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Integrated CO_2 Miscible Flooding-Storage Technologies for Complex Fault Block Reservoirs with Low Permeability

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ABSTRACT

During the production process of complex fault block reservoirs with low permeability, the systematic research on the combination of oil displacement and storage is fuzzy. This work aims at oil displacement and storage to supplement formation energy and evaluate storage potential. Firstly, the optimal development scheme is designed by layer division and miscible and ability. Secondly, based on large amounts of field data, the novel FAHP evaluation system for CO_2 storage site selection is established. Thirdly, since judging adaptability evaluation is suitable, the carbon storage simulation is conducted to contain mineralization, dissolved and structural mechanisms. The results indicate that after 1.2HCPV CO_2 injected cumulatively into reservoir, the cumulative oil increase reached $4001.80\times10^4 m^3$ and the final recovery rate was 44.46%, achieving a good effect. At the stage of injection, the CO_2 capacity remaining in the reservoir was nearly 1657.53×10^4t and the gas storage rate reached 43.84%. The novel evaluation system for CO_2 storage site selection shows that the target reservoir has more storage space, large injection capacity, high safety factor and low storage cost, which is allowed to storage. At the stage of storage, the effective storage capacity of target reservoir was 2257.48×10^4t, of which the structural storage capacity was 73.43% and the mineral storage capacity was the least (3.46%). The average annual CO_2 storage capacity is about 225.74×10^4t, which is equivalent to planting 2031.69×10^4t trees or shutting down 135.69×10^4 cars for one year, achieving oil displacement/storage synergetic optimization. The findings of this study can offer engineers guidance for ensuring the long-term, stable and safe operation of CO_2 storage. For complex fault block reservoirs with low permeability "green, low-carbon, efficient" development has a certain reference.

Keywords: miscible flooding, oil displacement/storage synergetic optimization, fuzzy analytic hierarchical process, adaptability evaluation system, storage capacity

NONMENCLATURE

Abbreviations	
CCUS	Carbon Capture, Utilization and Storage
EOR	Enhance Oil Recovery
FAPH	Fuzzy Analytic Hierarchical Process
MMP	Minimum Miscible Pressure
Symbols	
A	The weights set
A_J	The judgement matrix
a_{ij}	The importance of the B_i factor compared with the B_j factor
B_i/B_j	The intensity of importance of factor i compared to factor j
B_o	The crude oil volume factor
C_e	The effective storage coefficient
Cm	The mobility impact factor
Cb	The buoyancy impact factor
Ch	The reservoir heterogeneity impact factor
Cw	The water saturation impact factor
Ca	The saline impact factor
CI	The consistency index
CR	The consistency test number

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M_i	The product of the importance of the i^{th} factor in the judgment matrix
M_{co_2}	The theoretical storage capacity
$M^*_{co_2}$	The effective storage capacity
N_o	The original oil in place
n	The order of the judgment matrix
RI	The random consistency index
R_f	The ultimate recovery
V_{iw}	The water injection volume
V_{pw}	The water production volume
W_i	The n^{th} root of M_i
λ_{max}	The maximum eigenvalue of the judgment matrix
ρ_{co_2}	The CO_2 density under reservoir conditions

1. INTRODUCTION

In recent years, with the rapid development of China's economy, the demand for oil and natural gas has been increasing dramatically. However, the low oil and gas output is far from meeting domestic demand in China [1]. The development of conventional high and intermediate permeability reservoirs has entered into high water cut stage, and the development of ultra-low permeability reservoirs has gradually become a key focus in the oilfield [2]. The biggest characteristic of ultra-low permeability reservoirs is poor physical property, small pore-throat structure, high flow resistance, and fast decline in single-well production, which brings great challenges [3]. Low permeability reservoirs account for 60% of the remaining oil resources, and have huge development potential. Developing these reservoirs has important strategic significance for the sustainable development of China's petroleum industry [4, 5, 6].

Currently, greenhouse gas injection to enhance oil recovery is widely studied. Carbon Capture, Utilization and Storage (CCUS) is one of the most effective technologies for reducing CO2 emissions [7], as it can enhance oil recovery [8] and support geothermal resource development [9] while reducing the impact of greenhouse gas. Since the integrity of trap caps has been fully verified in the long-term oil exploration and development, the integrated improve oil recovery and CO_2 storage have been favored abroad [10, 11]. The field experiment of CO_2 injection into reservoir has been carried out in Jilin Oilfield, and good economic and social benefits have been achieved [12].

The low permeability reservoirs usually have complex pore structure and complicated seepage characteristics, leading to hardly establish a reasonable injection-production relationship. According to the great layer difference and strong water sensitivity, as shown in Fig.1, it is easy to precipitate and make the clay expanding in the process of water flooding in low permeability reservoir [13]. Due to gas is easy to flow, expand volume, reduce oil viscosity and interfacial tension, CO_2 flooding shows significant advantages in solving the development of low permeability reservoir, which could supplement formation energy and effectively control water [14-15]. Wang et al. [16] indicated that CO_2 miscible flooding is advisable for low-permeability reservoir. CO_2 has excellent oil displacement ability in low-permeability reservoirs, especially miscible flooding, and the core oil saturation is decreased obviously. In particular, the oil recovery factor is over 85% above the minimum miscible pressure. Kumar et al. [17] pointed CO_2 miscible flooding for production improvement in low-permeability reservoirs was an immense potential. Carbon dioxide capture (CCUS) is stored in geological sites or enhanced oil recovery (EOR) through miscible gas flooding technology is significant to mitigate atmospheric/anthropogenic CO_2 emissions. Olukoga and Feng [18] proposed machine learning clustering algorithms to evaluate the miscible flooding effect, using analogue reservoirs for comparison and benchmarking. The results show that the depleted volume after miscible flooding is huge, and the combination of oil displacement and CO_2 storage has a broad application prospect.

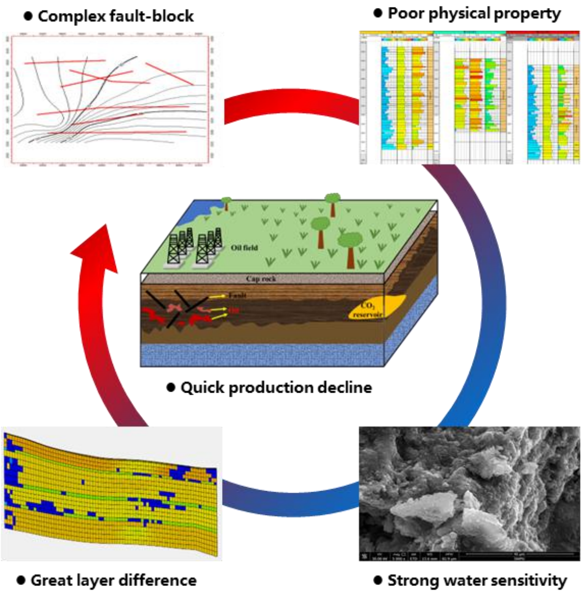


Fig. 1. The characteristics of complex fault block reservoir with low permeability

Over the past years, more and more people have been talking about the importance of carbon dioxide disposal, but it is going to take a movement to make it happen, which means putting CO_2 back underground. The CO_2 storage sites are often carefully selected, not all geological structures are suitable [19, 20]. The impact of storage is mainly limited by geological characteristics. If the alternative reservoir is not available for storage, the maximum storage capacity will not be obtained, even leading to gas leakage and water pollution. To ensure the sustainable storage in complex fault block reservoir, the adaptability evaluation must be established urgently.

