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Well Selection for CO_2 Huff-n-Puff in Unconventional Oil Reservoirs Based on Improved Fuzzy Method

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Abstract: The implementation of CO_2 huff-n-puff in unconventional oil reservoirs represents a green development technology that integrates oil recovery and carbon storage, emphasizing both efficiency and environmental protection. A rational well selection method is crucial for the success of CO_2 huff-n-puff development. This paper initially identifies eight parameters that influence the effectiveness of CO_2 huff-n-puff development and conducts a systematic analysis of the impact of each factor on development effectiveness. A set of factors for well selection decisions is established with seven successful CO_2 huff-n-puff cases. Subsequently, the influencing factors are classified into positive, inverse, and moderate indicators. By using an exponential formulation, a method for calculating membership degrees is calculated to accurately represent the nonlinearity of each parameter's influence on development, resulting in a dimensionless fuzzy matrix. Furthermore, with the oil exchange ratio serving as a pivotal parameter reflecting development effectiveness, recalibration of weighting factors is performed in conjunction with the dimensionless fuzzy matrix. The hierarchical order of weighting factors, from primary to secondary, is as follows: porosity, reservoir temperature, water saturation, formation pressure, reservoir thickness, crude oil density, crude oil viscosity, and permeability. The comprehensive decision factor and oil exchange ratio exhibit a positive correlation, affirming the reliability of the weighting factors. Finally, utilizing parameters of the Ordos Basin as a case study, the comprehensive decision factor is calculated, with a value of 0.617, and the oil exchange ratio is predicted as 0.354 t/t, which falls between the Chattanooga and Eagle Ford reservoirs. This approach, which incorporates exponential membership degrees and recalibrated weighting factors derived from actual cases, breaks the limitations of linear membership calculation methods and human factors in expert scoring methods utilized in existing decision-making methodologies. It furnishes oilfield decision-makers with a swifter and more precise well selection method.

Keywords: unconventional oil reservoir; CO_2 huff-n-puff; well selection; weighting factor; fuzzy evaluation

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1. Introduction

The increasing concentration of CO_2, a predominant greenhouse gas, has directly contributed to global warming and climate change, posing significant threats to human survival. Research indicates that the continuous emission of CO_2 from fossil fuel combustion into the atmosphere will persist as a pressing issue [1,2], exacerbating the likelihood of extreme heat events and significantly impacting the hydrological cycle [3]. Therefore, reinjecting greenhouse gases into reservoirs offers a dual benefit of reducing CO_2 emissions and enhancing oil recovery. On the other hand, as conventional oil and gas resources gradually enter their later stages, the exploitation of tight oil and gas resources with rich geological reserves has emerged as a primary direction for future development [4,5]. However, due to the complexity of their pore structures, these resources exhibit poor production performance and rapid decline in yields, with current recovery remaining low. Moreover, conventional methods such as water flooding make it difficult to replenish reservoir energy due to the intricate pore structures.

The unique properties of supercritical CO_2, such as its density approximation to liquid and viscosity close to gas, along with its strong diffusivity, enable effective replenishment of reservoir energy. It also exhibits multiple effects, including energy enhancement, viscosity reduction, and phase mixing. Field trials have demonstrated that CO_2 injection significantly enhances oil recovery and reduces carbon emissions, making it the most promising and effective alternative development method for tight oil reservoirs [6]. Previous researchers [7] began studying CO_2 injection technology in the 1970s. Hawthorne S.B. [8] conducted CO_2 injection experiments on Bakken tight reservoir rocks, verifying the feasibility of CO_2 injection in increasing oil recovery. Ma J. et al. [9–12] conducted CO_2 huff-n-puff experiments on tight rock cores with an average permeability of 2.3 mD, showing that three cycles could increase oil recovery to 30%.

The success rate of field applications varies between 50% and 70%, with the primary reason for failure being the blind well selection. Therefore, developing a rational evaluation method before implementing CO_2 injection in tight oil reservoirs is of significant importance. The process of selecting wells for CO_2 huff-n-puff among candidate wells is complex, involving various factors influencing the effectiveness of CO_2 injection and experts from different backgrounds [13,14]. While pressure indices are commonly used in chemical flooding to assess plugging effectiveness [15], the development modes of CO_2 flooding and injection often rely on selecting blocks with strong adaptability based on reasonable ranges of certain basic physical parameters. Xiong [16] and Yu [17] evaluated the development effectiveness of the Mahu and Bakken oil fields based on their geological, engineering, and production dynamics.

Due to the inherent uncertainty in well selection evaluation methods, fuzzy methods are commonly employed to establish evaluation systems [18–20]. This involves normalizing using membership functions and obtaining weighting factors for each influencing factor through expert scoring. Subsequently, a comprehensive assessment factor for decision-making is calculated, and the numerical ranking of this factor determines the order of decision-making. However, this well selection method has certain limitations, primarily concerning linear membership degrees and weight assignments. The establishment of membership functions often utilizes linear functions for normalization, which may have minimal impact on conventional reservoirs but fail to capture the nonlinearity of factors affecting unconventional reservoir development. Moreover, weighting factors obtained through expert scoring are significantly influenced by the composition of the expert pool and subjective experiential biases, leading to instability and potential bias in the decision process.

