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# Design of a $CO_2$ Enhanced Oil Recovery Reservoir Adaptability Scheme

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## ABSTRACT

$CO_2$ enhanced oil recovery (EOR) is a widely adopted and efficient method to improve oil recovery rates. Injecting $CO_2$ into a reservoir not only effectively sequesters $CO_2$ but also significantly enhances crude oil recovery. However, not all reservoirs are suitable for $CO_2$ injection, and reservoirs lacking appropriate conditions for $CO_2$ EOR may not yield better oil recovery results. Therefore, prior to reservoir development, an adaptability assessment for $CO_2$ EOR is essential. This paper uses grey relational analysis to calculate the grey relational degree and derive evaluation indicators, ranking the correlation and importance of crude oil recovery. After calculating the impact of various factors on oil recovery and the interrelationship between the indicators, evaluation criteria are selected to assess the adaptability of the reservoir for $CO_2$ EOR. A comprehensive evaluation of reservoir adaptability to $CO_2$ injection is conducted using cluster analysis, with applications to the Daqing and Jilin oil fields. The results demonstrate that the proposed method for indicator selection and the adaptability evaluation for $CO_2$ EOR is highly effective and reliable. The use of cluster analysis to evaluate the adaptability of $CO_2$ EOR in reservoirs can significantly enhance oil recovery, providing practical value. This method can be widely applied in actual reservoir development, offering theoretical guidance for field operations, and holds broad application prospects.

## KEYWORDS

$CO_2$ Enhanced Oil Recovery; Grey Relational Analysis; Cluster Analysis; Evaluation Indicator Selection; Scheme Design.

## 1. INTRODUCTION

With the rapid advancement of industrialization worldwide, the amount of greenhouse gases has continuously risen, with carbon dioxide ($CO_2$) being a significant component, accounting for 65% of the total. Excessive $CO_2$ emissions exacerbate global climate change. Utilizing $CO_2$ for enhanced oil recovery (EOR) allows for $CO_2$ sequestration in reservoirs, thereby reducing $CO_2$ emissions and mitigating climate change. The $CO_2$ EOR technology is cost-effective, environmentally friendly, and safe, effectively addressing carbon storage issues while significantly improving crude oil recovery rates. This technology not only enhances the supply of oil and gas resources but also contributes to environmental protection, reduces carbon emissions, and promotes sustainable energy development, yielding important economic, social, and environmental benefits.

China's natural $CO_2$ resources are relatively limited, yet research on $CO_2$ injection for enhanced oil recovery and field trials has never ceased. The difficulty of exploiting these newly discovered and developed reservoirs in China continues to increase. Among various injection gases, $CO_2$ EOR outperforms other gases, making it one of the fastest-developing and most effective methods, as $CO_2$ helps to reduce the greenhouse effect. In the context of carbon peak and carbon neutrality goals, $CO_2$ injection satisfies the dual requirements of enhanced oil recovery and carbon sequestration. Currently, low-permeability reservoirs are mostly developed using fracturing techniques. However, due to the rapid depletion of natural energy and the strong influence of capillary pressure effects, traditional water injection methods face many challenges. In contrast, gases such as $CO_2$ and natural gas have stronger injection capabilities, facilitating phase mixing with crude oil. Although $CO_2$ EOR started later in China's oilfields, it has considerable development potential. After 2009, $CO_2$ EOR has been widely applied in tertiary recovery, and due to its significant carbon emission reduction and economic advantages, it plays a crucial role in the redevelopment of water-flooded and depleted oilfields. For most of China's oilfields, most reservoirs are terrigenous sedimentary, and oil recovery after water injection is not significant. For low-permeability and ultra-low permeability reservoirs that commonly use fracturing techniques, water injection significantly improves short-term production, but quickly leads to increased water cut and reduced oil output. However, $CO_2$, due to its ability to mix and dissolve with oil, extract light hydrocarbons, and reduce oil viscosity and interfacial tension, has become a favored method for enhanced oil recovery. $CO_2$ has lower viscosity and stronger injection capacity than water. Due to the depletion of conventional oil reserves and the abundant but low-recovery tight oil resources, scholars have paid extensive attention to $CO_2$ EOR for tight oil reservoirs in recent decades.