The evaluation method highly determines the accuracy and reliability of adaptability results. The fuzzy analytic hierarchical process (FAHP) is proposed to express the influence degree of evaluation index on the final parameters in the form of fuzzy set, with combination of analytic hierarchy process (AHP) and fuzzy method [21]. The FAHP model combines quantitative evaluation with qualitative analysis, which calculates relative weight coefficient of each decision scheme reasonably. According to compare the order of advantages and disadvantages of weight coefficients, it is effectively applied to the ambiguity which is difficult to be solved by quantitative method [22].

Based on 13 reservoirs of potential points and 19 indexes for evaluation, Carlotto et al. [23] developed a multi-criteria approach to select the best site for storage in Peru, under the technical support in the laws related to Net-zero emissions. The survey results also indicated the existing infrastructure to transport CO_2 are a critical factor for storage in oilfield. Liang and Jiang [24] proposed a Delphi-AHP-TOPSIS decision-making framework, which incorporates both quantitative and qualitative key issues. The results show that this method could effectively utilize expert judgment and minimize decision-maker bias. By combining AHP and fuzzy method, Mi and Wang [25] established the novel index system for evaluating CO_2 geological storage suitability, with 3 index layers and 27 indexes. The evaluation system provides a scientific basis for storage site selection in the Junggar Basin, which could predict the development trend of the structural risk. Zhan et al. [26] developed a new CO_2 geological sequestration suitability evaluation model, which compared with the previous study by the accuracy of 83.33%, based on the measurement theory and comprehensive weight. With different evaluation indexes, the evaluation hierarchy system has the adaptability to evaluate the applicability of CO_2 storage sites at different levels. Moreover, the integrity of CO_2 storage site was analyzed based on AHP which can provide reference for risk management. Zhang et al. [27] aimed at evaluating EOR potential, storage site screening and storage capacity calculations in Shenli Oifield on 183 mature reservoirs data, considered that the large depleted volume is the main factor for storage site selection in the future. In addition to storage criteria, few studies have emphasized environmental and economic benefits as an essential part of CO_2 storage site selection [28]. Therefore, when establishing the site selection criteria, it is necessary to combine reservoir characteristics to screen indicators that have a high degree of impact on storage.

Currently, most researches only consider the effects of the normal conditions of gas injection process and do not contain the reactions of integrated CO_2 miscible flooding and storage [29, 30, 31]. However, there are a lot of reservoirs on the abandoned edge, or inefficient reservoirs, and even complex fault block reservoirs in China [32, 33]. Natural oil and gas reservoirs have objective potential as CO_2 storage. Therefore, it is necessary to improve the understanding of integrated CO_2 miscible flooding and storage technologies in complex fault block reservoirs with low permeability.

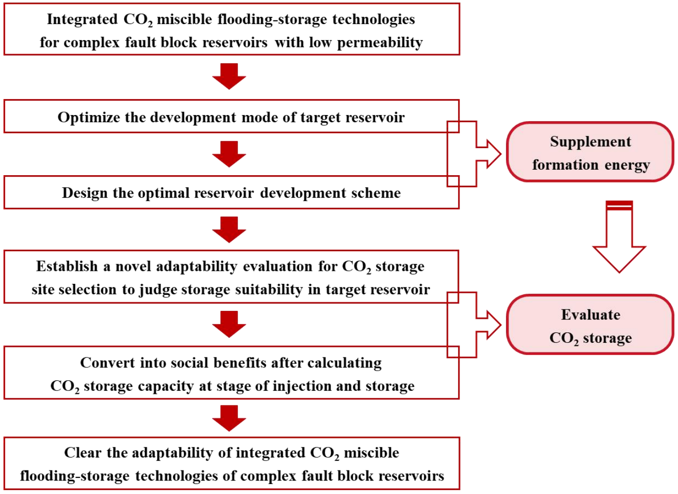


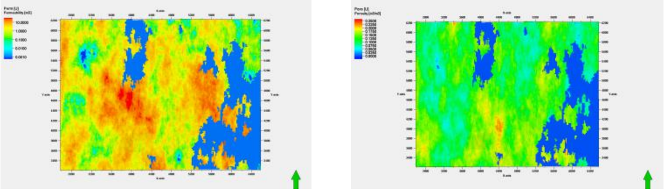
Fig. 2. Flowchart of the work

In the view of the above problems, the oil displacement-storage synergetic optimization system is developed to research how to supplement formation energy and evaluate CO_2 storage, as shown in Fig.2. In this report, the novel system of oil displacement and storage synergetic optimization is proposed to improve oil production and achieve Net-zero emissions. The numerical model is established to compare the development mode and design the optimal scheme. After that, the sensitivity of key parameters, such as reservoir conditions, rock properties and economic cots, is analyzed by storage site selection to ensure the long-term, stable and safe operation of CCS. And then, the CO_2 storage capacity is calculated combined numerical simulation and theoretical calculation. Finally, the storage capacity is converted into social benefits from carbon market and environment in the process of injection and storage. This work provides an effective method to understand integrated CO_2 miscible flooding-storage technologies for complex fault block reservoirs with low permeability. All of these are to form a “green, low-carbon, efficient” development.

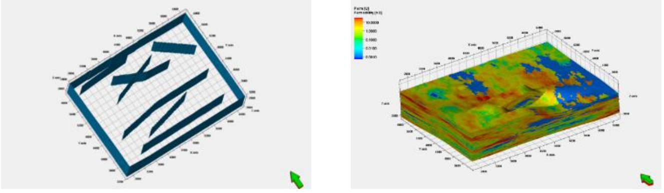
2. NUMERICAL MODEL AND DESIGN

2.1 Numerical model

The aquifer energy of oilfield is small; the CO_2 source near the reservoir is rich and the transportation is convenient. The total area of the trap is about 11.7km^2 and the geological formation depth is about 2800m to 3200m. The original formation pressure is 35MPa and the mean reservoir temperature is 90℃. Based on geological information and parameters, the numerical model is established to research integrated CO_2 flooding and storage technologies for complex fault block reservoirs with low permeability. In order to ensure the accuracy of simulation, the model plane grid size was set to be 50×50m. The attribute model of target reservoir is obtained by interpolation simulation with logging interpretation data. The results show that the average permeability of reservoir is 2.65mD and the average porosity is 10.8%.



