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Fuzzy Evaluation Method of Adaptability of Reservoir with CO_2 Injection

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ABSTRACT

CO_2displacement has become animportant technology to enhance the production efficiency of crude oil. Until now, there are no perfectevaluation criteria for the adaptability of reservoir with CO_2 injection. Based on the statistical analysis of the existing CO_2 injection projects,this paper selected 12 variables which may influence the effect of CO_2 displacement and established an evaluation system. Then it utilized the fuzzymathematicalcomprehensive evaluation methodto determine theweight of each indicator andestablish thefuzzy consistentjudgmentmatrix for the reservoir with CO_2 injection. The case study shows that thefuzzyidentification methodcould betterassociate various factors, which is conducive to finding the optimal reservoirblock with CO_2 injection.

KEYWORDS

Fuzzy mathematics; Gas injection, weight; Co_2; Adaptability; Reservoir.

INTRODUCTION

According to the incomplete statistics, there are nearly 80 CO_2 displacement projects in the world, among which United States has the most[1]. Every year, the amount of CO_2 injected into the reservoir is about 2000 to 3000 tons, of which 3million tons come from the emissions of coal gasification plant and fertilizer plant[2]. China has explored 6.32 billion tons of reserves with low permeability, where 50% of them are unused[3]. The CO_2 displacement is superior to the water displacement in technology[4].

Currently, for the screening of reservoirs which are suitable to CO_2 injection, a unified evaluation criteria system has not been formed due to various influence factors and the difference between geological characteristics of reservoirs. This hasbrought some difficulties for the accurate screening of reservoirs.

Indicator system of reservoir with co$_2$ injection

To meet the technical requirements of saturated reservoir with CO_2 injection, first conduct analysis for the influence factor of CO_2 injection and extract 12 representative reservoir- variables based on the existing projects[5-8]. Whether the targeted reservoir is suitable for the CO_2 injection, the properties of these 12 variables play a decisive role, including viscosity, density, saturation,etc. They are classified as the indicators of crude oil properties, reservoir proper- ties and rock properties based on their different natures, as shown in TABLE 1.

TABLE 1 : Evaluation indicator system of the oil field with gas injection

The second grade indicator	The first grade indicator
	oil saturation, S_o
crude oil characteristics	Viscosity,μ_o
	density,ρ_o
	Depth, H
	Pressure,P_r
reservoir characteristics	Temperature,ºC
	dip angle,º
	Thickness,h
	Permeability, K
rock characteristics	Porosity,φ
	Wettability,I_o
	Heterogeneity,β

Indicator evaluation criteria of the reservoir with co$_2$ injection

In the established indicators, a part of the evaluation scope can be obtained by the probability statistics for the instance database. Those parameters which are not in the database can be obtained by the theoretical analysis and field experience.

To determine the distribution density of evaluation parameters, first keep statistics for the interval of evaluation parameters from the CO_2 injection instances. The length is denoted by Δk_i, the mid-value of the evaluation parameters corresponding to each interval is denoted by k_i; calculate the density function value corresponding to k_i, denoted by$f(k_i)$.

$$f\left(k_i\right)=\frac{n_i}{\Delta k_i \sum n_i} \quad (1)$$

n_i refers to the number of gas injection of the evaluation interval.

Based on the existing CO_2 injection projects, analyze the density distribution value ($f(k_i)$)of evaluation parameters and draw out the density distribution pattern. Then, study the evaluation parameter distribution and use the mathematical theories to describe and analyze the evaluation parameter interval fitting the CO_2 injection, thus forming the objective evaluation criteria. It is conducive to guiding the selection of reservoir blocks with CO_2 displacement.

The distribution density of reservoir depth, temperature, porosity and permeability in different CO_2 injection projects is as shown in Figure 1. In most of the existing CO_2 injection projects, the burial depth is 1000~3000 m the reservoir temperature is 70~85ºC, the porosity is 5% to 12% and permeability is in the range of 0.1~10mD. The evaluation criteria of other indicators can be obtained based on similar statistics and empirical judgments. TABLE 2 shows the evaluation criteria of all the indicators of the candidate reservoirs with CO_2 injection.