The use of $CO_2$ for enhanced oil recovery can be traced back to the 1950s, when $CO_2$ was used as a non-miscible displacing agent. It wasn't until the 1970s that research on the solubility of $CO_2$ in crude oil with multi-stage contact spurred the development of $CO_2$ miscible flooding technology. The $CO_2$ miscible flooding technology has been extensively tested in countries such as the United States and the former Soviet Union, with results indicating a 15-25% improvement in recovery rates. Countries like the United States, the former Soviet Union, and Canada have already adopted $CO_2$ as a key technology to enhance oil recovery. By 2006, out of 94 $CO_2$-based projects, 82 were implemented in the United States, including all miscible flooding projects at that time. The U.S. has become one of the fastest-growing countries in $CO_2$ EOR development. In the 1950s, the Soviet Union pioneered the exploration of $CO_2$ injection technology to improve recovery efficiency. In Turkey, $CO_2$ flooding for heavy oil replacement has been widely applied and has proven successful. Reports indicate that Canada has injected $CO_2$ into reservoirs for four consecutive years, resulting in an increased oilfield output of 1,800,000 tons, a 50% increase compared to previous years.

## 2. $CO_2$ ENHANCED OIL RECOVERY RESERVOIR CHARACTERISTICS AND EVALUATION ADAPTABILITY INDICATORS

### 2.1. Basic Concept of $CO_2$ Enhanced Oil Recovery (EOR)

$CO_2$ enhanced oil recovery (EOR) is an efficient oil recovery technology that involves injecting carbon dioxide ($CO_2$) into a reservoir to improve crude oil recovery rates by utilizing its unique physicochemical properties. This method is particularly effective for medium- to low-permeability reservoirs and small block reservoirs with poor waterflooding performance.

The primary mechanisms of $CO_2$ EOR include:

Dissolved gas displacement mechanism: $CO_2$ dissolves into crude oil, reducing its viscosity and enhancing its flowability;

Alternate adsorption mechanism: $CO_2$ molecules interact with the components of crude oil, alternating adsorption and reducing the oil's viscosity and interfacial tension, thereby enhancing oil flowability;

Increased oil saturation mechanism: $CO_2$ enters and dissolves into residual oil layers, increasing the oil saturation and making more crude oil available for recovery;

Increased reservoir pressure mechanism: The injection of $CO_2$ raises the displacement pressure within the reservoir, enhancing the ability of crude oil to flow towards the production well.

$CO_2$ EOR significantly improves the development of medium- and low-permeability reservoirs. The injected $CO_2$ not only facilitates crude oil expansion and viscosity reduction, but also enables miscible displacement and replenishes reservoir energy, thus improving displacement efficiency. Additionally, the injection of $CO_2$ can reduce the reservoir's permeability and lower the initial reservoir pressure, which is beneficial for enhancing subsequent injection capacity. As a result, $CO_2$ EOR technology has been widely validated and successfully applied in the field, demonstrating its significant effectiveness in improving overall oil recovery rates.

## 2.2. Characteristics of $CO_2$ Enhanced Oil Recovery Reservoirs

$CO_2$ EOR technology has been extensively applied to reservoirs with complex geological conditions, especially in the development of hard-to-recover oil reserves. Limestone, dolomite, and sandstone reservoirs are all suitable for $CO_2$ EOR. After prolonged development, the geological characteristics of these reservoirs are well-understood, facilitating the efficient application of $CO_2$ EOR to enhance recovery rates. Furthermore, it enables the safe and efficient geological sequestration of $CO_2$, providing dual benefits in both environmental protection and economic gain.

$CO_2$ geological sequestration aims to reduce greenhouse gas emissions and mitigate climate change by injecting $CO_2$ into underground reservoirs, where it is physically and chemically trapped over the long term. Oil and gas fields, coal seams, and salt formations are all potential candidates for geological sequestration. However, the implementation of this process requires careful consideration of key aspects such as reservoir selection, $CO_2$ injection volume control, leakage monitoring, and geological risk assessment. Specifically:

A detailed geological analysis of depleted oil reservoirs is conducted to assess parameters such as thickness, porosity, permeability, and rock type, ensuring that $CO_2$ can be safely and effectively stored over the long term;

The $CO_2$ injection volume must be strictly controlled to avoid excessive reservoir pressure, which could trigger seismic events, subsidence, or other geological hazards;

A long-term monitoring system must be established to detect and address $CO_2$ leakage risks in a timely manner;

Before $CO_2$ injection, a comprehensive risk assessment of the reservoir and surrounding geological environment should be conducted, and appropriate risk management measures should be implemented.

$CO_2$ EOR and sequestration technologies combine both oil recovery and carbon storage functions. By injecting $CO_2$ into the reservoir, these technologies maintain reservoir pressure, reduce crude oil viscosity, and enhance recovery rates. Compared to traditional waterflooding, $CO_2$ EOR offers advantages such as lower viscosity, higher recovery rates, and greater injection capacity. A portion of the injected $CO_2$ remains trapped in the reservoir, achieving long-term storage, while another portion can be recycled, further enhancing economic returns and achieving environmental protection goals. Therefore, $CO_2$ EOR and sequestration is an ideal solution that balances both economic and environmental benefits.