This paper addresses the CO_2 huff-n-puff development process in unconventional oil reservoirs. Utilizing the widely applied fuzzy evaluation method, the nonlinear characteristics of each influencing factor on development are considered. A set of exponential-based membership degree expression models is established, which accurately improved fuzzy methods. Based on examples of unconventional reservoir development, with the oil exchange ratio as the target parameter, linear regression is employed to quantify the impact of various factors on CO_2 huff-n-puff development effectiveness in a manner that is more realistic and reduces subjective biases. This method facilitates the rapid calculation of priority for CO_2 huff-n-puff wells based on rock and fluid properties and enables the prediction of a relatively accurate oil exchange ratio. It effectively supports the implementation of CO_2 huff-n-puff development in unconventional oil reservoirs at field sites.

2. Evaluation of Individual Factors

The evaluation index system for CO_2 huff-n-puff is established based on mechanisms such as CO_2, causing oil expansion, viscosity reduction, extraction of light components from crude oil, improvement in the oil–water mobility ratio, and enhancement of reservoir permeability, in conjunction with reservoir petrophysical and fluid properties [21–23]. The evaluation factors for CO_2 injection include reservoir thickness, formation pressure, reservoir temperature, porosity, permeability, water saturation, crude oil viscosity, and crude oil density. Subsequent production dynamics, including gas injection volume, injection rate, injection pressure, and soaking time, are controllable factors. The objective of this method is to screen wells suitable for CO_2 huff-n-puff; we do not discuss time-varying parameters such as water cut and gas–oil ratio within the scope of this paper. Therefore, the aforementioned production dynamic parameters are not considered in this study.

(1) Reservoir Thickness (h)

Reservoirs with a thickness greater than 10 m demonstrate relatively higher success rates for CO_2 huff-n-puff. This is primarily attributed to the density and viscosity contrast between CO_2 and crude oil, resulting in CO_2 inducing volumetric expansion of crude oil while displacing it along with the overlying oil and water in the far zones of the well, thus creating elastic gas drive energy accumulation. Therefore, increasing reservoir thickness facilitates the occurrence of effective overlying action of CO_2 in the near-well zone, thereby aiding in carrying residual mobile oil during well production. Thinner reservoirs are less prone to gas channeling, making it easier for CO_2 to push residual oil toward the deeper parts of the reservoir, affecting the efficiency of enhanced oil recovery by CO_2 huff-n-puff.

On the other hand, thicker reservoirs exhibit a non-uniform vertical distribution of CO_2, leading to significant differences in CO_2 dissolution concentrations within the fluid in the operational range. Consequently, the overall dissolution and viscosity reduction effects, as well as expansion capacity, tend to decrease with increasing reservoir thickness. Therefore, excessively thick reservoirs are not favorable for CO_2 huff-n-puff.

(2) Reservoir Temperature (T)

Lower reservoir temperatures pose challenges for CO_2 in achieving phase mixing with formation fluids. Conversely, higher reservoir temperatures facilitate CO_2 expansion upon injection, enhancing its dissolution gas drive effect and improving the effectiveness of CO_2 huff-n-puff in enhanced oil recovery.

(3) Formation Pressure (P)

CO_2 effectively induces crude oil flow primarily due to factors such as viscosity reduction, light component extraction, and expansion to increase oil mobility. For a given reservoir temperature, higher pressure results in greater CO_2 solubility and a closer approach to phase mixing. Phase mixing enhances the mobility of reservoir oil and allows CO_2 to penetrate deeper into the reservoir, expanding the affected volume. However, excessively high formation pressure can lead to effective conventional depletion, diminishing the incremental production effect of CO_2 huff-n-puff. Therefore, the effectiveness of CO_2 huff-n-puff-enhanced production weakens as formation pressure continues to rise, and reasonable formation pressure should be maintained near the minimum miscibility pressure.

(4) Porosity (Φ)

The success rate of CO_2 injection is highest when reservoir porosity is within the range of 10–20%. Excessive porosity can lead to CO_2 channeling and bypassing, reducing the efficiency of carrying residual oil during CO_2 huff-n-puff.

(5) Permeability (k)

The oil exchange ratio exhibits a logarithmic relationship with reservoir permeability levels. For ultra-low permeability reservoirs (permeability less than 1×10^{-3} μm^2), permeability significantly influences the oil exchange ratio, with increasing permeability leading to a noticeable increase in oil recovery. However, for very low permeability reservoirs (permeability greater than 1×10^{-3} μm^2 but less than 10×10^{-3} μm^2), the influence of permeability on the oil exchange ratio is relatively minor. Excessively high permeability is susceptible to gas channeling, resulting in rapid gas diffusion to the far reaches of the reservoir, significantly reducing oil recovery efficiency. This is the primary reason why high-permeability reservoirs are not suitable for CO_2 huff-n-puff in enhanced oil recovery.

(6) Water Saturation (S_w)

Higher water saturation leads to lower oil and gas production rates and a higher water cut, which is unfavorable for CO_2 huff-n-puff development. Excessive water saturation hinders the formation of continuous oil bands during displacement, thus failing to achieve the expected CO_2 injection effect. Lower water saturation is more conducive to CO_2 huff-n-puff development.

(7) Crude Oil Density (ρ)

Crude oil density typically falls below 0.86 g·cm^{-3}. Generally, lower crude oil density results in higher cumulative oil production. However, for CO_2 huff-n-puff, the enhanced oil recovery compared to conventional depletion tends to decrease with lower crude oil density. This is because higher crude oil density, indicating higher heavy component content, enhances the CO_2 extraction effect, resulting in better overall CO_2 huff-n-puff effectiveness.

