation S_{oi}

The homogeneity coefficient $\sigma_R = \frac{A_i \sqrt{H_i}}{V_i \lg k_i}$

The relative position of the high-permeability layer

$H_D = \frac{h_i}{H}$

The injection pressure parameter $P_{injD} = \frac{P_{inj} - P_{MM}}{P_{MM}}$

The producing pressure parameter $P_{pD} = \frac{P_p - P_{MM}}{P_{MM}}$

The reservoir pressure parameter $P_{eD} = \frac{P_e - P_{MM}}{P_{MM}}$

The water body size $N_D = \frac{V_w}{V_\phi}$

where H is the reservoir thickness, m; L is the reservoir length, m; k_x is the horizontal permeability, mD; k_z is the vertical permeability, mD; μ_o is the oil viscosity, mPa·s; μ_g is the gas viscosity, mPa·s; k_{rg}^o is the gas relative permeability; k_{ro}^o is the oil relative permeability; $\Delta\rho$ is the oil-water density difference, kg/m^3; ΔP is the difference between the injection and producing pressures, MPa; P_{MM} is the minimum miscible pressure, MPa; α is the dip angle; A_i is the hydrodynamic communication in the horizontal direction; V_i is the permeability variation coefficient; H_i is the net/gross thickness ratio; K_i is the permeability contrast (maximum to minimum permeability ratio); h_i is the distance from the high-permeability layer to the top of the reservoir, m; P_{inj} is the injection pressure, MPa; P_p is the producing pressure, MPa; P_e is the reservoir pressure, MPa; V_w is the water body volume, m^3; V_Φ is the reservoir pore volume, m^3.

4 Evaluation model of CO_2 flooding and sequestration

4.1 Box-Behnken experimental design

Based on a Box-Behnken design for 10 factors and 3 levels, we designed a response surface analysis experiment, which consisted of a total of 220 simulations. Ten dimensionless groups were chosen as independent variables; and oil recovery and CO_2 utilization coefficient as response values. The maximum of the positive factors and the minimum of the negative factors were chosen to calculate the high level value of dimensionless groups; the minimum of the positive factors and the maximum of the negative factors were chosen to calculate the low level value of dimensionless groups; the intermediate value of all factors were chosen to calculate the intermediate level value of dimensionless groups. All test factors and their ranges are listed in Table 1. These values of all dimensionless groups were normalized such that the values ranged from −1 to 1, see Table 2.

Table 1 Range of group values

Factor	Value		
	Low	Intermediate	High
R_L	0.499	2.23	3.525
M_g^o	25	37.5	50
N_g^o	0.097	0.165	0.23
S_{oi}	0.3	0.5	0.7
H_D	0.1	0.5	0.9
σ_R	0.89	60.77	102.4
P_{injD}	–0.1	0.2	0.5
P_{pD}	–0.5	–0.2	0.1
P_{eD}	–0.3	0	0.3
N_D	0	5	10

Table 2 Normalized group values

Factor	Level		
	Low	Intermediate	High
R_L	–1	0.144	1
M_g^o	–1	0	1
N_g^o	–1	0.026	1
S_{oi}	–1	0	1
H_D	–1	0	1
σ_R	–1	0.18	1
P_{injD}	–1	0	1
P_{pD}	–1	0	1
P_{eD}	–1	0	1
N_D	–1	0	1

4.2 Calculation

A geological model built was a non-homogeneous, 3-D, Cartesian, dipping reservoir in which a five-spot pattern was adopted. Fig. 2 shows the geometry diagram of the CO_2 driving system. The reservoir was divided into 2,420 grid-blocks — 11 *x*-grid-blocks, 11 *y*-grid-blocks and 20 *z*-grid-blocks. The matching result of the PVT*i* model was given as the fluid model, and the pseudo-component of oil used is shown in Table 3.

According to the experimental points obtained from the Box-Behnken design, we adjusted the initial values of the parameters and then calculated the oil recovery and CO_2 utilization coefficient, which provided the data base for the following establishment of the CO_2 sequestration and enhanced oil recovery evaluation model.