## 2.3. Reservoir Evaluation Indicator Standards

Reservoir Type and Characteristics: The specific characteristics of a reservoir are directly related to the complexity of its exploration and development. Therefore, relevant evaluation indicators must be selected accordingly.

Purpose and Application Scenario: The selection of reservoir evaluation indicators should be tailored to the specific objectives and practical application scenarios of the evaluation process.

Reliability and Accuracy: The chosen indicators must demonstrate sufficient reliability and accuracy to ensure the robustness of the evaluation results.

Economic Feasibility and Operability: The economic aspects and practical feasibility of the indicators should be considered to ensure their applicability in real-world engineering contexts.

Comprehensiveness and Applicability: The indicators should be comprehensive and broadly applicable, reflecting the integrated performance of the reservoir under evaluation.

### 2.3.1. Reservoir Property Indicators

(1) Reservoir Depth

To ensure that the reservoir pressure meets the minimum miscibility pressure required for $CO_2$ miscible flooding and to maintain caprock integrity during gas injection, a certain burial depth is required for $CO_2$ EOR projects. However, as reservoir depth increases, the minimum miscibility pressure also rises, thereby increasing the complexity, risk, and capital expenditure of the engineering operation. Consequently, an upper limit for reservoir depth must be considered in the evaluation process.

**Table 1** Reservoir Depth Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Reservoir Depth (m) | 1500-2000 | 2000-2500<br>1200-1500 | 2500-3000<br>1000-1200 | 3000-3500<br>800-1000 | >3500<br><800 |

(2) Reservoir Pressure

As the pressure within the reservoir increases, the miscibility phenomenon becomes more pronounced. Concurrently, higher pressures lead to greater risks, which can significantly impact the overall effectiveness of reservoir exploitation. Therefore, it is essential to establish an appropriate pressure threshold for the reservoir.

**Table 2** Reservoir Pressure Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Reservoir Pressure (MPa) | 15-20 | 20-25<br>12-15 | 25-30<br>10-12 | 30-35<br>8-10 | >35<br><8 |

(3) Reservoir Temperature

The minimum miscibility pressure of a specific reservoir is significantly influenced by the reservoir temperature. As the extraction capacity of light hydrocarbons decreases with temperature, higher pressure is required to achieve miscibility by increasing $CO_2$ density. Additionally, as the reservoir temperature rises, the viscosity of crude oil increases, which is detrimental to $CO_2$ enhanced oil recovery. Therefore, it is essential to maintain the reservoir temperature within an optimal range.

**Table 3** Reservoir Temperature Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Reservoir Temperature (°C) | 80-90 | 90-100<br>70-80 | 100-110<br>60-70 | 100-120<br>50-60 | 120<br>55-60 |

(4) Reservoir Dip Angle

The reservoir dip angle significantly influences gravity drainage, which has become an effective method for improving oil sweep efficiency and crude oil recovery. In inclined reservoirs, $CO_2$ can be injected from the uppermost position, maintaining a low displacement velocity, allowing $CO_2$ to separate from the crude oil without viscous fingering. The calculation formula is given by Equation (2-1):

$$\nabla_c = \frac{g\Delta\rho_{oR}\sin\alpha}{\mu_o/k_o-\mu_g/k_g} \tag{1}$$

In the equation:

vc——Maximum injection velocity, cm/s;

ΔρOR——Density difference between oil and $CO_2$, kg/cm$^3$;

μo，μg——Viscosity of oil and $CO_2$, mPa·s;

ko，kg——Permeability of oil and $CO_2$, $10^{-3}$ μm$^2$;

α——Reservoir dip angle, (°).

The results indicate that a larger reservoir dip angle is preferable.

**Table 4** Reservoir Dip Angle Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Reservoir Dip Angle (°) | >70 | 50-70 | 30-50 | 10-30 | <10 |

(5) Reservoir Thickness

Reservoir thickness refers to the thickness of the formation that contains oil and gas. An increase in reservoir thickness introduces greater heterogeneity between layers. However, as the reservoir thickness decreases, the gravitational release of $CO_2$ is reduced, allowing $CO_2$ to disperse more evenly within the formation. Therefore, as the reservoir thickness decreases, the development becomes more efficient.

**Table 5** Reservoir Thickness Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Reservoir Thickness (m) | <10 | 10-20 | 20-30 | 30-40 | >40 |

### 2.3.2. Rock Property Indicators

(1) Porosity

Porosity refers to the ratio of the volume of voids (pores) to the total volume of a rock or soil. The magnitude of porosity is typically determined by various factors, including the rock or soil type, formation process, and its physical and chemical characteristics. For $CO_2$-driven oil wells, effective porosity may not necessarily be high. This is due to the occurrence of phenomena such as supercritical flow and viscous fingering, which prevent the attainment of miscibility conditions. Therefore, porosity must fall within an optimal range for efficient $CO_2$ injection and enhanced oil recovery.