(8) Crude Oil Viscosity (μ)

Similarly, higher crude oil viscosity leads to better CO_2 huff-n-puff development effectiveness. The viscosity reduction during CO_2 injection depends on CO_2 solubility in crude oil. Higher crude oil viscosity enhances the dissolution and viscosity reduction effect of CO_2, thereby increasing CO_2 huff-n-puff effectiveness.

3. Dimensionless Processing

Based on the analysis of the eight influencing factors discussed in Section 2, the factor set U^i for evaluating the i-th well can be established as follows:

$$U^i = \{u_1, u_2, u_3, \ldots, u_m\} \tag{1}$$

The factor set U can be represented as a matrix of $m \times n$, where m is the number of influencing factors, and n represents the number of wells to be evaluated.

Previous studies have traditionally categorized factors into positive and inverse correlations and often employed linear processing models. However, the impact of some factors on development exhibits nonlinear characteristics. For instance, increasing purity from 90% to 90.1% is relatively easy, but further improving purity from 99% becomes exceedingly difficult. Moreover, linear membership calculation methods commonly set the fuzzy value of the minimum to 0, eliminating the influence of this factor on the object. This approach is questionable, as shown in Appendix A. Thus, this study considers the nonlinear nature of factors affecting development effectiveness and employs exponential functions to normalize the factor set. It also retains the impact of each factor's minimum value on development, even though it may be relatively minor. The influencing factors are categorized into positive, inverse, and moderate indicators.

(1) Positive indicator

Positive indicators correspond to factors that are more favorable for CO_2 huff-n-puff as their values increase. These include permeability, reservoir temperature, crude oil density, and crude oil viscosity, totaling four parameters. A fuzzy quantification model for these indicators is established using exponential functions as follows:

$$f_{P,i} = e^{\frac{x_i - x_{i,\min}}{x_{i,\max} - x_{i,\min}}} - 1 \tag{2}$$

In the equation, x_i represents the parameter value of the i-th indicator, $x_{i,\min}$ denotes the minimum value of the indicator, and $x_{i,\max}$ represents the maximum value of the indicator.

(2) Inverse indicator

Inverse indicators require lower values for better CO_2 huff-n-puff development effectiveness, contrasting with positive indicators. As the values decrease, they become more beneficial for CO_2 huff-n-puff development. This category includes two parameters:

porosity and water saturation. The fuzzy quantification model for inverse indicators is defined as follows:

$$f_{N,i} = e^{\frac{x_{i,\max} - x_i}{x_{i,\max} - x_{i,\min}}} - 1 \tag{3}$$

(3) Moderate indicator

In contrast to positive and inverse indicators, when a factor has an optimal value, it exhibits characteristics of both positive and inverse indicators. Specifically, when the indicator value is less than the optimal value, it aligns with positive indicator characteristics, while it aligns with inverse indicator characteristics when the value exceeds the optimal value. This category includes two parameters: formation pressure and reservoir thickness. The fuzzy quantification model for moderate indicators can be expressed as

$$f_{M,i} = \begin{cases} e^{\frac{x_i - x_{i,\min}}{x_{oi} - x_{i,\min}}} - 1 & x_{i,\min} \prec x_i \leq x_{oi} \\ e^{\frac{x_{i,\max} - x_i}{x_{i,\max} - x_{oi}}} - 1 & x_{oi} \prec x_i \leq x_{i,\max} \end{cases} \tag{4}$$

We calculate the membership degree of each factor for each well. This entails identifying the distribution type of each factor (positive, inverse, and moderate indicators). Then, the factor set U (a matrix of $m \times n$) of the evaluation objects is normalized and transformed into a fuzzy comprehensive judgment matrix $R(r_{i,j})$.

$$R = \begin{bmatrix} r_{1,1} & r_{2,1} & \cdots & r_{m,1} \\ r_{1,2} & r_{2,2} & \cdots & r_{m,2} \\ \vdots & \vdots & \ddots & \vdots \\ r_{1,n} & r_{2,n} & \cdots & r_{m,n} \end{bmatrix} \tag{5}$$

where r_{ij} represents the dimensionless coefficient of the i-th influencing factor for the j-th well, ranging from 0 to 1. A higher value indicates greater suitability for CO_2 huff-n-puff development.

4. Inverse Calculation of the Weighting Factors

The impact of various factors on development effectiveness varies, with some parameters having a greater effect while others have a lesser impact. Therefore, it is necessary to allocate weight coefficients to each factor. The widely used method for determining weight coefficients is the expert scoring method, where multiple experts anonymously score the factors to calculate their weight coefficients. However, this method is significantly influenced by the composition of the experts and subjective biases, making it difficult to accurately reflect the actual development outcomes.