(a) Permeability model (b) Porosity model



(c) Boundary and fault (b) 3D geological model

Fig. 3 The view of numerical model

The 3D geological model includes attribute model and construct model in Fig.3. The permeability model is related to the migration and accumulation of reservoir fluids. The porosity model reflects the pore volume distribution of reservoir fluid and is highly matched with the permeability model [34]. The target model is a layered reservoir dominated by complex faults and supplemented by lithology control, which contains 7 faults within the working area.

2.2 Optimization of development mode

2.2.1 Layer division

As shown in Fig.4, The reservoir is divided into four Zones (S1, S2, S3 and S4) from top to bottom layers. Because there are interlayers between each zone, and the vertical formation has strong heterogeneity. According to the principle of layer division, the reservoir is divided into four sets (1, 2, 3 and 4) based on the formation properties and micro-pore structure, which can fully improve the use of target reservoir and effectively prevent layer longitudinal channeling.

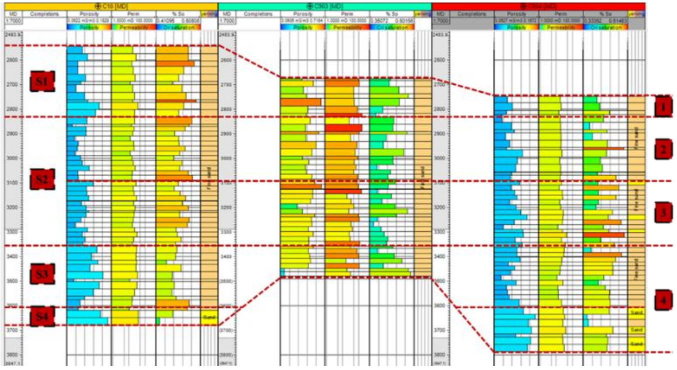


Fig. 4 The layer division of well logging

The classification criteria is described in Table 1. The Type I is defined as the good quality layer, and the Type IV means invalid layer. From the classification criteria, Zones S2 is classified as a good quality layer; Zones S1 and Zones S3 are medium quality layer and Zones S1 is defined as poor quality layer.

Table 1 The classification criteria of target reservoir formation

Parameters	Reservoir types			
	I	II	III	IV
Porosity, %	>12	10-12	6-10	<6
Permeability, mD	>12	2-12	0.5-2	<0.5
Saturation, %	>0.5	0.4-0.5	0.3-0.4	<0.3
Displacement pressure, MPa	<0.05	0.05-0.2	0.2-0.5	>0.5
Median capillary pressure, MPa	<0.2	0.2-0.5	0.5-1	>1
Daily oil production, m^3/d	>15	5-15	1-5	<1
Reservoir evaluation	Good	Medium	Poor	Invalid

2.2.2 Miscible ability

Minimum miscible pressure (MMP) is an important parameter to determine whether miscible in formation, which refers to the minimum pressure required by injected gas to oil and eliminate interfacial tension for a given crude oil and reservoir temperature [35].

Table 2 The results of slim tube simulation

Displacement pressure, MPa	21	24	27	30	33	36

Recover factor, %	69.1	78.6	85.5	92.5	95.9	97.9

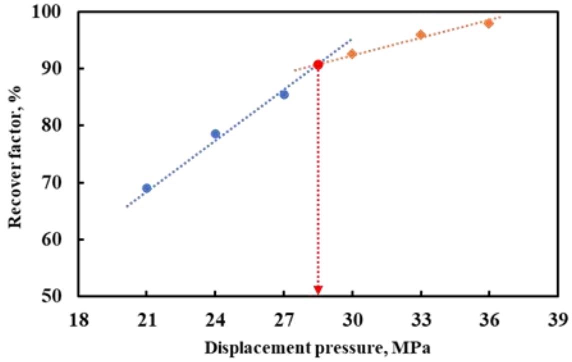


Fig. 5 The relationship between pressure and recovery

As shown in Table 2, CO_2 is injected at reservoir temperature to simulate oil recovery under different displacement pressures (21MPa, 24MPa, 27MPa, 30MPa, 33MPa and 36MPa). Finally, the relationship between pressure and recovery curve is obtained in Fig.5. The pressure at the inflection point is the minimum miscible pressure (MMP=28.5MPa). Given the current formation pressure of 33MPa, gas flooding has the potential to achieve miscible oil displacement.

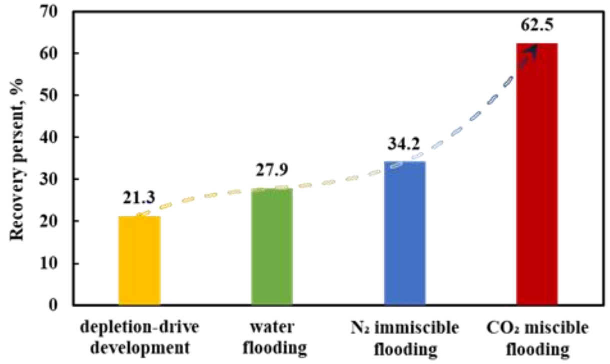


Fig. 6 The development effect of experiment results

This work adopts a long core model and compares physical simulation of development effects by depletion-drive development, water flooding, N_2 flooding and CO_2 flooding under reservoir conditions as shown in Fig.6. The long core experiment shows strong water sensitive damage during water flooding, which causes excessive water injection pressure and low recovery factor of 27.9%. In the same core model, the final recovery factors of water flooding and N_2 flooding are close due to the higher MMP of N_2. The Experiment results show that CO_2 miscible recovery factor is beyond 60%, including advantages such as expanding oil, reducing viscosity and so on. It's clear from Fig.7 that oil displacement efficiency of miscible flooding is higher among them.

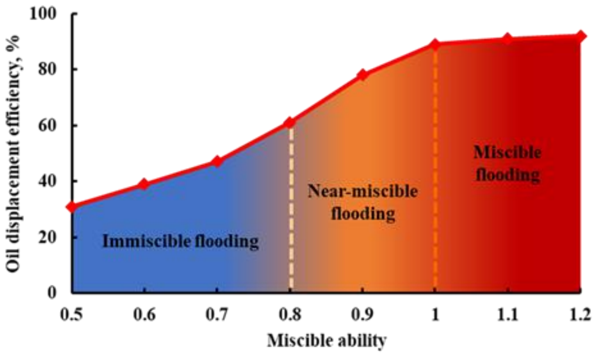


Fig. 7 Miscible ability at oil displacement stage

The saturation pressure of the crude oil is 11.29MPa; the viscosity is 1.98mPa·s; the gas-oil ratio is 46.7m^3/t. The crude oil has the characteristics of low viscosity, low sulfur content and high freezing point. Considering the high intermediate hydrocarbon content of crude oil in Fig.8, the good crude oil quality and high gas-oil ratio provide sufficient power for fluid flow.

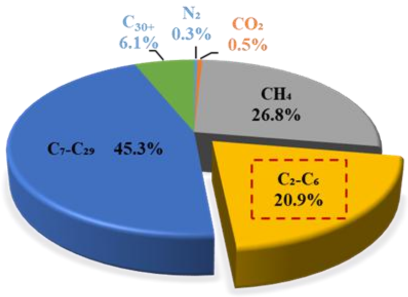


Fig. 8 Intermediate hydrocarbon content of crude oil

Based on the layer division result and miscible ability evaluation The combination of fractured horizontal well and vertical well is used to fully enhance oil recovery factor. Combined CCUS-EOR concept, the development model of fractured horizontal well -CO_2 miscible flooding is selected to supplement formation energy and improve oil recovery factor.