**Table 6** Effective Porosity Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Effective Porosity (%) | 10-15 | 15-20 | 20-25 | 25-30 | >30 |
| | | 8-10 | 6-8 | 4-6 | <4 |

(2) Wettability

The wettability of reservoir rocks refers to the property of the reservoir rock surface in relation to the wetting of fluids such as oil and gas. The formula is as follows:

$$W_w = \frac{V_{o1}}{V_{o1}+V_{o2}} \tag{2}$$

$$W_o = \frac{V_{w1}}{V_{w1}+V_{w2}} \tag{3}$$

In the equation:

Vo1——Automatic water absorption and oil displacement volume;

Vo2——Centrifugal water absorption and oil displacement volume;

Vw1——Automatic oil absorption and water displacement volume;

Vw2——Centrifugal oil absorption and water displacement volume.

The results indicate that a larger oil-wet index is preferable.

**Table 7** Wettability Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Oil Wetting Index | 0.8-1 | 0.6-0.8 | 0.4-0.6 | 0.2-0.4 | 0-0.2 |

(3) Heterogeneity

Rock heterogeneity is primarily caused by original sedimentary processes, but may also result from subsequent diagenetic alterations and structural changes. Reservoir heterogeneity significantly influences the effectiveness of $CO_2$ flooding and plays a critical role in reservoir evaluation.

**Table 8** Heterogeneity Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Heterogeneity | <0.5 | 0.5-0.55 | 0.55-0.6 | 0.6-0.65 | >0.65 |

### 2.3.3. Crude Oil Property Indices

(1) Oil Saturation

Oil saturation refers to the proportion of the pore volume in the rock that is occupied by oil, and its value can be expressed as a percentage or a decimal. In the process of $CO_2$ miscible flooding, if the oil saturation is less than 25%, the expected displacement efficiency cannot be achieved. Therefore, considering all factors, higher oil saturation enhances the effectiveness of $CO_2$ miscible flooding in reservoirs.

**Table 9** Oil Saturation Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Oil Saturation (%) | >70 | 55-70 | 40-55 | 25-40 | <40 |

(2) Crude Oil Density

Crude oil with different densities exerts varying impacts on oil displacement efficiency. Generally, the higher the density, the greater the content of heavy components, leading to higher viscosity and lower oil displacement efficiency. Therefore, lower crude oil density is more favorable for $CO_2$ injection and EOR.

**Table 10** Crude Oil Density Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Crude Oil Density ($g/cm^3$) | <0.82 | 0.82-0.86 | 0.86-0.88 | 0.88-0.90 | >0.90 |

(3) Crude Oil Viscosity

Crude oil viscosity characterizes the resistance to flow within a specified temperature range. As viscosity increases, oil mobility decreases; conversely, lower viscosity enhances mobility. Higher oil viscosity accelerates the consumption of displacement energy and, during $CO_2$ injection, can result in premature $CO_2$ breakthrough due to viscous fingering. Therefore, lower viscosity enhances the effectiveness of $CO_2$ EOR.

**Table 11** Crude Oil Viscosity Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Viscosity (mPa·s) | <2 | 2-4 | 4-8 | 8-10 | >10 |

**Table 12** $CO_2$ Miscible Flooding Reservoir Index Evaluation Table

| Evaluation | Good | Fairly Good | Moderate | Fairly Poor | Poor |
|---|---|---|---|---|---|
| Reservoir Depth (m) | 1500-2000 | 2000-2500 | 2500-3000 | 3000-3500 | >3500 |
| | | 1200-1500 | 1000-1200 | 800-1000 | <800 |
| Reservoir Pressure (MPa) | 15-20 | 20-25 | 25-30 | 30-35 | >35 |
| | | 12-15 | 10-12 | 8-10 | <8 |
| Reservoir Temperature (°C) | 80-90 | 90-100 | 100-110 | 100-120 | 120 |
| | | 70-80 | 60-70 | 50-60 | 55-60 |
| Reservoir Dip Angle (°) | >70 | 50-70 | 30-50 | 10-30 | <10 |
| Reservoir Thickness (m) | <10 | 10-20 | 20-30 | 30-40 | >40 |
| Effective Porosity (%) | 10-15 | 15-20 | 20-25 | 25-30 | >30 |
| | | 8-10 | 6-8 | 4-6 | <4 |
| Permeability ($10^{-3}$ μ$m^2$) | 0.1 | 10-50 | 50-200 | 200-500 | >500 |
| Oil Wetting Index | 0.8-1 | 0.6-0.8 | 0.4-0.6 | 0.2-0.4 | 0-0.2 |
| Heterogeneity (Permeability Variation Coefficient) | <0.5 | 0.5-0.55 | 0.55-0.6 | 0.6-0.65 | >0.65 |
| Oil Saturation (%) | >70 | 55-70 | 40-55 | 25-40 | <40 |
| Crude Oil Density ($g/cm^3$) | <0.82 | 0.82-0.86 | 0.86-0.88 | 0.88-0.90 | >0.90 |
| Viscosity (mPa·s) | <2 | 2-4 | 4-8 | 8-10 | >10 |