Table 3 Oil composition

Component	CO_2	N_2	C_1	C_2	C_{3+4}	C_{5+6}	C_7-C_{19}	C_{19}-C_{35}	C_{35+}
Mole fraction, %	0.3	2.0	16.7	5.9	5.5	4.0	37.9	20.4	7.3

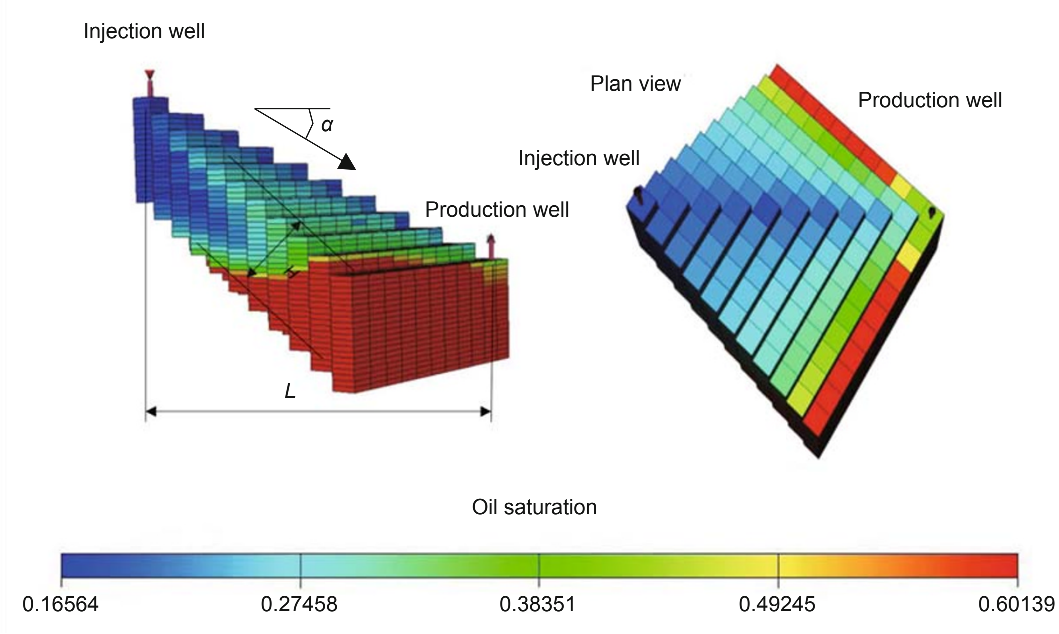

Fig. 2 Geometry diagram of the CO_2 driving system

4.3 Response surface design and evaluation model

The response surface method is a combination of mathematics and statistics. Because it can build a functional relationship between the objective value and independent variables, then quantitatively analyze the influencing relation between the objective value and independent variables, this method is widely used in the test data analysis. As the response surface method includes many types of response surface models, it is necessary to screen models in the response surface analysis. In this paper, we used different response surface models to fit the results of 220 simulations. Error analysis shows that the fitting effect of the quadratic model (Eq. (6)) is the best. Eq.(6) was chosen as the initial model for the following research.

$$\hat{Y} = C_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i \le j} b_{ij} x_i x_j + \sum_{i=1}^{n} c_i x_i^2 \qquad (6)$$

where $\hat{Y}$ is the predicted response value (predicted value of the oil recovery R or CO_2 utilization coefficient R_{CO_2}); x_i, x_j are the coded values of independent variables; C_0 is the constant term; a_i is the linear coefficient; b_{ij} is the interaction coefficient; c_i is the quadratic coefficient; n is the number of factors, which is 10 in this test.

Using the least-squares method we fitted the relationship between the response values and the independent variables obtained from numerical calculation with the quadratic model. The results are shown as follows.

The evaluation equation for the oil recovery:

$$\begin{aligned}R = {} & 0.4234 - 0.024R_L - 0.04341M_g^o - 0.059N_g^o + 0.1222S_{oi} + 0.0254H_D + 0.0663\sigma_R + 0.034P_{injD} + 0.01663P_{pD} \\ & +0.0765P_{eD} + 0.0503N_D - 0.0036R_L M_g^o + 0.000767R_L N_g^o - 0.00602R_L S_{oi} + 0.00131R_L H_D - 0.00386R_L \sigma_R \\ & +0.00986R_L P_{injD} - 0.01006R_L P_{pD} + 0.001554R_L P_{eD} - 0.00196R_L N_D + 0.0309M_g^o N_g^o - 0.00633M_g^o S_{oi} + 0.0127M_g^o H_D \\ & +0.0371M_g^o \sigma_R + 0.04881M_g^o P_{injD} - 0.04848M_g^o P_{pD} + 0.01093M_g^o P_{eD} - 5\times10^{-6} M_g^o N_D + 0.0224N_g^o S_{oi} + 0.00607N_g^o H_D \\ & -0.01481N_g^o \sigma_R + 0.00368N_g^o P_{injD} - 0.00805N_g^o P_{pD} - 0.00317N_g^o P_{eD} - 0.00059N_g^o N_D + 0.00522S_{oi} H_D - 0.00212S_{oi} \sigma_R \\ & +0.00288S_{oi} P_{injD} + 0.0149S_{oi} P_{pD} + 0.0181S_{oi} P_{eD} + 0.00038S_{oi} N_D - 0.04451H_D \sigma_R + 0.0053H_D P_{injD} - 0.00465H_D P_{pD} \\ & +0.003344H_D P_{eD} + 0.000118H_D N_D + 0.0357\sigma_R P_{injD} - 0.0318\sigma_R P_{pD} + 0.01138\sigma_R P_{eD} - 0.0007\sigma_R N_D - 0.03043P_{injD} P_{pD} \\ & +0.00274P_{injD} P_{eD} - 0.00039P_{injD} N_D - 0.00345P_{pD} P_{eD} - 0.00058P_{pD} N_D + 0.000926P_{eD} N_D + 0.004{R_L}^2 + 0.00407M_g^{o2} \\ & -0.0234N_g^{o2} - 0.0141{S_{oi}}^2 - 0.00751{H_D}^2 + 0.0129{\sigma_R}^2 + 0.000132{P_{injD}}^2 + 0.000326{P_{pD}}^2 + 0.0359{P_{eD}}^2 - 0.00727{N_D}^2\end{aligned} \tag{7}$$

The evaluation equation for the CO_2 utilization coefficient:

$$\begin{aligned}R_{CO_2} = {} & 2.018 - 0.087R_L + 0.088M_g^o + 0.052N_g^o - 1.186S_{oi} + 0.028H_D + 0.034\sigma_R + 0.047P_{injD} + 0.082P_{pD} \\ & +0.373P_{eD} + 0.119N_D - 0.0043R_L M_g^o - 0.02R_L N_g^o + 0.185R_L S_{oi} + 0.0092R_L H_D - 0.029R_L \sigma_R + 0.0083R_L P_{injD} \\ & -0.0062R_L P_{pD} - 0.027R_L P_{eD} + 0.0033R_L N_D - 0.016M_g^o N_g^o - 0.188M_g^o S_{oi} - 0.0014M_g^o H_D - 0.049M_g^o \sigma_R \\ & -0.16M_g^o P_{injD} + 0.163M_g^o P_{pD} + 0.0096M_g^o P_{eD} + 0.0011M_g^o N_D - 0.197N_g^o S_{oi} + 0.032N_g^o H_D - 0.0094N_g^o \sigma_R \\ & -0.125N_g^o P_{injD} + 0.129N_g^o P_{pD} + 0.00057N_g^o P_{eD} - 0.0056N_g^o N_D - 0.151S_{oi} H_D + 0.394S_{oi} \sigma_R + 0.148S_{oi} P_{injD} \\ & -0.152S_{oi} P_{pD} - 0.232S_{oi} P_{eD} - 0.0082S_{oi} N_D + 0.0076H_D \sigma_R + 0.019H_D P_{injD} - 0.018H_D P_{pD} + 2.53\times10^{-5} H_D P_{eD} \\ & +0.0003H_D N_D + 0.074\sigma_R P_{injD} - 0.075\sigma_R P_{pD} + 0.004\sigma_R P_{eD} - 0.0029\sigma_R N_D - 0.073P_{injD} P_{pD} - 0.021P_{injD} P_{eD} \\ & +0.0099P_{injD} N_D + 0.002P_{pD} P_{eD} - 0.0049P_{pD} N_D - 0.001P_{eD} N_D - 0.034{R_L}^2 - 0.044M_g^{o2} - 0.066N_g^{o2} + 0.494{S_{oi}}^2 \\ & +0.034{H_D}^2 + 0.0091{\sigma_R}^2 - 0.0028{P_{injD}}^2 - 0.0007{P_{pD}}^2 - 0.064{P_{eD}}^2 + 0.053{N_D}^2\end{aligned} \tag{8}$$