2.2.3 Scheme design

This work adopts 28 horizontal wells and 80 vertical wells as shown in Fig.9. The horizontal well is used for oil production, and the vertical wells are divided into injection well and production well.

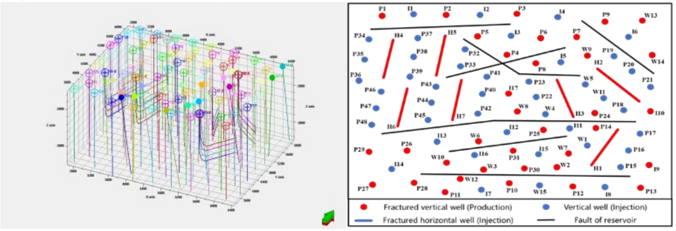


Fig. 9 The well pattern deployment in target oilfield

The parameters of gas flooding scheme are determined by analogical method and empirical equation with field data. The reasonable well spacing is set to be 350-450m; the gas well injection rate is determined to be $3\times10^4 m^3$ and the injection-production ratio of the whole region is maintained at 1:1. After injecting 1.2HCPV CO_2 into the reservoir, the cumulative oil production reaches 2789.48×10^4t and the final recovery rate is 44.46%, achieving a good effect in comparison to depletion drive. At the stage of injection, the CO_2 storage capacity remaining in the reservoir is nearly 1657.53×10^4t and the gas storage ratio reaches about 43.84%.

3. ADAPTABILITY EVALUATION OF STORAGE SITE SELECTION

3.1 Site selection criteria

There are a lot of indexes involved in the long-term injection process, which can directly affect storage safety, stability, and cost. As shown in Fig.10, if injected CO_2 leaks from the injection well into water source through the fracture, which would cause environmental damage and pollute groundwater. The previous findings show that the caprock fracture pressure is the key factor affecting the storage safety. The tight and thick cap layer indicates that the sealing property is good and the probability of cracks is smaller during storage. The depth is too shallow and CO_2 has not reached the supercritical state. If the depth is too deep, it will increase the difficulty of injection and increase the cost of storage. Similarly, porosity and permeability determine the storage capacity in a certain extent. At the same time, the convenient transportation provides source guarantee for oil displacement and storage. There are various physical and chemical reactions during the long-term injection process.

The multi-objective evaluation system of CO_2 storage site selection is addressed in this part, which consists of three level-2 components: reservoir conditions, rock properties and economic costs. Each level-2 element is composed of several level-3 components, for a total of 12, as shown in Fig.11.

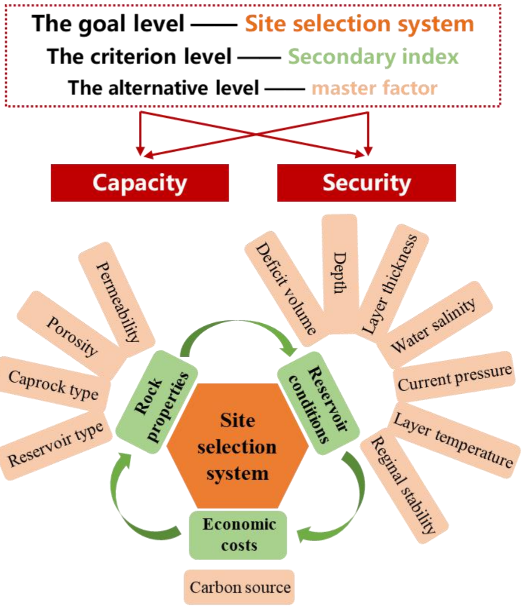


Fig. 11 The multi-objective evaluation system

Based on literature survey and experts survey, the adaptability evaluation criteria is obtained as shown in the Table 3. With reservoir conditions, rock properties and economic costs, the evaluation criteria is divided into five categories based on storage adaptability from high to low, which is composed of five levels: excellent, good, average, fair, and poor. Each level of evaluation is determined by storage capacity and security. The range of the indexes with higher success ratio is more suitable for CO_2 storage.

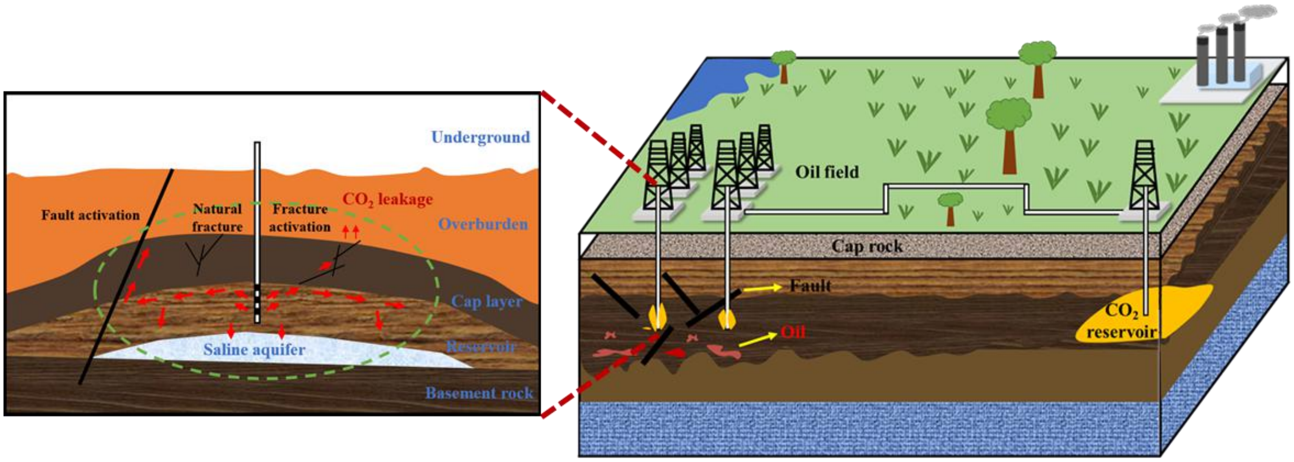


Fig. 10. CO_2 displacement and storage during the long-term injection process

Table 3 The adaptability evaluation criteria of CO_2 storage site selection

Optimal index	Level				
	Excellent	Good	Average	Fair	Poor
Deficit volume ($\times 10^4$t)	>3000	2000-3000	1000-2000	500-1000	<500
Depth (m)	800-2000	2000-3000	3000-4000	4000-5000	<800 or >5000
Layer thickness (m)	>300	200-300	100-200	50-100	<50
Water salinity (mg/L)	>20000	15000-20000	10000-15000	5000-10000	<5000
Current pressure (MPa)	8-12	12-18	18-24	24-30	>30
Layer temperature (℃)	35-60	60-80	80-90	90-100	>100
Reginal stability	Stable	Relatively stable	Generally stable	Relatively unstable	Unstable
Reservoir type	Sandstone	Mixed	Carbonatite	Clasolite	Mudstone
Caprock type	Mudstone	Siltstone	Shale	Evaporite	Carbonatite
porosity (%)	>20	15-20	10-15	5-10	<5
permeability (mD)	>50	10~50	1~10	0.1~1	<0.1
Carbon source (km)	<100	100-200	200-300	300-400	>400