As shown in Table 12, this chapter establishes reservoir evaluation index standards for $CO_2$ flooding by analyzing reservoir characteristics and referencing previous studies. Based on research and summary, it is concluded that reservoirs suitable for $CO_2$ injection should meet the following criteria: reservoir depth should be greater than 800 m and less than 3500 m; reservoir pressure should be within the range of 10–30 MPa; reservoir temperature between 60–110°C; reservoir dip angle greater than 30°; reservoir thickness less than 30 m; porosity between 6% and 25%; permeability between 0.1 and 200 mD; wettability index >0.4; permeability variation coefficient <0.4; oil saturation >40%; crude oil density <0.88 $g/cm^3$; crude oil viscosity <8 mPa·s; and crude oil gravity within the range of 25–48°API.

# 3. CORRELATION ANALYSIS BETWEEN $CO_2$ ENHANCED OIL RECOVERY RESERVOIR INDICATORS

Cluster analysis is a method used to compare various attributes of objects directly. Objects with similar properties are grouped into the same category, while those with significant differences are classified into different categories. Cluster analysis is useful for data preprocessing because it allows complex structured multivariate data to be summarized, standardizing the data. Similarities between data can be distinguished using distance metrics or similarity coefficients.

## 3.1. Classification of Cluster Analysis Algorithms

Cluster analysis algorithms can be broadly classified into five categories based on their methods of application:

Partition-Based Clustering Methods

For a given dataset D containing n data objects, the data objects are organized into k（$k \leq n$） sub-regions, with each sub-region representing a cluster. Additionally, these k clusters must satisfy two conditions: each cluster must contain at least one data point, and each data point must belong to only one cluster.

Hierarchical Clustering Methods

Hierarchical clustering methods involve the hierarchical allocation of data until certain conditions are met. Data nodes are progressively merged based on their similarity, from high to low. However, hierarchical clustering algorithms suffer from issues such as computational complexity, irreversibility, and sensitivity to noise and outliers.

Density-Based Clustering Methods

The core idea of this method is to find regions of varying density within the dataset and partition these regions into different clusters.

Grid-Based Clustering Methods

Grid-based clustering methods are algorithms based on grid partitioning. They divide the dataset into multiple grids, each of which is considered a cluster. The goal of this method is to minimize the sum of squared distances between data points and the center of each grid.

Model-Based Clustering Methods

In this method, a model is defined for each cluster, and data points are assigned to the model corresponding to their characteristics. Model-based clustering methods are a type of probabilistic model-based algorithm. They assume that the dataset is a mixture of multiple probability distributions and attempt to fit the parameters of these distributions to achieve clustering.

## 3.2. Cluster Analysis Research Objects

This study focuses on reservoirs as the research objects, where each reservoir represents a sample containing numerous variables. By performing a comprehensive analysis of indicator variables, the reservoirs are classified into several categories, and the $CO_2$ flooding adaptability of the reservoirs is evaluated.

Given n reservoirs, each with m indicator variables, the matrix of the original observational data can be defined as follows:

$$X=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{4}$$

In the equation, xij（i=1,2,⋯,n；j=1,2,⋯,m） represents the observed value of the jth variable for the iiith reservoir.

### 3.3. Data Transformation Processing for Cluster Analysis

Prior to conducting cluster analysis, it is necessary to transform the original observational data. This is because, during computation, discrepancies in dimensions and magnitudes among the various indicators prevent direct comparisons. To address this issue, data transformation is typically required to ensure the accuracy and reliability of the results. The following are four commonly used data transformation methods:

(1) Mean Centering Transformation

Let xij′denote the mean-centered data, and xij denote the original observed data. $\overline{x_j}=\frac{1}{n}\sum_{i=1}^{n}x_{ij}$is the mean of the jth variable. The transformation formula is:

$$x_{ij}^{'}=x_{ij}-\overline{x_j},(i=1,2,\cdots,n;j=1,2,\cdots,m) \tag{5}$$

where n is the number of reservoirs, and m is the number of variables.