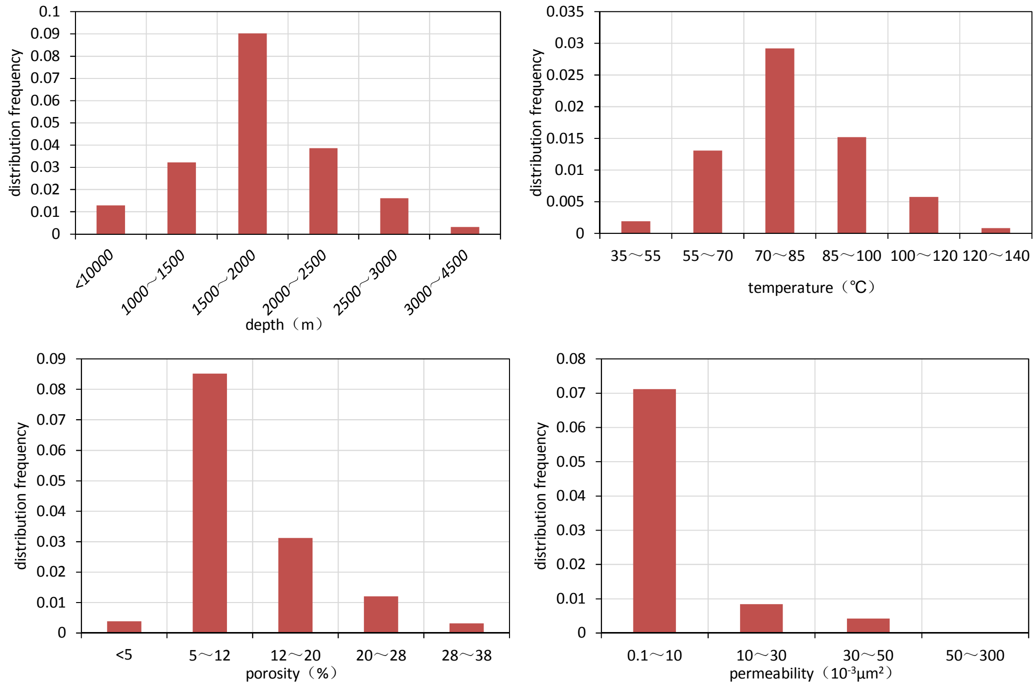

Figure 1 : The distribution interval of reservoir dept

TABLE 2 : The evaluation criteria of all the indicators of candidate reservoirs with CO_2 injection.

Indicator	Evaluation				
	Better	**Good**	**Moderate**	**Bad**	**Worse**
Reservoir depth (m)	1500~2000	2000~2500 1200~1500	2500~3000 1000~1200	3000~3500 800~1000	>3500 <800
Reservoir pressure (MPa)	30~35	35~40 20~25	40~45 18~20	45~50 18~15	>50 <15
Reservoir temperature (ºC)	80~90	90~100 70~80	100~110 60~70	110~120 50~60	>120 <50
Reservoir dip angle (°)	>70	50~70	30~50	10~30	<10
Reservoir thickness (m)	<10	10~20	20~30	30~40	>40
Porosity (%)	10~15	15~20 8~10	20~25 6~8	25~30 4~6	>30 <4
Viscosity (mPa.s)	<1	1~2	2~3	3~4	>4
Crude oil density (g/cm^3)	<0.80	0.80~0.84	0.84~0.88	0.88~0.92	>0.92
S_0(%)	>70%	55~70%	40~55%	25~40%	<25%
Wettability	0.8~1	0.6~0.8	0.4~0.6	0.2~0.4	0~0.2
Permeability ($10^{-3}\mu m^2$)	1500~2000	2000~2500	2500~3000	3000~3500	>3500
Variation coefficient of permeability		1200~1500	1000~1200	800~1000	<800

Evaluation method of the adaptability of reservoir with CO_2 injection

For the adaptability of reservoir with CO_2 injection, fuzzy evaluation set A {better, good, moderate, bad, worse} can be used to describe. Assume that the influence of a reservoir parameter X can be described by the intensity of each element in the fuzzy evaluation set A, written as the vector, as shown in formula (1).

$$\mu(x)=\{\mu_1(x),\mu_2(x),\mu_3(x),\mu_4(x),\mu_5(x)\} \quad \textbf{(2)}$$

The evaluation criteria of various indicators of the reservoir are as shown in TABLE 3