3.2 *Fuzzy mathematical method*

Analytic Hierarchy Process (AHP) is mainly used to determine the importance of each index to the evaluation object for a given object, which is one of the most widely used multiple criteria decision-making tool. The workflow of AHP method shows in Fig. 12. Firstly, the evaluation object is divided into three levels, including the goal level, the criterion level and the alternative level. After that, the judgment matrix is established by nine-point scale method. Then, the weight is calculated by the judgment matrix, and the relative weight of each index is obtained with the consistency results. Finally, the AHP model is constructed to evaluate the adaptability for CO_2 storage site selection in the target reservoir.

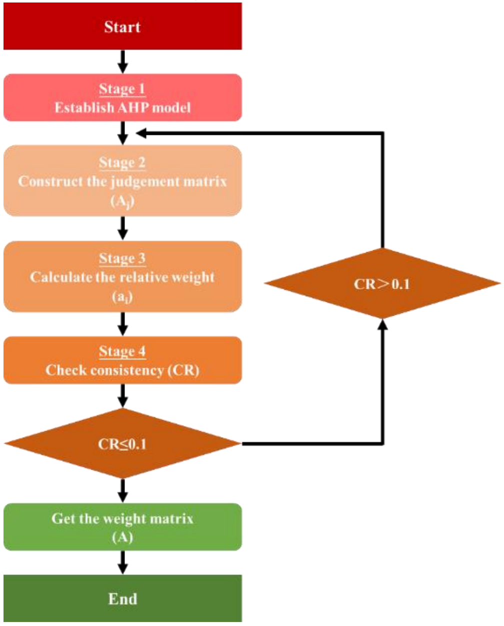


Fig. 12. The workflow of AHP model

3.2.1 Establish AHP model

In this work, the AHP model is established by 3 levels to assess the adaptability of CO_2 storage site selection in complex fault block reservoir. The goal level represents the site selection system. The criterion level consists of reservoir conditions, rock properties and economic costs, including 12 indexes in alternative level, as shown in Fig.13.

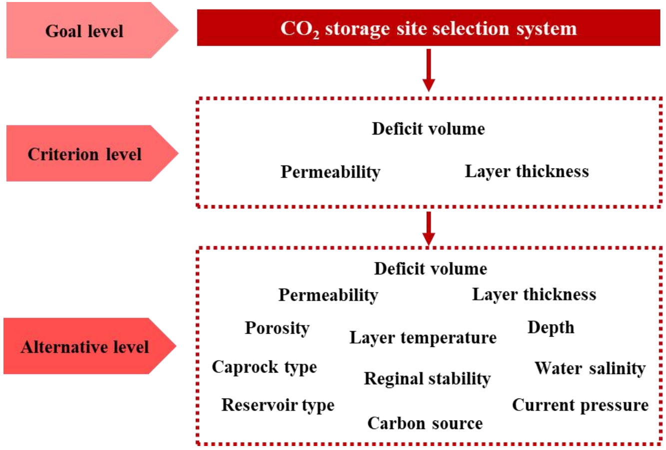


Fig. 13. The AHP model for CO_2 storage site selection system

3.2.2 Construct the judgement matrix

According to the importance of each index on site selection, the judgment matrix is constructed by Eq. (1-2). Table 4 displays the value assignment criteria for two indexes, according to the influence of each index on storage site selection. Table 5 represents for the storage site selection system, Table 6 and Table 7 display the criterion level of rock properties and reservoir conditions.

$$A_J = \left[a_{ij}\right]_{n \cdot n} \tag{1}$$

Table 7 The judgement matrix of criterion level of reservoir conditions

Reservoir conditions	Reginal stability	Deficit volume	Depth	Layer temperature	Layer thickness	Current pressure	Water salinity
Reginal stability	1	1/7	1/3	1	1/2	1	1/2
Deficit volume	7	1	3	3	1	5	3
Depth	3	1/3	1	5	2	2	3
Layer temperature	1	1/3	1/5	1	1/2	1/2	1
Layer thickness	2	1	1/2	2	1	3	1
Current pressure	1	1/5	1/2	2	1/3	1	1
Water salinity	2	1/3	1/3	1	1	1	1

$$a_{ij} = \frac{B_i}{B_j}, i = 1, 2, \ldots, n; j = 1, 2, \ldots, n \tag{2}$$

Where A_J is the judgment matrix and a_{ij} means the importance of the B_i factor compared with the B_j factor.

Table 4 nine-point scale method in AHP model

Ratio	Definition	Description
$B_i/B_j = 1$	Equally important	Index B_i is equally important as Index B_j
$B_i/B_j = 3$	Slightly important	Index B_i is slightly important as Index B_j
$B_i/B_j = 5$	Obviously important	Index B_i is obviously important as Index B_j
$B_i/B_j = 7$	Strongly important	Index B_i is strongly important as Index B_j
$B_i/B_j = 9$	Extremely important	Index B_i is extremely important as Index B_j
2, 4, 6, 8	Intermediate values	The importance is between B_i and B_j above
Reciprocal	Reverse comparison	The opposite of B_i and B_j comparison above

Table 5 The judgement matrix of goal level of site selection

Site selection	Reservoir conditions	Rock properties	Economic costs
Reservoir conditions	1	3	5
Rock properties	1/3	1	2
Economic costs	1/5	1/2	1

Table 6 The judgement matrix of criterion level of rock properties

Rock properties	Permeability	Porosity	Reservoir type	Caprock type
Permeability	1	1	1/5	1/3
Porosity	1	1	1/5	1/3
Reservoir type	5	5	1	2
Caprock type	3	3	1/2	1

3.2.3 Calculate relative weight

According to the judgement matrix A_J, the relative weight A is calculated by Eqs. (3-6).

$$M_i = \prod_{j=1}^{n} a_{ij}, i = 1, 2, \ldots, n \tag{3}$$

$$W_i = \sqrt[n]{M_i}, i = 1, 2, \ldots, n \tag{4}$$

$$a_i = \frac{W_i}{\sum_{i=1}^{n} W_i}, i = 1, 2, \ldots, n \tag{5}$$

$$A = \left[a_1, a_2, \ldots, a_n\right]^T \tag{6}$$

Where M_i gives the importance of the B_i factor in the judgment matrix; W_i is the n roots of M_i; a_i means the weight coefficient; A is the weight coefficient.

3.2.4 Check consistency

Consistency test is conducted to check the accuracy between the importance of each index, in order to avoid the occurrence of A is more important than B, B is more important than C, and C is more important than A. The consistency of the weight coefficient is given by Eq. (7-9).