The characteristic of this method is that, after transformation, the sum of each column is zero.

(2) Range Normalization Transformation

First, the maximum $\underset{1\le i\le m}{max}\{x_{ij}\}$and minimum $\underset{1\le i\le m}{min}\{x_{ij}\}$values of each variable are identified. The difference between the maximum and minimum values is called the range. This method distributes the values of each column within the range of 0 to 1. The transformation formula is:

$$x_{ij}^{'}=\frac{x_{ij}-\underset{1\le i\le m}{min}\{x_{ij}\}}{\underset{1\le i\le m}{max}\{x_{ij}\}-\underset{1\le i\le m}{min}\{x_{ij}\}},(i=1,2,\cdots,n;j=1,2,\cdots,p) \tag{6}$$

(3) Logarithmic Transformation

Logarithmic transformation refers to applying the logarithm to the data. This method is inherently suitable for converting exponential-type data into a linear form. The formula is:

$$x_{ij}^{'}=log\{x_{ij}\},x_{ij}>0,(i=1,2,\cdots,n;j=1,2,\cdots,p) \tag{7}$$

(4) Standardization (Z-score Normalization)

The purpose of standardization is to alter the properties of the variables by first mean-centering each column in the matrix and then dividing the processed data by the column’s standard deviation. The result is that each column has a mean of zero and a variance of one, thereby eliminating the effects of differing dimensions. After standardization, the data are relatively stable and not arbitrarily variable.

$$\overline{x_j}=\frac{1}{n}\sum_{i=1}^{n}x_{ij} \tag{8}$$

$$S_j=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ij}-\overline{x_j}\right)^2},(i=1,2,\cdots n;j=1,2,\cdots,m) \tag{9}$$

$$x_{ij}^{'}=\frac{x_{ij}-\overline{x_j}}{S_j} \tag{10}$$

where:

n — number of reservoirs;

m— number of indicators;

$\overline{x_j}$— sample mean;

$S_j$— standard deviation;

$x_{ij}^{'}$— standardized data;

$x_{ij}$— original observed data.

### 3.4. Similarity Measurement in Cluster Analysis

(1) Distance Metrics

In n-dimensional space, each sample (reservoir) is treated as an independent point. The geometric distance between these points defines their similarity: points that are closer together are more similar and can be classified into the same category; points farther apart have lower similarity and are classified differently. The sample matrix is defined as:

$$X = \begin{array}{c} \\ X_1 \\ X_2 \\ X_3 \\ X_4 \end{array} \begin{array}{c} \begin{array}{cccc} x_1 & x_2 & \cdots & x_m \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \end{array} \tag{11}$$

There are multiple ways to represent the distance d(x,y), with the Minkowski distance being the most commonly used, as follows:

$$d(x,y) = [\sum_{i=1}^{m} |x_i - y_i|^q]^{\frac{1}{q}}, (q > 0) \tag{12}$$

$$d(x,y) = \sum_{i=1}^{m} |x_i - y_i|, (q = 1) \tag{13}$$

$$d(x,y) = [\sum_{i=1}^{m} |x_i - y_i|^2]^{\frac{1}{2}}, (q = 2) \tag{14}$$

where d(x,y) is the distance, and P is the number of indicator variables.

(2) Similarity Coefficients

In addition to using distance, similarity coefficients can also be employed to evaluate sample similarity. The more similar the samples, the closer the similarity coefficient approaches positive or negative one; for unrelated samples, the coefficient tends toward zero. This determines whether the samples are similar in nature.

## 4. ANALYSIS OF GAS INJECTION EFFECT AND OPTIMIZATION OF EVALUATION INDICATORS

### 4.1. Evaluation and Analysis of $CO_2$ Flooding Adaptability

#### 4.1.1. Cluster Analysis Method for Evaluation

(1) Data Collection

Relevant data samples required for cluster analysis are collected, and the clustering objectives are determined. In this study, reservoirs are selected as the research objects. The dataset includes parameters from both domestic and international reservoirs where $CO_2$ flooding has been successfully implemented, as well as reservoirs from Daqing Oilfield North District 1 (East and West Fault Blocks) and the Bei Fang 48 fault block in the Songliao Basin.

(2) Data Transformation and Processing

Based on the classification objects and indicator variables, data transformation is conducted to eliminate the influence of dimensional units, thereby facilitating data comparison and analysis.

(3) Similarity Measurement

This step is crucial in the clustering analysis process. To assess the correlation between samples, distance or similarity coefficients are adopted as the criteria for constructing the similarity matrix.