This study investigated some reported practical cases to collect data reflecting the CO_2 flooding development effectiveness, particularly focusing on the oil exchange ratio as an indicator. Based on the oil exchange ratio, combined with the factor set U, weighting factors are calculated. Firstly, the oil exchange ratios of practical cases are statistically analyzed to establish the judgment set vector V, such as Equation (5).

$$V = \{v_1, v_2, v_3, \ldots, v_n\} \tag{6}$$

Subsequently, a set of weighting factors, denoted as w, is established for each corresponding influencing factor.

$$w = \{w_1, w_2, w_3, \ldots, w_m\} \tag{7}$$

The multiplication of the fuzzy comprehensive judgment matrix R and the weighting factors yields a vector of n elements, representing the comprehensive decision factor C reflecting the CO_2 huff-n-puff development effectiveness of each well.

$$C_j = \sum_{i=1}^{m} w_i \times r_{ij} \tag{8}$$

The comprehensive decision factor C_j for the j-th well is obtained by summing the products of all factors and their corresponding weighting factors for that well. Since both the decision factor and the oil exchange ratio can reflect the effectiveness of CO_2 huff-n-puff development, we reverse the process by using the statistically obtained oil exchange ratio parameters and the fuzzy comprehensive judgment matrix R to calculate the combined weighting factors. This is expressed as

$$w = V \cdot R^{-1} \tag{9}$$

Furthermore, the calculated set of weighting factors is adjusted to ensure that the sum of them equals 1.

$$\sum_{i=1}^{m} w_i = 1 \tag{10}$$

The weighting factors derived from actual production parameters eliminate or reduce human factors and have a certain theoretical basis. In the subsequent CO_2 huff-n-puff well selection work, these weighting factors can be directly utilized as the basis for identification.

Finally, based on Equation (8), the comprehensive decision factor is calculated. The calculated decision factor represents the evaluation results of each factor and serves as the basis for well selection and prioritization for CO_2 huff-n-puff operations. A higher numerical value indicates a higher priority for CO_2 huff-n-puff operations. The specific calculation process is shown in Figure 1.

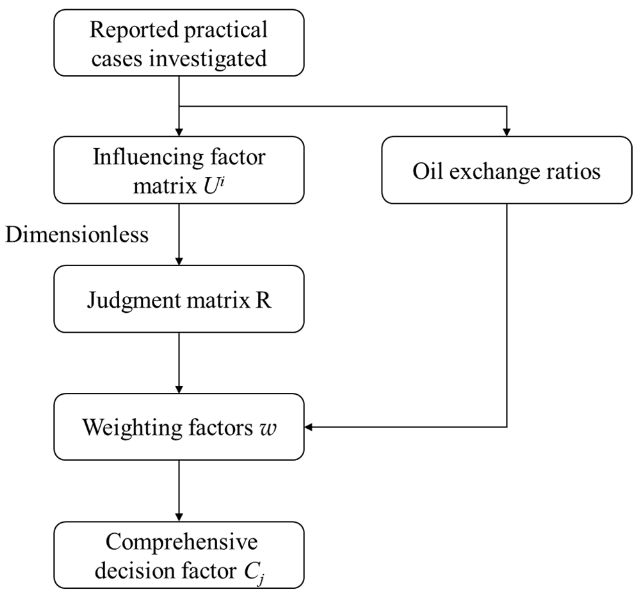

Figure 1. Comprehensive decision factors calculation flow chart.

5. Case Analysis

Due to the predominant use of depletion-driven development in unconventional reservoirs, there are limited cases of CO_2 huff-n-puff, and they have not generally reached a significant scale. This study systematically surveyed and compiled data on eight key parameters and oil exchange ratios (R_{oe}) from seven successful cases, establishing a set of factors for CO_2 huff-n-puff well selection, as presented in Table 1.

Table 1. Statistical table of parameters for each typical block.

Block	k	P	h	T	ρ	Φ	S_w	μ	R_{oe}
Bakken [24]	0.5	27.7	10	75	0.79	7.5	30	2.5	0.3595
Eagle Ford [25]	0.01	32	40	80	0.82	7	35	3.2	0.3537
Chattanooga [26]	0.25	30	13	40	0.83	5.5	27	2.5	0.348
Appalachian [27]	10	6.89	12	20	0.86	15	35	3.6	0.304
Lost Soldier [27]	0.6	18.4	56	82	0.85	5.4	20	1.26	0.383
Fuyu [28]	1.54	16.9	13	79	0.8	14.2	46	2	0.39
Mahu [29]	0.1	38.11	20	81	0.82	8.03	32	15	0.33

The table includes permeability, temperature, crude oil density, and crude oil viscosity, where higher values are considered more favorable, while porosity and water saturation are optimal at lower values. Reservoir thickness and formation pressure are considered suitability indicators with optimal values. The membership degrees for each factor are calculated separately, transforming the table into a fuzzy matrix, as shown in Table 2. The optimal values for formation pressure and reservoir thickness are taken as 25 MPa and 20 m, respectively. We mainly emphasize this method, and the selection of the optimal value is not representative. The determination of optimal values necessitates careful analysis in conjunction with specific issues encountered in indoor experimental setups or field applications within mines.

Table 2. Dimensionless fuzzy matrix.

Block	k	P	h	T	ρ	Φ	S_w	μ
Bakken	0.386	0.513	0.368	0.893	0.368	0.804	0.681	0.403
Eagle Ford	0.368	0.447	0.521	0.968	0.565	0.846	0.562	0.424
Chattanooga	0.377	0.477	0.393	0.508	0.651	0.990	0.764	0.403
Appalachian	1	0.368	0.384	0.368	1	0.368	0.562	0.436
Lost Soldier	0.390	0.532	0.368	1	0.867	1	1	0.368
Fuyu	0.429	0.507	0.393	0.953	0.424	0.400	0.368	0.388
Mahu	0.371	0.368	0.457	0.984	0.565	0.760	0.630	1

Using the statistically obtained oil exchange ratios as the target parameter and the parameters of seven blocks, namely Bakken, Eagle Ford, Chattanooga, Appalachian, Lost Soldier, Fuyu, and Mahu, and based on the literature survey-derived oil exchange rate parameters, the weighting factors are calculated in reverse, as shown in Table 3.