We compared the values obtained from Eqs. (7) and (8) with the results from the numerical calculation. The error analysis results indicate that the correlation coefficients for the recovery and the CO_2 utilization coefficient are 0.941 and 0.958, respectively. Eqs. (7) and (8) fit well with the results from the numerical calculation, so they can be used to evaluate the oil displacement recovery and the CO_2 storage potential in the reservoir.

Using Design Expert software (Stat-Ease, Inc, Minneapolis), we carried out variance analysis of influencing factors to the test data of reservoir recovery and CO_2 utilization coefficient. A significant analysis of variance was done and the results are listed in Tables 4 and 5. As can be seen from the data in the tables, in the quadratic model the minimum significance level for rejecting the original hypothesis is less than 0.001, which indicates that the model is good and the errors are small.

If the minimum significance level for rejecting the original hypothesis is set at 0.05, as can be seen from Tables 4 and 5, the influence of all dimensionless groups on the objective function are significant in the oil recovery regression equation, which proves that the introduction of dimensionless groups characterizing reservoir properties is effective. In the quadratic of the recovery regression equation, the buoyancy parameter, initial oil saturation, and the reservoir pressure parameter are the most significant. Amongst the interactive effects, the CO_2-crude oil mobility ratio and the producing pressure parameter, the initial oil saturation and the reservoir pressure parameter, the high-permeability layer position parameter and the homogeneity coefficient, the homogeneity coefficient and the injection pressure parameter, the homogeneity coefficient and the producing pressure parameter, the injection pressure parameter and the producing pressure parameter are significant, and the other interactions are weak.

In the regression equation for the CO_2 utilization coefficient (Eq. (8)), the influence of all dimensionless groups on the objective function are also significant. In the quadratic terms in Eq. (8), the initial oil saturation is significant; in the aspect of interactive effects, the CO_2-crude oil mobility ratio and the injection pressure parameter, the CO_2-crude oil mobility ratio and the producing pressure parameter, the buoyancy parameter and the initial oil saturation, the initial oil saturation and the homogeneity coefficient, the initial oil saturation and the injection pressure parameter, the initial oil saturation and the producing pressure parameter, the initial oil saturation and the reservoir pressure parameter, and the injection pressure parameter and the producing pressure parameter are significant; and the other interactions are weak.

Table 4 Significant terms in the quadratic regression equation of oil recovery

Source	Mean square	F value	P-value
Model	0.1128	69.1	< 0.0001
R_L	0.0171	10.46	0.0014
M^0_g	0.019	11.67	0.0008
N^0_g	0.1385	84.86	< 0.0001
S_{oi}	0.4885	299.31	< 0.0001
H_D	0.0542	33.2	< 0.0001
σ_R	0.0237	14.51	0.0002
P_{injD}	0.0207	13.44	0.0005
P_{pD}	0.0635	38.9	< 0.0001
P_{eD}	0.3027	185.51	< 0.0001
N_D	0.1038	63.59	< 0.0001
$M^0_gP_{injD}$	0.0365	22.37	< 0.0001
$M^0_gP_{PD}$	0.0233	14.29	0.0002
$S_{oi}P_{eD}$	0.00875	5.36	0.0216
$H_D\sigma_R$	0.008023	4.92	0.0277
σ_RP_{injD}	0.01954	11.97	0.0007
σ_RP_{pD}	0.00758	4.64	0.0324
$P_{injD}P_{pD}$	0.01594	9.77	0.0020
$(N^0_g)^2$	0.03128	19.17	< 0.0001
S_{oi}^2	0.00722	4.42	0.0367
P_{eD}^2	0.00946	6.09	0.0125

Table 5 Significant terms in the quadratic regression equation of CO_2 utilization coefficient