(4) Hierarchical Cluster Analysis

A systematic hierarchical clustering method is selected based on the established similarity matrix, and the clustering analysis is performed in combination with practical examples. Hierarchical cluster analysis groups the samples successively from the closest to the most distant, gradually merging categories until all samples are incorporated into a single cluster according to the classification criteria.

## 4.2. Optimization of Evaluation Indicators

### 4.2.1. Screening of Evaluation Indicators by Cluster Analysis

Based on the actual development status of the reservoirs, the results of the cluster analysis are summarized to obtain the final classification and to evaluate the adaptability of reservoirs to $CO_2$ flooding. The results of the analysis are shown in Tables 4-1, 4-2, and 4-3.

**Table 13** Data Transformation Processing Table

| Index | Wettability (Oil Wetting Index) | Oil Saturation (%) | Density ($g/cm^3$) | Reservoir Temperature (°C) | Reservoir Pressure (MPa) | Heterogeneity | RQI | Reservoir Thickness (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.4361 | -0.6762 | 0.1081 | -1.6132 | -1.1974 | -0.3594 | 0.8258 | -2.0335 |
| 2 | -1.4341 | -0.7865 | -0.4332 | 0.3011 | 0.3626 | 1.4391 | -0.7597 | 0.3292 |
| 3 | -2.0575 | -1.7822 | -0.0267 | 0.7723 | 0.6523 | 1.6192 | -1.0796 | 0.7293 |
| 4 | -0.3117 | 0.0969 | -0.1893 | -0.4508 | 0.0521 | 0.8993 | -1.2911 | -0.3091 |
| 5 | 0.0619 | 0.5281 | -0.7314 | 1.0532 | 1.3975 | -0.7192 | 0.1723 | 0.9684 |
| 6 | 0.3112 | 0.9373 | -0.4331 | 1.0909 | 1.4079 | -0.8991 | 0.8498 | 1.0001 |
| 7 | 0.5608 | -0.8201 | 0.7042 | -0.1899 | -0.5473 | 0.1795 | 1.3033 | -0.0872 |
| 8 | 0.8102 | 0.0968 | 0.2433 | -0.9051 | -0.9962 | -0.5394 | 0.1902 | -0.6949 |
| 9 | 0.6859 | 1.2028 | 2.2758 | -1.1118 | -1.3184 | -0.3596 | 0.9881 | -0.8704 |
| 10 | 0.9351 | 1.2028 | -1.5169 | 1.0536 | 0.1863 | -1.2593 | -1.1995 | 0.9683 |

**Table 14** Similarity Matrix Table

| Reservoir | Squared Euclidean Distance | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 0.000 | 21.248 | 31.771 | 13.206 | 25.722 | 26.520 | 7.146 | 3.527 | 9.940 | 29.388 |
| 2 | 21.248 | 0.000 | 2.1447 | 3.746 | 11.637 | 16.254 | 12.369 | 15.458 | 28.361 | 19.235 |
| 3 | 31.771 | 2.144 | 0.000 | 10.108 | 18.065 | 23.997 | 19.112 | 25.680 | 39.944 | 28.750 |
| 4 | 13.206 | 3.746 | 10.108 | 0.000 | 11.094 | 14.910 | 10.133 | 7.172 | 17.714 | 13.128 |
| 5 | 25.722 | 11.637 | 18.065 | 11.094 | 0.000 | 0.811 | 12.668 | 14.071 | 26.140 | 5.475 |
| 6 | 26.520 | 16.254 | 23.997 | 14.910 | 0.811 | 0.000 | 12.470 | 14.623 | 23.655 | 7.459 |
| 7 | 7.146 | 12.369 | 19.112 | 10.133 | 12.668 | 12.470 | 0.000 | 3.954 | 9.028 | 20.714 |
| 8 | 3.527 | 15.458 | 25.680 | 7.172 | 14.071 | 14.623 | 3.954 | 0.000 | 6.213 | 14.800 |
| 9 | 9.940 | 28.361 | 39.944 | 17.714 | 26.140 | 23.655 | 9.028 | 6.213 | 0.000 | 30.394 |
| 10 | 29.388 | 19.235 | 28.750 | 13.128 | 5.475 | 7.459 | 20.714 | 14.800 | 30.394 | 0.000 |

The similarity matrix reflects the degree of similarity between the reservoir samples. By utilizing distance metrics, the similarity among reservoirs can be evaluated, allowing for further classification.