TABLE 3 : Evaluation criteria of engineering factor X

Remarks	better	good	moderate	bad	worse
x	a_0~ a_1	a_1~ a_2	a_2~ a_3	a_3~ a_4	a_4~ a_5

To establish the single-factor evaluation matrix for evaluation parameters is the most critical step to evaluate the adaptability of reservoir with gas injection. In fuzzy math, the single factor evaluation matrix follows the maximum membership degree law, namely: if $x \in (a_i, a_{i+1})$, then:

$$\mu_{i+1}(x)=\max_{j=1,2,\ldots 5}\{\mu_j(x)\} \ i=0,1,2,3,4 \quad \textbf{(2)}$$

In order to make the membership function meet the maximum membership degree law, this paper extended the traditional ridge shape function and linearly transformed the non-isometric intervals into isometric intervals; then determine the left and right zero of the distribution density function according to the limit criteria, as shown in the following four steps:

(1) Conduct linear isometric interval transformation for the evaluation criteria for each indicator:

$$s=\min\{a_1-a_0,a_2-a_1,a_3-a_2,a_4-a_3,a_5-a_4\} \begin{cases} a_0^*=a_0 \\ a_i^*=a_0^*+is, i=1,2,\ldots\ldots 5 \end{cases} \quad \textbf{(3)}$$

$$x^*=a_0^*+\left(i+\frac{x-a_i}{a_{i+1}-a_i}\right)s$$

(2) Determine the left zero and right zero:

Leftzero:

$$D(x)=-4s-0.6a_0+1.6x^* \quad \textbf{(4)}$$

Right zero:

$$C(x)=s-0.6a_0+1.6x^* \quad \textbf{(5)}$$

(3) Determine the distribution den- sity function:

When $x^*<\frac{a_0^*+a_5^*}{2}$, based on three different intervals of independent variable x, there are three kinds of distribution density functions:

① $x\in\left[\min\{2x^*-c(x^*),a_0^*\},x^*\right]$

② $x\in\left[x^*,c(x^*)\right]$

③Other: **(6)**

$$f(y)=0.5\begin{cases}1-\sin\frac{\pi}{c(x^*)-x^*}\left(2x^*-x-\frac{c(x^*)+x^*}{2}\right)\\1-\sin\frac{\pi}{c(x^*)-x^*}\left(x-\frac{c(x^*)+x^*}{2}\right)\\0\end{cases}$$

When $x^*\geq\frac{a_0^*+a_5^*}{2}$, based on three different intervals of independent variable x, there are three kinds of distribution density functions:

① $x\in\left[x^*,\min\left\{a_5^*,2x^*-D(x^*)\right\}\right]$

② $x\in\left[D(x),x^*\right]$

③Other:

$$f(y)=0.5\begin{cases}1+\sin\frac{\pi}{x^*-D(x^*)}\left(2x^*-x-\frac{D(x^*)+x^*}{2}\right)\\1+\sin\frac{\pi}{x^*-D(x^*)}\left(x-\frac{D(x^*)+x^*}{2}\right)\\0\end{cases}\quad(7)$$

(4) Determine the degree of membership

The average distribution density of this interval is used to represent its membership:

$$\mu_i^*(x)=\frac{1}{a_i^*-a_{i-1}^*}\int_{a_{i-1}^*}^{a_i^*}f(y)dy,i=1,2,\ldots\ldots,5\quad(9)$$

After normalization:

$$\mu_i(x)=\frac{\mu_i^*}{\sum_{i=1}^{5}\mu_i^*},i=1,2,\ldots\ldots,5\quad(10)$$

The fuzzy AHP could solve the weight distribution of things by establishing a fuzzy judgment matrix which could reflect the consistency of thinking, and the weight distribution could better reveal the actual situation[9].

The fuzzy consistent judgment matrix R represents the comparison of the relative importance between elements in this hierarchy related to a certain element of the upper hierarchy[10]. Assume that the element C is related to element$a_1,a_2,\ldots,a_n$ of the upper hierarchy, and the fuzzy consistent judgment can be expressed as:

C	a_1	a_2	$\ldots$	a_n
a_1	r_{11}	r_{12}	$\ldots$	r_{1n}
a_2	r_{21}	r_{22}	$\ldots$	r_{2n}
$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$
a_n	r_{n1}	r_{n2}	$\ldots$	r_{nn}

r_{ij} means when we compare element $a_i$and a_j element relative to element C,a_i and a_j have the membership of fuzzy relationship "... is much more important than...". To obtain a quantitative description of any two options relative to a certain criterion, 0.1-0.9 in TABLE 4 can be used as the digital scale.