Source	Mean square	F value	P-value
Model	0.6666	102.13	< 0.0001
R_L	0.05756	8.82	0.0033
M^0_g	0.02464	3.78	0.0534
N^0_g	0.000254	0.0389	0.8439
S_{oi}	2.8163	431.53	< 0.0001
H_D	0.01842	2.82	0.0945
σ_R	0.02426	3.717	0.0553
P_{injD}	0.00524	0.803	0.3713
P_{pD}	0.1578	24.185	< 0.0001
P_{eD}	0.8125	124.49	< 0.0001
N_D	0.09472	14.51	0.0002
$M^0_gP_{injD}$	0.04488	6.88	0.0094
$M^0_gP_{PD}$	0.05178	7.934	0.0053
$N^0_gS_{oi}$	0.0297	4.55	0.0341
$S_{oi}\sigma_R$	0.09953	15.251	0.0001
$S_{oi}P_{injD}$	0.0275	4.213	0.0414
$S_{oi}P_{pD}$	0.02893	4.432	0.0365
$S_{oi}P_{eD}$	0.05064	7.758	0.0059
$P_{injD}P_{pD}$	0.0814	12.48	0.0005
S_{oi}^2	1.2783	195.86	< 0.0001

4.4 A simplified evaluation model

Because the interactive effects of all the ten dimensionless groups were taken into consideration, the equations are too complicated to evaluate rapidly for the target reservoir. We selected the significant terms in the Eqs. (7) and (8) to simplify the previous evaluation equations as follows:

The evaluation equation for the oil recovery:

$$\begin{aligned} R = {} & 0.4259 - 0.02R_L - 0.03541M^o_g - 0.05854N^o_g + 0.1278S_{oi} + 0.02447H_D + 0.068\sigma_R + 0.03307P_{injD} + 0.01481P_{pD} \\ & +0.0849P_{eD} + 0.0497N_D + 0.01608M^o_gP_{injD} + 0.01482M^o_gP_{pD} + 0.027S_{oi}P_{eD} - 0.04415H_D\sigma_R + 0.04048\sigma_RP_{injD} \\ & -0.02521\sigma_RP_{pD} - 0.01159P_{injD}P_{pD} - 0.02467N^{o2}_g - 0.01488S_{oi}^2 - 0.03675P_{eD}^2 \end{aligned} \tag{9}$$

The evaluation equation for the CO_2 utilization coefficient:

$$\begin{aligned} R_{CO_2} = {} & 2.01 - 0.093R_L + 0.073M^o_g + 0.0057N^o_g - 1.16S_{oi} + 0.053H_D + 0.06\sigma_R - 0.032P_{injD} + 0.18P_{pD} + 0.35P_{eD} + 0.12N_D \\ & -0.16M^o_gP_{injD} + 0.17M^o_gP_{pD} - 0.2N^o_gS_{oi} + 0.39S_{oi}\sigma_R + 0.15S_{oi}P_{injD} - 0.15S_{oi}P_{pD} - 0.23S_{oi}P_{eD} - 0.14P_{injD}P_{pD} + 0.5S_{oi}^2 \end{aligned} \tag{10}$$

5 Sensitivity analysis and validation

5.1 Sensitivity analysis of factors

5.1.1 Single factors

We plotted the oil recovery and CO_2 utilization coefficient against various influencing factors (Figs. 3 and 4). These figures show that these factors have significant but different effects on the oil recovery and CO_2 utilization coefficient.

The factors are listed in order of importance to the oil recovery: the initial oil saturation, reservoir pressure parameter, homogeneity coefficient, buoyancy parameter, water body size parameter, CO_2-oil mobility ratio, injection pressure parameter, high-permeability layer position parameter, effective aspect ratio, and the producing pressure parameter.

The factors influencing the CO_2 utilization coefficient are also ranked in descending order: the initial oil saturation, reservoir pressure parameter, producing pressure parameter, water body size parameter, effective aspect ratio, CO_2-oil mobility ratio, homogeneity coefficient, high-permeability layer position parameter, injection pressure parameter, and the buoyancy parameter.