Table 3. Weighting factors by inverse calculation.

Parameter	Weighting Factor
Permeability	0.092
Formation pressure	0.137
Reservoir thickness	0.108
Reservoir temperature	0.150
Crude oil density	0.102
Porosity	0.171
Water saturation	0.147
Crude oil viscosity	0.093

The weighting factors also reflect the relative importance of each factor in influencing the effectiveness of CO_2 huff-n-puff development. The priority order of the weighting factors is porosity, reservoir temperature, water saturation, formation pressure, reservoir thickness, crude oil density, crude oil viscosity, and permeability. By incorporating the weighting factors and the fuzzy evaluation matrix into Equation (8), the comprehensive decision factors are calculated, as shown in Table 4.

Table 4. Comprehensive decision factors.

Block	Comprehensive Decision Factors
Bakken	0.592
Eagle Ford	0.621
Chattanooga	0.604
Appalachian	0.527
Lost Soldier	0.739
Fuyu	0.496
Mahu	0.655

The relationship between the oil exchange ratio response and the comprehensive well selection decision factors is plotted in Figure 2. It is evident that the oil exchange ratios of the seven blocks exhibit a clear positive correlation with the comprehensive decision factors, validating the accuracy of the weighting factors. The well selection decision method established in this study accurately reflects the effectiveness of CO_2 huff-n-puff.

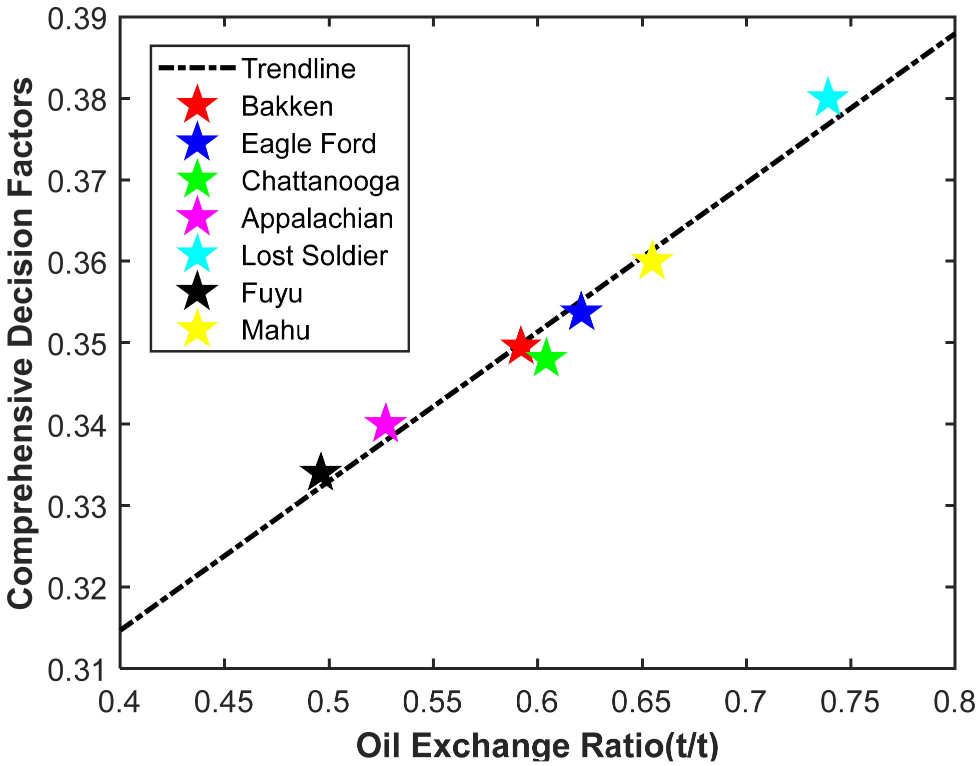

Figure 2. Corresponding relationship between oil exchange ratio and comprehensive decision factors.

In the practical application of this method, the relevant parameters of the target wells can first be statistically gathered, as shown in Table 1. Using the membership degree calculation method, the data from Table 1 can be transformed into dimensionless data in Table 2. Subsequently, the comprehensive decision factors for each well are calculated based on the weighting factors we have determined, representing the priority of CO_2 huff-n-puff. The wells are then prioritized for CO_2 injection operations based on the magnitude of these factors. By considering the linear relationship between the comprehensive decision factors and the oil exchange ratio, the oil exchange ratio of this scheme can be predicted based on actual data. Taking the tight oil reservoirs in the Ordos Basin as an example, the basic model parameters are presented in Table 5.

Table 5. Parameters of tight oil reservoirs in the Ordos Basin [30].

Parameter	Value
Permeability	0.1×10^{-3} μm^2
Formation pressure	15 MPa
Reservoir thickness	15 m
Reservoir temperature	70 °C
Crude oil density	0.85×10^3 kg·m^{-3}
Porosity	10%
Water saturation	30%
Crude oil viscosity	1.27 mPa·s

Utilizing the nonlinear membership degree calculation method, each parameter is separately made dimensionless, and the parameter matrix is transformed into a fuzzy matrix. Among them, the maximum and minimum values of each parameter are based on the data in Table 1.