TABLE 4 : Digital scale table of fuzzy AHP

Scale	Definition	Explaination
0.5	Equally important	Compare two elements and they are equally important.
0.6	A little bit more important	Compare two elements and one element is a little bit more important than another one.
0.7	Apparently important	Compare two elements and one element is apparently important than another one.
0.8	Much more important	Compare two elements and one element is much more important than another one.
0.9	Extremely important	Compare two elements and one element is much more important than another one.
0.1,0.2, 0.3,0.4	reverse comparison	Compare element a_i and $a_j$to obtain the judgment matrix r_{ij}, thus, comparing comparison the element a_j and $a_i$could obtain the judgment r_{ji}=1-r_{ij}.

Based on the above digital scale, compare elementa_1,a_2,…,a_n and element C in the upper hierarchy and obtain the following fuzzy judgment matrix:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix}$$

The weight ω of this fuzzy judgment matrix R is obtained by the formula (9):

$$\omega_j = \frac{1}{n} - \frac{1}{2a} + \frac{1}{na}\sum_{k=1}^{n} r_{ij}\ ;\ i \in \Omega \quad \textbf{(11)}$$

Wherein: a is a kind of measurement for the difference between objects perceived by different people, and it is related to the number of evaluation objects and the degree of difference. The larger a is, the smaller the weight difference will be; vice versa. When a= (n-1)/2, the weight difference reaches its maximum value. Thus, smaller *a* shows that policy-makers attach great importance to the difference between the importance of elements; vice versa. In practice, the value of a should be taken as: a=(n-1)/2.

For these 12 evaluation indicators of CO_2 injection, construct fuzzy consistent judgment matrix R. The weight distribution of indicators is as shown in TABLE 5.

$$R=\begin{bmatrix}
0.5 & 0.5 & 0.1 & 0.1 & 0.1 & 0.3 & 0.3 & 0.6 & 0.2 & 0.8 & 0.2 & 0.4 \\
0.5 & 0.5 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.3 & 0.2 & 0.8 & 0.3 & 0.6 \\
0.9 & 0.9 & 0.5 & 0.5 & 0.2 & 0.6 & 0.7 & 0.8 & 0.4 & 0.7 & 0.7 & 0.9 \\
0.9 & 0.9 & 0.5 & 0.5 & 0.6 & 0.7 & 0.8 & 0.8 & 0.6 & 0.8 & 0.9 & 0.9 \\
0.9 & 0.9 & 0.8 & 0.4 & 0.5 & 0.6 & 0.6 & 0.8 & 0.3 & 0.6 & 0.7 & 0.8 \\
0.7 & 0.9 & 0.4 & 0.3 & 0.4 & 0.5 & 0.6 & 0.4 & 0.4 & 0.8 & 0.6 & 0.3 \\
0.7 & 0.9 & 0.3 & 0.2 & 0.4 & 0.4 & 0.5 & 0.4 & 0.5 & 0.8 & 0.6 & 0.6 \\
0.4 & 0.7 & 0.2 & 0.2 & 0.2 & 0.6 & 0.6 & 0.5 & 0.3 & 0.9 & 0.2 & 0.4 \\
0.8 & 0.8 & 0.6 & 0.4 & 0.7 & 0.6 & 0.5 & 0.7 & 0.5 & 0.8 & 0.8 & 0.9 \\
0.2 & 0.2 & 0.3 & 0.2 & 0.4 & 0.2 & 0.2 & 0.1 & 0.2 & 0.5 & 0.1 & 0.4 \\
0.8 & 0.7 & 0.3 & 0.1 & 0.3 & 0.4 & 0.4 & 0.8 & 0.2 & 0.9 & 0.5 & 0.7 \\
0.6 & 0.4 & 0.1 & 0.1 & 0.2 & 0.7 & 0.4 & 0.6 & 0.1 & 0.6 & 0.3 & 0.5
\end{bmatrix}$$