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A_J A)_i}{n a_i} \tag{7}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

Where $\lambda_{\max}$ is the maximum eigenvalue of the judgement matrix; CI is the consistency index and RI is the random consistency index selected in the Table 8; CR means the consistency ratio calculated in combination with CI and RI. If $CR \leqslant 0.1$, the consistency of the judgment matrix is considered reasonable; otherwise, reconstruct the judgement matrix and repeat steps in the above process until $CR \leqslant 0.1$.

Table 8 Values of the random consistency index (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.59

3.2.5 Evaluation results

The target oilfield properties and the composite weight of CO_2 storage site selection is shown in Table 9. The results show that the oilfield has more storage space, large injection capacity, high safety factor and low storage cost. The final score of the storage site is 86.07, recommended to storage.

Table 9 The relative weight of target oilfield

Indexes	Target oilfield	Weight
Deficit volume (×10^4t)	2852	0.3007
Depth (m)	3000	0.1131
Layer thickness (m)	446	0.0740
Water salinity (mg/L)	62428	0.0490
Current pressure (MPa)	10	0.0421
Layer temperature (℃)	126	0.0154
Reginal stability	Relatively stable	0.0340
Reservoir type	Sandstone	0.1190
Caprock type	Mudstone	0.0652
Porosity (%)	10.8	0.0327
Permeability (mD)	2.65	0.0327
Carbon source (km)	55	0.1221

4. ASSESSMENT OF CO_2 STORAGE POTENTIAL

4.1 Theoretical calculation

The evaluation of CO_2 storage potential is more simple than that of other storage media. In general, the CO_2 storage capacity can be calculated by the depleted volume of oil production in reservoir.

The theoretical storage capacity calculation equation is given by:

$$M_{CO_2} = \rho_{CO_2}(R_\mathrm{f} \bullet N_\mathrm{o} \bullet B_\mathrm{o} + V_\mathrm{iw} + V_\mathrm{pw}) \tag{10}$$

Where M_{CO_2} represents theoretical storage capacity of depleted reservoir, 10^8t; ρ_{CO_2} is CO_2 density under reservoir conditions, t/m^3; R_f is ultimate recovery, %; N_o means original oil in place, 10^8m^3; B_o represents crude oil volume factor; V_{iw} means water injection volume, 10^8m^3; V_{pw} is water production volume, 10^8m^3.

Considering that gas drive development is selected in the target reservoir, the dissolution storage capacity can be ignored. Therefore, it is assumed that only structural storage capacity is included, which means CO_2 injection volume occupies the depleted reservoir volume. It is known that CO_2 density under supercritical conditions is 60%-80% water density, taking 0.7t/m^3. The ultimate recovery of the optimal scheme is 44.46%; the original geological reserves are 6274.14×10^4t, and the crude oil volume factor is 1.1436. According to Eq. (10), the theoretical storage capacity is estimated to be 2791.55×10^4t.

The effective storage capacity calculation equation is given by:

$$M^*_{CO_2} = C_\mathrm{e} \bullet M_{CO_2} \tag{11}$$

Where $M^*_{CO_2}$ represents effective storage capacity of depleted reservoir, 10^8t; C_e means effective storage coefficient.

The effective storage coefficient is calculated by using Eq. (12):

$$C_e = C_\mathrm{m} C_\mathrm{b} C_\mathrm{h} C_\mathrm{w} C_\mathrm{a} \tag{12}$$

Where C_m represents mobility impact factor; C_b means buoyancy impact factor; C_h is reservoir heterogeneity impact factor; C_w represents water saturation impact factor; C_a means saline impact factor.

Based on empirical equations and storage cases, the effective storage coefficient is 0.55, including impact factors of mobility, buoyancy and heterogeneity on the effective storage coefficient. It is estimated that the effective storage capacity of supercritical CO_2 is 1535.35×10^4t by Eqs. (10-12).

4.2 Numerical simulation

The previous studies have shown that carbon dioxide can react with formation water to form carbonic acid in the process of injection and storage. The carbonated water can react with many minerals, such as calcite, dolomite, kaolinite and so on. When numerical simulation is performed, the Eqs (13-18) of ion chemical reaction need to be added.

$$\mathrm{CO_2(aq)+H_2O} \rightleftharpoons \mathrm{H_2CO_3} \rightleftharpoons \mathrm{H^+ + HCO_3^-} \rightleftharpoons \mathrm{2H^+ + CO_3^{2-}} \tag{13}$$

$$\mathrm{Calcite+H^+ = Ca^{2+} + HCO_3^-} \tag{14}$$

$$\mathrm{Dolomite+2H^+ = Ca^{2+} + Mg^{2+} + 2HCO_3^-} \tag{15}$$

$$\mathrm{Kaolinite+6H^+ = 5H_2O + 2SiO_2(aq) + 2Al^{3+}} \tag{16}$$

$$\mathrm{HCO_3^- + Ca^{2+}} \rightleftharpoons \mathrm{CaCO_3 + H^+} \tag{17}$$

$$\mathrm{HCO_3^- + Mg^{2+}} \rightleftharpoons \mathrm{MgCO_3 + H^+} \tag{18}$$

At stage of storage, the simulation capacity was nearly 2257.43×10^4t, the structural capacity composition was 73.43% and the mineral capacity composition was the least (3.46%). From simulation results, nearly 45% CO_2 of the produced gas, compared with storage capacity， we can achieve associated gas reinjection Net-zero emissions.

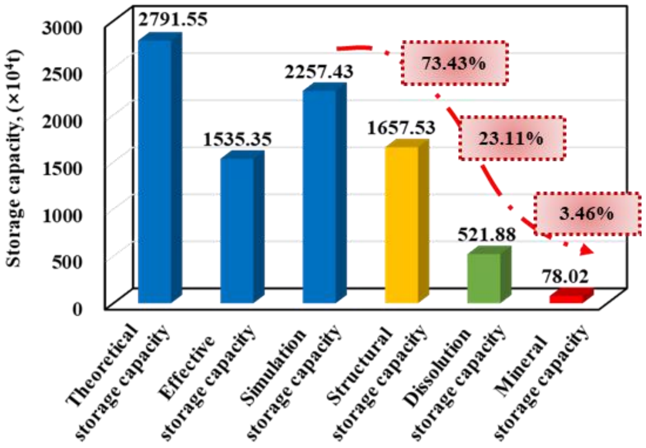
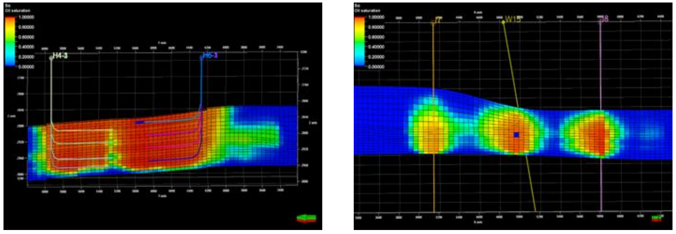


Fig. 14. Storage capacity results

As shown in Fig.15, the liquid carbon dioxide is continuously injected into horizontal wells. Due to the effects of gravity differentiation and formation heterogeneity, CO_2 tends to accumulate at the bottom of the reservoir to form structural storage. A small portion of CO_2 diffuses and dissolves into the water body, forming a relatively stable dissolution deposit. Very little carbon dioxide reacts with water and rock to form stable mineralized deposits.