Substituting the coefficients from Table 6 and the weighting factors into Equation (8) yields the comprehensive decision factor for CO_2 huff-n-puff of the tight oil reservoirs in the Ordos Basin, with a value of 0.617. From the data in Table 4, this value falls between the Chattanooga and Eagle Ford reservoirs. Using the linear trend line in Figure 1, it can be predicted that the oil exchange rate of CO_2 huff-n-puff in Ordos Basin is approximately 0.354 t/t.

Table 6. Dimensionless fuzzy matrix in the Ordos Basin.

Parameter	Fuzzy Value
Permeability	0.371
Initial reservoir pressure	0.477
Effective thickness	0.607
Temperature	0.824
Oil density	0.867
Porosity	0.619
Initial water saturation	0.681
Oil viscosity	0.368

6. Conclusions

Effective well selection is imperative for the successful implementation of CO_2 huff-n-puff techniques in unconventional oil reservoirs. This study introduces an improved decision-making framework, building upon fuzzy evaluation methodologies to address the deficiencies of existing approaches. In doing so, it furnishes oilfield decision-makers with a more expedient and precise means of well selection. The following conclusions are delineated:

(1) Eight key parameters influencing CO_2 huff-n-puff are identified: formation pressure, reservoir thickness, reservoir temperature, porosity, permeability, water saturation, crude oil density, and crude oil viscosity. These influential factors are classified into positive, negative, and moderate indicators. To surmount the limitations associated with linear membership degrees in prevailing decision-making methodologies, a method for computing membership degrees utilizing exponential functions is established.

(2) Through an examination of seven successful CO_2 huff-n-puff cases, with the oil exchange rate as the targeted parameter, and employing dimensionless fuzzy matrix calculations to derive weighting factors, a positive correlation between the computed comprehensive decision factors and oil exchange rates is discerned. This substantiates the reliability of the weighting factors and circumvents the constraints of current decision-making methodologies that rely on expert scoring for weighting factor determination.

(3) Utilizing the computed weighting factors, the primary and secondary influence of each factor on the effectiveness of CO_2 huff-n-puff development can be preliminarily assessed. The hierarchical order of weighting factors, from primary to secondary, is as follows: porosity, reservoir temperature, water saturation, formation pressure, reservoir thickness, crude oil density, crude oil viscosity, and permeability.

(4) Employing the tight oil reservoir in the Ordos Basin as a case study and leveraging the collection of fundamental reservoir parameters, an enhanced fuzzy method is utilized to compute its comprehensive decision factor. Based on the statistical correlation between oil exchange rates and the comprehensive decision factor, the predicted oil exchange rate for CO_2 huff and puff in the Ordos Basin is determined to be 0.354, falling within the range of Chattanooga and Eagle Ford reservoirs.

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Conflicts of Interest: All Authors were employed by the company SINOPEC. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The company SINOPEC had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

Based on the data in Table 1, a linear equation is used to calculate the membership degree of each parameter. The equation is divided into three categories: positive indicator, inverse indicator, and moderate indicator. Among them, the dimensionless calculation model of the positive is

$$f_{p,i} = \frac{x_i - x_{i,\min}}{x_{i,\max} - x_{i,\min}} \tag{A1}$$

The dimensionless calculation model of the inverse indicator is

$$f_{N,i} = \frac{x_{i,\max} - x_i}{x_{i,\max} - x_{i,\min}} \tag{A2}$$

Similarly, we write the moderate indicator as

$$f_{M,i} = \begin{cases} \frac{x_i - x_{i,\min}}{x_{oi} - x_{i,\min}} & x_{i,\min} \prec x_i \leq x_{oi} \\ \frac{x_{i,\max} - x_i}{x_{i,\max} - x_{oi}} & x_{oi} \prec x_i \leq x_{i,\max} \end{cases} \tag{A3}$$

Still, using the classification of the three indicators in the article, the dimensionless fuzzy matrix based on the linear model can be calculated, as shown in Table A1.

Table A1. Dimensionless fuzzy matrix based on the linear model.

Block	k	P	h	T	ρ	Φ	S_w	μ
Bakken	0.049	0.794	0	0.887	0	0.781	0.615	0.09
Eagle Ford	0	0.466	0.444	0.968	0.429	0.833	0.423	0.141
Chattanooga	0.024	0.619	0.3	0.323	0.571	0.99	0.731	0.09
Appalachian	1	0	0.2	0	1	0	0.423	0.17
Lost Soldier	0.059	0.636	0	1	0.857	1	1	0
Fuyu	0.153	0.553	0.	0.952	0.143	0.083	0	0.054
Mahu	0.009	0	1	0.984	0.429	0.726	0.538	1

It can be seen from Table A1 that each parameter in the dimensionless fuzzy matrix calculated by the linear equation contains 0, and there are generally two 0 s in the moderate index, which will lose the influence of this parameter on the well selection decision. The exponential form chosen in this article will retain the impact of these parameters on the final decision, using a small value to reflect this impact instead of 0, as shown in Table 2.

By multiplying the fuzzy matrix calculated by this linear model and the weight coefficient, the comprehensive decision factor can be obtained. In Figure A1, we compare this method with the original method. It can be clearly seen that the linear trend of the original method is obviously not as good as the proposed method in this paper. In the improved fuzzy method, the original method will have a large error in the oil change rate prediction.