TABLE 5 : Weight of indicators calculated by the fuzzy AHP

The second grade indicator	Weight of the second grade indicator	The first grade indicator	Weight of the first grade indicator	Total distribution of weight
crude oil characteristics	0.350	oil saturation	0.364	0.127
		viscosity	0.316	0.111
		density,	0.320	0.112
reservoir characteristics	0.371	depth	0.192	0.071
		pressure	0.310	0.115
		temperature	0.229	0.085
		dip angle	0.102	0.038
		thickness	0.167	0.062
rock characteristics	0.279	permeability	0.174	0.048
		porosity	0.196	0.055
		wettability	0.315	0.088
		heterogeneiy	0.315	0.088

CASE STUDY

The geological reservoir characteristics of a candidate reservoir block with CO_2 injection is as shown in TABLE 6. Use the fuzzy evaluation method to conduct evaluation screening for these 12 gas injection indicators and obtain the comprehensive evaluation results for the adaptability of CO_2 injection, as shown in TABLE 7. It can be further developed to filter out the target reservoir suitable to CO_2 injection.

TABLE 6 : Reservoir parameters

Reservoir	H m	Pr Mpa	T ºC	γ º	ρ_o g/cm^3	μ_o mPa.s	h m	φ %	S_o %	K $10^{-3}\mu m^2$	B	Io
1-1 block Ng	1800.0	19.5	75.0	2.75	0.70	1.65	22.15	27.48	62.0	1640.0	0.56	0.76
1-1 block Ed1	2340.0	25.0	91.5	4.5	0.65	0.80	28.72	23.80	61.0	227.4	0.55	0.82
1-3 block Nm	1600.0	16.0	64.5	14	0.67	1.00	33.90	31.30	60.0	2681.0	0.62	0.68
1-3 block Ng	1810.0	19.5	82.0	12	0.68	1.01	18.30	26.90	63.0	1640.0	0.63	0.56
1-3 block Ed1	2280.0	25.0	88.5	8.5	0.73	2.30	45.57	24.07	60.0	227.4	0.58	0.63

TABLE 7 : The comprehensive evaluation results for the adaptability of CO_2 injection

Reservoir	Adaptability value					
	Better	Good	Moderate	Bad	Worse	Membership
1-1 block Ng	0.3387	0.3524	0.1676	0.0945	0.0474	Good
1-1 block Ed_1	0.4360	0.3463	0.1514	0.0413	0.0248	Better
1-3 block Nm	0.3210	0.2554	0.2146	0.1311	0.0783	Better
1-3 block Ng	0.2927	0.3108	0.2266	0.1434	0.0266	Good
1-3 block Ed_1	0.3411	0.2889	0.2815	0.0798	0.0087	Better

This paper utilized the fuzzy evaluation method to determine that: (1) the reservoir is a kind of porous medium with high porosity and high permeability, so it is not appropriate to provide adequate space for CO_2 and crude oil to contact; (2) Crude oil in reservoir has low viscosity, low density and high oil saturation, which is conducive to the evaporative miscible displacement, and the injected gas is not easy to produce viscous fingering and overlap phenomenon; (3) the large thickness of the reservoir makes CO_2 and oil easy to produce gravity separation, thus causing overlap flow of CO_2; (4) reservoir inclination is small and gravity-stable displacement is weak; (5) The reservoir shows strong heterogeneity in vertical direction, but the oil layer shows the relatively homogeneous feature. For the homogeneous reservoir, gas injection is suitable; (6) the reservoir rock shows hydrophilic in its wettability, due to the water shelter effect in the hydrophilic medium, the strongly hydrophilic reservoir is not conducive to gas displacement. All these factors are interdependent and mutually contradictory and the fuzzy comprehensive evaluation could better associate with these contradictions, thus finding the most suitable reservoir block for CO_2 injection.

CONCLUSIONS

1.Through the statistics for the CO_2 injection projects and combined with field experience, this paper established the evaluation criteria for the CO_2 injection indicators. And then use the fuzzy comprehensive evaluation method to establish the weight distribution of each indicator.

2.Case study indicates that all these factors are interdependent and mutually contradictory and the fuzzy comprehensive evaluation could better associate with these contradictions, thus finding the most suitable reservoir block for CO_2 injection.

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