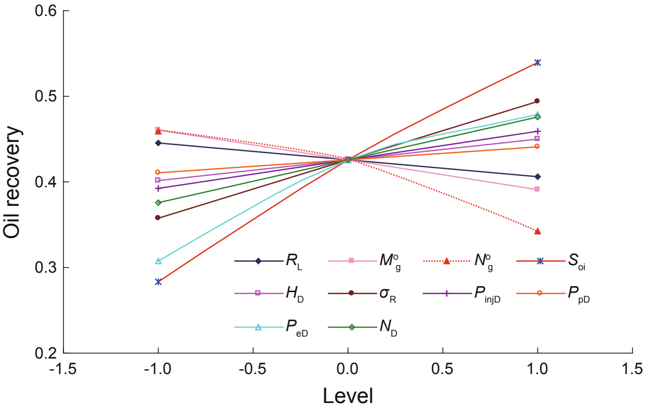

Fig. 3 Influence curves of single factors on oil recovery

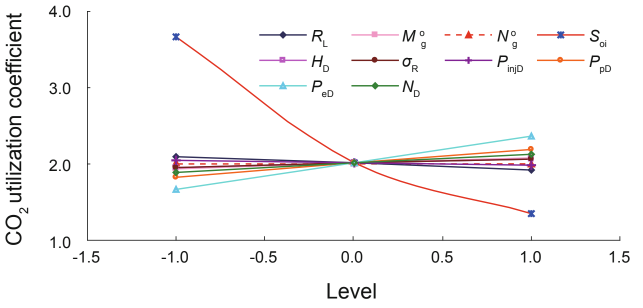

Fig. 4 Influence curves of single factors on the CO_2 utilization coefficient

5.1.2 Interaction between any two factors

Figs. 5 and 6 are two response surface diagrams of oil recovery and CO_2 utilization coefficient. Fig. 5 shows that the interaction of the homogeneity coefficient and high-permeability layer position parameter to the oil recovery is significant in the recovery response surface diagram. It is specifically manifested as follows: when the homogeneity coefficient is large, lower high-permeability layer position parameter leads to higher oil recovery. Fig. 6 shows that the interaction of the CO_2-crude oil mobility ratio and the injection pressure parameter is significant in the CO_2 utilization coefficient response surface diagram. It is specifically manifested as follows: when the CO_2-crude oil mobility ratio is large, lower injection pressure parameter leads to greater CO_2 utilization coefficient.

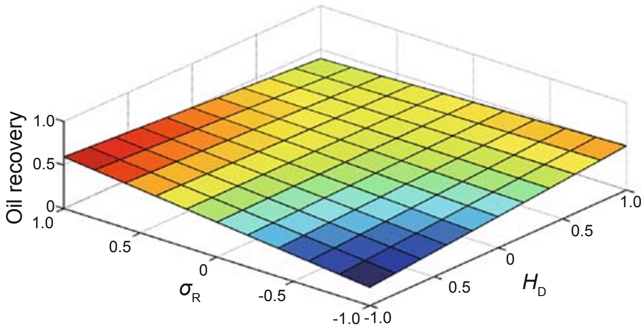

Fig. 5 The interaction of the homogeneity coefficient and high-permeability layer position on oil recovery

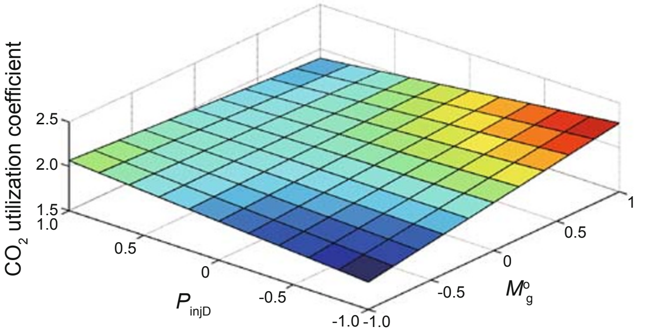

Fig. 6 The interaction of the CO_2-crude oil mobility ratio and the injection pressure on CO_2 utilization coefficient

5.2 Model calculation and analysis

After adjusting each parameter value, the values of all dimensionless groups were calculated using the data of a typical reservoir. Then the numerical method and Eqs. (9) and (10) were used respectively to calculate oil recovery and CO_2 utilization coefficient. The calculated results are shown in Figs. 7 and 8.