**Table 15** Agglomerative Clustering Process Table

| Step | Cluster Combination | | Coefficient | First Appearance Step | | Next Step |
|---|---|---|---|---|---|---|
| | Cluster 1 | Cluster 2 | | Cluster 1 | Cluster 2 | |
| 1 | 5 | 6 | 0.811 | 0 | 0 | 5 |
| 2 | 2 | 3 | 2.144 | 0 | 0 | 6 |
| 3 | 1 | 8 | 3.527 | 0 | 0 | 4 |
| 4 | 1 | 7 | 5.550 | 3 | 0 | 7 |
| 5 | 5 | 10 | 6.467 | 1 | 0 | 8 |
| 6 | 2 | 4 | 6.927 | 2 | 0 | 8 |
| 7 | 1 | 9 | 8.394 | 4 | 0 | 9 |
| 8 | 2 | 5 | 17.452 | 6 | 5 | 9 |
| 9 | 1 | 2 | 20.556 | 7 | 8 | 0 |

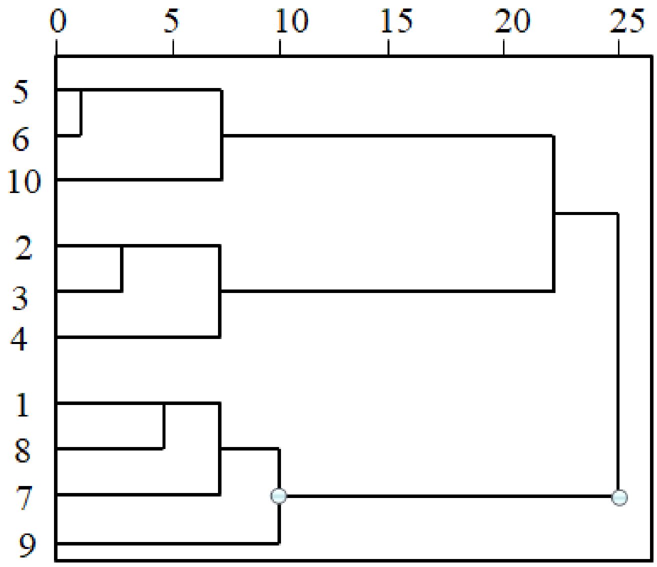

**Fig 1.** Dendrogram of Cluster Analysis

As shown in Fig 1, the final result of the cluster analysis indicates that, after successive merging steps, all reservoirs are ultimately grouped into a single major category. Classification can be performed according to various criteria, provided that the results are consistent with the actual characteristics of the reservoirs.

Research indicates that parameters such as oil saturation, wettability, reservoir temperature, crude oil density, reservoir heterogeneity, reservoir pressure, reservoir thickness, and Reservoir Quality Index (RQI) can be used as evaluation indicators for cluster analysis. Compared with grey relational analysis, the cluster analysis method is more straightforward, user-friendly, and easier to operate, especially when dealing with a large number of reservoirs. It facilitates overall evaluation by integrating multiple indicators, without the need to consider individual indicator evaluation intervals. Therefore, cluster analysis is of practical significance and is feasible for assessing the adaptability of reservoirs to $CO_2$ flooding. The computational simplicity of the cluster analysis method and its suitability for scenarios with numerous evaluation objects make it highly adaptable for such applications.

## 5. SUMMARY

$CO_2$ enhanced oil recovery (EOR) technology is characterized by low cost, greater environmental friendliness and safety, effective carbon storage, and the ability to significantly increase crude oil recovery. In this study, the characteristics of reservoirs suitable for $CO_2$ injection were analyzed, and, in combination with previous research, standards for reservoir evaluation indicators were established. The following research content for evaluating the adaptability of reservoirs to $CO_2$ EOR is proposed:

(1) Evaluation indicators were selected using the grey relational analysis method, calculating the degree of association between each indicator and the ultimate oil recovery. Indicators with redundant influences were excluded based on their interrelationships. On this basis, the Reservoir Quality Index (RQI) was proposed as a novel indicator to replace permeability and porosity. After optimization and selection of indicators, the optimal set was used to assess the adaptability of reservoirs to $CO_2$ EOR.

(2) Following the optimization and screening of indicators, a comprehensive mathematical evaluation model was constructed and applied in cluster analysis. The cluster analysis method was employed to assess the adaptability of reservoirs in Daqing and Songyuan Oilfields to $CO_2$ EOR. The results demonstrated that the eastern and western fault blocks of District 1 in Daqing Oilfield, as well as the

Fang 48 fault block in the northern Songliao Basin, are suitable for $CO_2$ injection EOR and exhibit significant oil displacement effects, thereby confirming the feasibility of the cluster analysis method.

(3) The indicator screening method and adaptability evaluation method for $CO_2$ EOR proposed in this study have shown notable effectiveness and reliability in practical application. They can be widely applied in actual reservoir development and provide theoretical guidance for field operations. The application of these methods can further advance research and practice, thus promoting the development and application of $CO_2$ EOR technology.

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