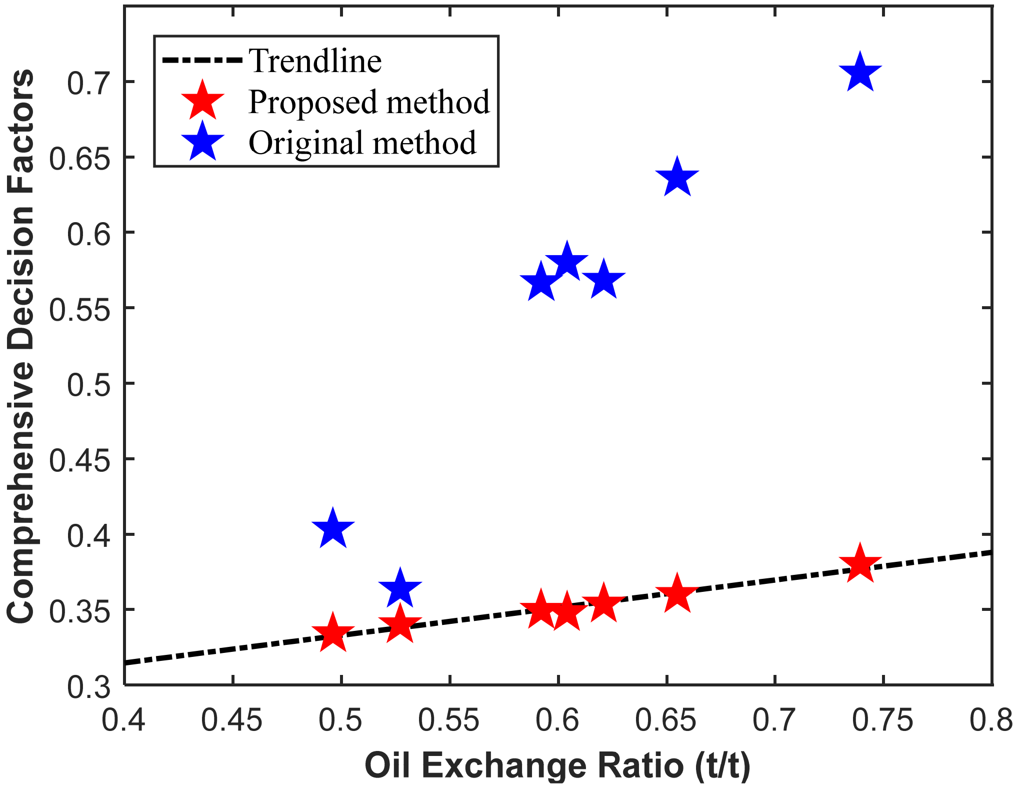

Figure A1. Comparison between proposed method and original method.

References

1. Roh, K.; Lim, H.; Chung, W.; Oh, J.; Yoo, H.; Al-Hunaidy, A.S.; Imran, H.; Lee, J.H. Sustainability analysis of CO_2 capture and utilization processes using a computer-aided tool. *J. CO2 Util.* **2018**, *26*, 60–69. [CrossRef]
2. Zhao, K.; Jia, C.; Li, Z.; Du, X.; Wang, Y.; Li, J.; Yao, Z.; Yao, J. Recent advances and future perspectives in carbon capture, transportation, utilization, and storage (CCTUS) technologies: A comprehensive review. *Fuel* **2023**, *351*, 128913. [CrossRef]
3. Skinner, C.B.; Poulsen, C.J.; Mankin, J.S. Amplification of heat extremes by plant CO_2 physiological forcing. *Nat. Commun.* **2018**, *9*, 1094. [CrossRef] [PubMed]
4. Yao, J.; Ding, Y.; Sun, H.; Fan, D.; Wang, M.; Jia, C. Productivity Analysis of Fractured Horizontal Wells in Tight Gas Reservoirs Using a Gas–Water Two-Phase Flow Model with Consideration of a Threshold Pressure Gradient. *Energy Fuels* **2023**, *37*, 8190–8198. [CrossRef]
5. Forrest, J.; Birn, K.; Brink, S.; Comb, T.J.; Cuthbert, B.; Dunbar, R.B.; Harju, J.A.; Isaacs, E.; Jones, F.; Kjanna, P.; et al. *Working Document of the Npc North American Resource Development Study-Unconventional Oil*; US National Petroleum Council (NPC): Washington, DC, USA, 2011; pp. 1–6.
6. Sheng, J.J. Critical review of field EOR projects in shale and tight reservoirs. *J. Pet. Sci. Eng.* **2017**, *159*, 654–665. [CrossRef]
7. Haskin, H.K.; Alston, R.B. An evaluation of CO_2 huff'n'puff tests in Texas. *J. Pet. Technol.* **1989**, *41*, 177–184. [CrossRef]
8. Hawthorne, S.B.; Gorecki, C.D.; Sorensen, J.A.; Steadman, E.N.; Harju, J.A.; Melzer, S. Hydrocarbon mobilization mechanisms from upper, middle, and lower Bakken reservoir rocks exposed to CO_2. In Proceedings of the SPE Unconventional Resources Conference Canada, Calgary, AB, Canada, 5–7 November 2013.