(a) horizontal wells (b) vertical wells

Fig.15 CO_2 storage distribution in different well types

4.3 Analysis of storage benefits

CCUS-EOR is a green development technology that combines oil displacement and storage, also combines benefits and environmental protection. At present, the economic benefits directly restrict the development of CCUS-EOR projects. Therefore, as shown in Fig.16, the storage site removes greenhouse gas and the plant releases excess pollution gas under government global control. Based on carbon tax subsidies and greenhouse gas (e.g. CO_2, CH_4 and so on) trading, it is helpful to achieve the goal of Net-zero emissions through carbon trading market with regulation and allocation.

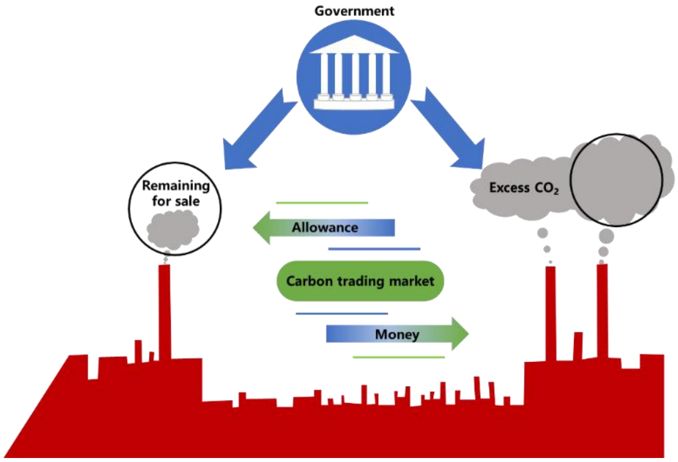


Fig. 16. Carbon trading flow chart

In this work, the economic evaluation of CO_2 storage project of target reservoir is constructed by actual carbon price referring to carbon trading market and carbon source company. In addition, the storage capacity is quantitatively converted into environmental dividends referring to the storage benefits of Shengli Oilfield.

Table 10 Carbon trading profits calculation

Effective storage capacity (simulation), $\times10^4$t	Trading price, yuan/t	Profits, million yuan
2257.43	58	13.09

Table 11 Environmental benefits calculation

Effective storage capacity (simulation), $\times10^4$t/a	Planting trees number, $\times10^4$	Parking cars number, $\times10^4$/a
225.74	2031.69	135.69

The process costs about 58 yuan for every ton of carbon trading, according to the carbon market price. The calculation of profits about 13.09 million yuan can be obtained in Table 10, combined with the simulation results of effective storage capacity. From the environmental perspective, The CCS project could capture CO_2 over 225.74×10^4t each year, which is equivalent to planting 2031.69×10^4 trees or shutting down 135.69×10^4 cars for one year, achieving oil displacement and storage synergetic optimization. Therefore, it is imperative to implement regulations, allowance and carbon taxes for achieving carbon-neutral.

5. SUMMARY AND CONCLUSIONS

This paper analyzes the effect of CO_2 miscible flooding in complex fault block reservoir, and proposes a new method of oil displacement and storage synergetic optimization through numerical simulation and theoretical calculation, which provides guidance for integrated CO_2 miscible flooding and storage technologies for complex fault block reservoirs with low permeability. Finally, This work draws the following 3 conclusions:

(1) At stage of injection, the cumulative oil increase reaches $4001.80\times10^4m^3$; the final recovery rate is 44.46%; the CO_2 storage capacity is 1657.53×10^4t; the CO2 storage ratio reaches 43.84%.

(2) Establish the novel evaluation system for storage site selection, showing that the oilfield has more storage space, large injection capacity, high safety factor and low storage cost. The final score is 86 points recommended to storage.

(3) At stage of storage, the effective storage capacity is 2257.48×10^4t achieving Net-zero emissions. The profit of carbon market is about 13 million yuan; The average annual storage capacity is about 225.74×10^4t, which is equivalent to planting 2031.69×10^4 trees or shutting down 135.69×10^4 cars for one year.

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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.

REFERENCE

[1] Wanfen Pu, Haiming Gao, Shuai Zhao, et al. Microscopic Oil Displacement Mechanism of CO2 in Low-Permeability Heterogeneous Glutenite Reservoirs in the Junggar Basin. ACS Omega 2022 7 (5), 4420-4428.

[2] Mengyu Wang, Shenglai Yang, Meng Li, et al. Influence of Heterogeneity on Nitrogen Foam Flooding in Low-Permeability Light Oil Reservoirs. Energy & Fuels, 2021 35 (5), 4296-4312.

[3] Zhengru Yang, Mohammadebrahim Shabani, Nisael Solano, et al. Experimental determination of gas-water relative permeability for ultra-low-permeability reservoirs using crushed-rock samples: Implications for drill cuttings characterization, Fuel, Volume 347, 2023, 128331, ISSN 0016-2361.

[4] Zijian Wei, J.J. Sheng. Study of thermally-induced enhancement in nanopores, microcracks, porosity and permeability of rocks from different ultra-low permeability reservoirs. Journal of Petroleum Science and Engineering, Volume 209, 2022, 109896, ISSN 0920-4105.

[5] Xiangzeng Wang, Hailong Dang, Tao Gao. Method of moderate water injection and its application in ultra-low permeability oil reservoirs of Yanchang Oilfield, NW China. Petroleum Exploration and Development, Volume 45, Issue 6, 2018, Pages 1094-1102, ISSN 1876-3804.

[6] Yong Wang, Yong Tang, Shilun Li, et al. Cyclic gas injection huff-n-puff in multi-stage fracturing horizontal wells to improve recovery of shale oil and gas reservoirs: Taking Eagle Ford Shale in North America as an example. Natural Gas Industry, 2023, 43(01): 153-161.

[7] Jiazheng Qin, Qianhu Zhong, Yong Tang, et al. CO2 storage potential assessment of offshore saline aquifers in China, Fuel, Volume 341, 2023, 127681, ISSN 0016-2361.

[8] Yueliang Liu, Zhenhua Rui. A Storage-Driven CO2 EOR for a Net-Zero Emission Target. Engineering, Volume 18, 2022, Pages 79-87, ISSN 2095-8099.

[9] Yueliang Liu, Ting Hu, Zhenhua Rui, et al. An Integrated Framework for Geothermal Energy Storage with CO2 Sequestration and Utilization. Engineering, 2023, ISSN 2095-8099.

[10] Amine Tadjer, Aojie Hong, Reidar B. Bratvold. A sequential decision and data analytics framework for maximizing value and reliability of CO2 storage monitoring. Journal of Natural Gas Science and Engineering, Volume 96, 2021, 104298, ISSN 1875-5100.