Figs. 7 and 8 show that the results calculated by formulae proposed in this paper is consistent with those obtained from numerical calculation. The correlation coefficients for oil

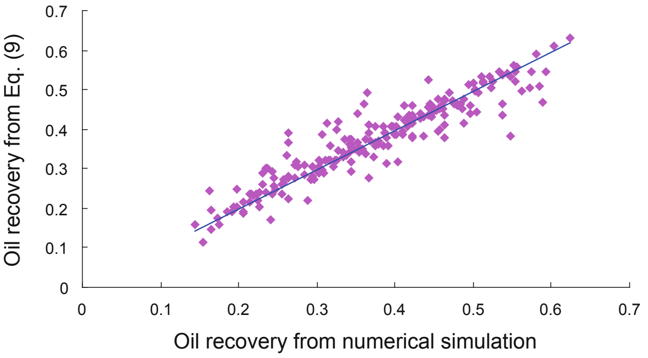

Fig. 7 A comparison of oil recovery calculated by numerical simulation with Eq. (9)

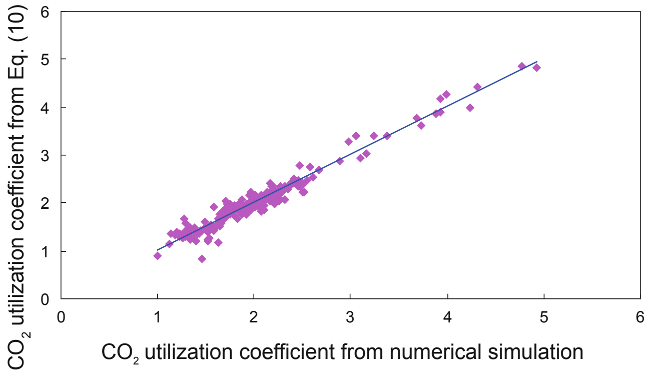

Fig. 8 A comparison of CO_2 utilization coefficient calculated by numerical simulation and by Eq. (10)

recovery evaluation equation and CO_2 utilization coefficient evaluation equation are respectively 0.935 and 0.952, which indicates that the simplified model can be used to predict oil recovery and CO_2 utilization coefficient.

6 Conclusions

After analyzing the factors influencing the CO_2 utilization coefficient and oil recovery, we introduced ten dimensionless groups to characterize the reservoir. Based on the Box-Behnken design, all factors with varying values affecting storage and recovery were calculated, the results were interpreted by the response surface method, and a quick evaluation model for evaluating CO_2 sequestration and oil recovery was obtained finally. The main understandings are shown as follows:

1) There are many factors influencing the CO_2 sequestration and oil recovery: the most influencing factors are stratum heterogeneity, oil and CO_2 viscosity ratio, sedimentary rhythm, miscible/immiscible phases, buoyancy/gravity; the secondary ones are formation thickness, diffusion/dispersion, and gas injection rate and water body size.

2) Based on analysis of main factors influencing the CO_2 utilization coefficient and oil recovery, the affiliation relation between every reservoir parameter and every factor was determined by dimensional analysis and the theory of physics and mechanics. Ten dimensionless groups were selected (such as the effective aspect ratio, CO_2-oil mobility ratio, buoyancy number, initial oil saturation, reservoir heterogeneity, sedimentary rhythm, injection pressure, producing pressure, reservoir pressure, and water body size), and the ten dimensionless groups were qualified to systematically scale reservoir properties.

3) The evaluation model established through the Box-Behnken design and response surface method is accurate and simple for calculating oil recovery and the CO_2 utilization coefficient. It can be used to quickly evaluate the oil recovery and CO_2 storage potential for reservoirs in China, and can also provide criteria for screening candidate reservoirs for CO_2 sequestration and flooding.

4) Based on sensitivity analysis and test of the evaluation model, the factors are listed in order of importance as follows: For reservoir recovery: the initial oil saturation, reservoir pressure parameter, homogeneity coefficient, buoyancy parameter, water body size parameter, CO_2-oil mobility ratio, injection pressure parameter, high-permeability layer position parameter, effective aspect ratio, and the producing pressure parameter. For the CO_2 utilization coefficient: the initial oil saturation, reservoir pressure parameter, producing pressure parameter, water body size parameter, effective aspect ratio, CO_2-oil mobility ratio, homogeneity coefficient, high-permeability layer position parameter, injection pressure parameter, and the buoyancy parameter.

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