9. Ma, J.; Wang, X.; Gao, R.; Zeng, F.; Huang, C.; Tontiwachwuthikul, P.; Liang, Z. Enhanced light oil recovery from tight formations through CO_2 huff 'n'puff processes. *Fuel* **2015**, *154*, 35–44. [CrossRef]
10. Chen, C.; Balhoff, M.; Mohanty, K.K. Effect of reservoir heterogeneity on primary recovery and CO_2 huff 'n'puff recovery in shale-oil reservoirs. *SPE Reserv. Eval. Eng.* **2014**, *17*, 404–413. [CrossRef]
11. Abedini, A.; Torabi, F. Oil recovery performance of immiscible and miscible CO_2 huff-and-puff processes. *Energy Fuels* **2014**, *28*, 774–784. [CrossRef]
12. Yu, W.; Lashgari, H.R.; Wu, K.; Sepehrnoori, K. CO_2 injection for enhanced oil recovery in Bakken tight oil reservoirs. *Fuel* **2015**, *159*, 354–363. [CrossRef]
13. Mohaghegh, S.; Balanb, B.; Platon, V.; Ameri, S. Hydraulic fracture design and optimization of gas storage wells. *J. Pet. Sci. Eng.* **1999**, *23*, 161–171. [CrossRef]
14. Zeng, F.; Cheng, X.; Guo, J.; Chen, Z.; Xiang, J. Investigation of the initiation pressure and fracture geometry of fractured deviated wells. *J. Pet. Sci. Eng.* **2018**, *165*, 412–427. [CrossRef]
15. Chen, C.; Han, X.; Liu, X.; Wang, C. A new well selection method based on improved pressure index for polymer flooding. In Proceedings of the International Petroleum Technology Conference, Dhahran, Saudi Arabia, 13–15 January 2020.
16. Xiong, Q.; Ma, X.; Wu, B.; Ren, G.; Pan, J.; Yi, X.; Deng, W.; Yi, Y. Re-Fracturing Wells Selection by Fuzzy Comprehensive Evaluation Based on Analytic Hierarchy Process—Taking Mahu Oilfield as An Example. *Front. Energy Res.* **2022**, *10*, 851582. [CrossRef]
17. Yu, W.; Lashgari, H.R.; Sepehrnoori, K. Simulation study of CO_2 huff-n-puff process in Bakken tight oil reservoirs. In Proceedings of the SPE Western North American and Rocky Mountain Joint Meeting, Denver, CO, USA, 16–18 April 2014.
18. Zeng, F.; Wang, D.; Guo, J.; Zhang, S.; Zhang, P. Optimal selection of stimulation wells using a fuzzy multicriteria methodology. *Math. Probl. Eng.* **2019**, *2019*, 4084982. [CrossRef]
19. Gong, P.; Sun, B.; Liu, G.; Wang, Y. Fuzzy comprehensive evaluation in well control risk assessment based on AHP: A case study. *Adv. Pet. Explor. Dev.* **2012**, *4*, 13–18. [CrossRef]
20. Bybee, K. Screening criteria for carbon dioxide huff'n'puff operations. *J. Pet. Technol.* **2007**, *59*, 55–59. [CrossRef]
21. Monger, T.G.; Coma, J.M. A laboratory and field evaluation of the CO_2 huff'n'puff process for light-oil recovery. *SPE Reserv. Eng.* **1988**, *3*, 1168–1176. [CrossRef]
22. Bondarenko, A.; Islamov, S.; Mardashov, D.; Mingaleva, T. Features of oil well killing in abnormal carbonate reservoirs operating conditions. In Proceedings of the Engineering and Mining Geophysics 2019 15th Conference and Exhibition; European Association of Geoscientists & Engineers, Gelendzhik, Russia, 22–26 April 2019; pp. 1–5.
23. Islamov, S.R.; Bondarenko, A.V.; Mardashov, D.V. Substantiation of a well killing technology for fractured carbonate reservoirs. In *Youth Technical Sessions Proceedings*; CRC Press: Boca Raton, FL, USA, 2019; pp. 256–264.
24. Sun, R. Reservoir Characterization and Simulation of Enhanced Oil Recovery for Bakken. Master's Thesis, The University of North Dakota, Grand Forks, ND, USA, 2019.
25. Wang, L.; Yu, W. Gas huff and puff process in eagle ford shale: Recovery mechanism study and optimization. In Proceedings of the SPE Oklahoma City Oil and Gas Symposium/Production and Operations Symposium, Oklahoma City, OK, USA, 9–10 April 2019.
26. Cudjoe, S.; Vinassa, M.; Gomes, J.H.B.; Barati, R.G. A comprehensive approach to sweet-spot mapping for hydraulic fracturing and CO_2 huff-n-puff injection in Chattanooga shale formation. *J. Nat. Gas Sci. Eng.* **2016**, *33*, 1201–1218. [CrossRef]
27. Branting, R.A. CO2 Huff-n-Puffs: Field Tests and Simulation. Ph.D.; Thesis, University of Wyoming, Laramie, WY, USA, 1994.
28. Yao, T.; Sun, L.; Cui, C. Optimization design of CO_2 huff and puff parameters in Fuyu tight oil reservoir. *Spec. Oil Gas Reserv.* **2024**, *1*, 1–9.
29. Shi, L.; Zhang, Y.; Ye, Z.; Zhang, J.; Wang, Y.; Wang, R.; Wu, S. Field test effect analysis of CO_2 huff and puff for EOR of horizontal wells in tight glutenite reservoir of Mahu Oilfield. *Pet. Reserv. Eval. Dev.* **2021**, *11*, 871–877.
30. Liu, Y.; Zhu, Y.; Liao, H.; Yu, H.; Fang, X.; Zhang, Y. Mathematical Model of Imbibition Replacement and Optimization of Soaking Time for Massively Fractured Tight Oil Reservoirs. *ACS Omega* **2023**, *8*, 35107–35120. [CrossRef] [PubMed]