[11] Hongbing Ding, Yu Zhang, Yuanyuan Dong, et al. High-pressure supersonic carbon dioxide (CO2) separation benefiting carbon capture, utilisation and storage (CCUS) technology. Applied Energy, Volume 339, 2023, 120975, ISSN 0306-2619.

[12] Xinmin Song, Feng Wang, Desheng Ma, et al. Progress and prospect of carbon dioxide capture, utilization and storage in CNPC oilfields. Petroleum Exploration and Development, Volume 50, Issue 1, 2023, Pages 229-244, ISSN 1876-3804.

[13] Hasan N. Al-Saedi, Patrick V. Brady, Ralph E. Flori, et al. Insights into the role of clays in low salinity water flooding in sand columns. Journal of Petroleum Science and Engineering, Volume 174, 2019, Pages 291-305, ISSN 0920-4105.

[14] Yong Tang, Haochuan Zhang, Youwei He, et al. 2022. A novel type curve for estimating oil recovery factor of gas flooding. Petroleum Exploration and Development. 2022. 49(3): 9.

[15] Yong Tang, Shilai Hu, Yong Wang, et al. Phase behaviors of CO2 in the whole process of injection-fracturing-flowback: A case study of Well SH52 in a tight sandstone gas reservoir of the Shenmu Gas Field, Ordos Basin. 2019, 39(09): 58-64.

[16] Tengfei Wang, Liangliang Wang, Xingbang Meng, et al. Key parameters and dominant EOR mechanism of CO2 miscible flooding applied in low-permeability oil reservoirs. Geoenergy Science and Engineering, Volume 225, 2023, 211724, ISSN 2949-8910.

[17] Narendra Kumar, Marcio Augusto Sampaio, Keka Ojha, et.al. Fundamental aspects, mechanisms and emerging possibilities of CO2 miscible flooding in enhanced oil recovery: A review. Fuel, Volume 330, 2022, 125633, ISSN 0016-2361.

[18] Tolu A. Olukoga, Yin Feng. Determination of miscible CO2 flooding analogue projects with machine learning. Journal of Petroleum Science and Engineering, Volume 209, 2022, 109826, ISSN 0920-4105.

[19] Jiazheng Qin, Junjie Song, Yong Tang, et al. Well applicability assessment based on fuzzy theory for CO2 sequestration in depleted gas reservoirs. Renewable Energy, Volume 206, 2023, Pages 239-250, ISSN 0960-1481.

[20] Xiaolei Wang, Dongming Zhang, Erlei Su, et al. Pore structure and diffusion characteristics of intact and tectonic coals: Implications for selection of CO2 geological sequestration site. Journal of Natural Gas Science and Engineering, Volume 81, 2020, 103388, ISSN 1875-5100.

[21] Amirali Foukerdi, Sara Esmaeili, Abbas Shahrabadi. A hybrid FAHP-MCGP approach to sustainable assessment of candidate EOR methods for a given oil reservoir. Journal of Petroleum Science and Engineering, Volume 207, 2021, 109143, ISSN 0920-4105.

[22] Moein Besharati Fard, Donya Hamidi, Mehdi Ebadi, et al. Optimum landfill site selection by a hybrid multi-criteria and multi-Agent decision-making method in a temperate and humid climate: BWM-GIS-FAHP-GT. Sustainable Cities and Society, Volume 79, 2022, 103641, ISSN 2210-6707.

[23] Víctor Carlotto, Alexis Dueñas, Eusebio Ingol-Blanco, et al. A multi-criteria approach to the selection of geological storage of CO2 sites in Peru. International Journal of Greenhouse Gas Control, Volume 114, 2022, 103600, ISSN 1750-5836.

[24] Bin Liang, Hanqiao Jiang, Junjian Li, et al. Novel enhanced-oil-recovery decision-making work flow derived from the delphi-AHP-TOPSIS Method: A Case Study. SPE Reservoir Evaluation & Engineering, 2017, 21, 10.2118/176444-PA.

[25] Zhaoxu Mi, Fugang Wang, Yongzhi Yang, et al. Evaluation of the potentiality and suitability for CO2 geological storage in the Junggar Basin, northwestern China. International Journal of Greenhouse Gas Control, Volume 78, 2018, Pages 62-72, ISSN 1750-5836.

[26] Jie Zhan, Zezhong Su, Chao Fan, et al. Suitability Evaluation of CO2 Geological Sequestration Based on Unascertained Measurement. 2022, Arab J Sci Eng 47, 11453–11467.

[27] Liang Zhang, Shu Wang, Li Zhang, et al. Assessment of CO2 EOR and its geo-storage potential in mature oil reservoirs, Shengli Oilfield, China. Petroleum Exploration and Development, Volume 36, Issue 6, 2009, Pages 737-742.

[28] Curtis M. Oldenburg, Jennifer L. Lewicki, Laura Dobeck, et al. Modeling Gas Transport in the Shallow Subsurface During the ZERT CO2 Release Test. Transp Porous Med, 2010, 82, 77–92.

[29] Hao Shen, Zihao Yang, Xiaochen Li, et al. CO2-responsive agent for restraining gas channeling during CO2 flooding in low permeability reservoirs. Fuel, Volume 292, 2021, 120306, ISSN 0016-2361.

[30] Haibo Li, Zhengming Yang, Ruishan Li, et al. Mechanism of CO2 enhanced oil recovery in shale reservoirs, Petroleum Science, Volume 18, Issue 6, 2021, Pages 1788-1796, ISSN 1995-8226.

[31] Kaiqiang Zhang, Na Jia, Songyan Li, et al. Millimeter to nanometer-scale tight oil–CO2 solubility parameter and minimum miscibility pressure calculations, Fuel, Volume 220, 2018, Pages 645-653, ISSN 0016-2361.

[32] Zhou Yuan, Xinwei Liao, Kuaile Zhang, et al. The effect of inorganic salt precipitation on oil recovery during CO2 flooding: A case study of Chang 8 block in Changqing oilfield, NW China. Petroleum Exploration and Development, Volume 48, Issue 2, 2021, Pages 442-449, ISSN 1876-3804.

[33] Xiaoying Han, Shang Deng, Liangjie Tang, et al. Geometry, kinematics and displacement characteristics of strike-slip faults in the northern slope of Tazhong uplift in Tarim Basin: A study based on 3D seismic data. Marine and Petroleum Geology, Volume 88, 2017, Pages 410-427, ISSN 0264-8172.

[34] Hui Li, Chengyan Lin, Lihua Ren, et al. An Integrated quantitative modeling approach for fault-related fractures in tight sandstone reservoirs. Journal of Petroleum Science and Engineering, Volume 194, 2020, 107552, ISSN 0920-4105.

[35] Frode Ungar, Sourabh Ahitan, Shawn Worthing, et al. A new fluidics method to determine minimum

miscibility pressure, Journal of Petroleum Science and Engineering, Volume 208, Part B, 2022, 109415, ISSN 0920-4105.