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A Closed-Loop Optimization System for Evaluating the Development Effect and Potential of Producers with Water Alternating Gas Flooding

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Abstract

Water alternating gas (WAG) flooding is a relatively mature technology for enhanced oil recovery (EOR). It combines the advantages of water flooding and gas flooding to maintain reservoir pressure and effectively mitigate the issues of high mobility ratio and fingering, demonstrating preferable application prospects. However, the evaluation of its development effect faces the challenges of complexity and lack of adaptability attributed to the multiple interactions of various factors involved in WAG flooding. Moreover, there are few studies evaluating the development effect of producers. Therefore, the traditional hierarchical analysis process (AHP) is improved in this study to fill the gap in this technological field. This process is combined with the entropy weight method (EWM) to establish a coupled evaluation model. Subsequently, this study classifies the contribution weights of producers and proposes adjustment suggestions for the primary development contradictions. This study finds that the contribution weight of producers to the well group indicates that the development effect of producers is no longer influenced by a single factor, but is determined by the coupling effect of geological, engineering, and development factors. By constructing a coupled model and fully utilizing on-site data to objectively characterize the underground production situation, the development effect of producers can be more accurately reflected. Finally, a closed-loop optimization system for evaluating the development effect and potential of producers with WAG flooding is established, laying a theoretical foundation for dynamic analysis and development adjustment of on-site engineers.

Keywords: low-permeability reservoir; water alternating gas; development effect; coupled evaluation model; contribution weight; closed-loop optimization

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1. Introduction

Water flooding and gas flooding have long been widely employed as the primary enhanced oil recovery (EOR) technologies in oilfield development. However, it is difficult to satisfy the demand for achieving high recovery rates with the traditional single displacement method [1–3]. This is owing to the increasing complexity of development stages and reservoir characteristics, such as high water cut stages [4,5], fractured-cavernous carbonate reservoirs [6,7], and unconventional reservoirs [8]. Generally, injected water preferentially

flows through a high permeability region during the process of water flooding, attributed to the reservoir heterogeneity, fluid viscosity difference, and gravity differentiation effect. Then a phenomenon of 'finger-in' or 'tongue-in' is generated. Consequently, the sweep efficiency in the low-permeability area is relatively low [9–11]. Special reservoirs show significant sensitivity to injected water. In high temperature and high pressure (HTHP) reservoirs, the deposition probability of calcium carbonate increases with the increase in formation water volume and temperature, while the increase in pressure has the opposite effect [12]. Additionally, the high viscosity of injected water considerably differs from the flow characteristics of crude oil [13], further restricting the application of water flooding technology in complex reservoirs. Gas flooding has demonstrated excellent performance in improving the sweep efficiency in low-permeability areas [14,15]. Nonetheless, the high mobility and the difference in density with crude oil can induce severe high mobility ratios and viscous fingering phenomena [16,17], such as in ultra-heavy oil reservoirs with strong heterogeneity and natural fracture development [18,19]. As a result, uneven displacement appears, affecting displacement efficiency and EOR [20].

WAG flooding, as a mature technology to improve recovery, remarkably improves the final recovery [21–23] while maintaining the reservoir pressure [24] and effectively alleviating headaches of high mobility ratio and fingering [25] by combining the advantages of water flooding and gas flooding [26]. Simultaneously, it lowers gas injection volume and possesses favorable economic prospects compared to gas flooding, which exhibits great potential for the development of complex reservoirs [27]. Wang et al. [28] conducted experimental and modeling studies following continuous CO_2 injection. The research showed that the application of mixed CO_2-WAG injection could significantly enhance oil recovery. It was also identified that asphaltene deposition and inorganic scaling were the primary factors contributing to the reduction in porosity. Majidaie et al. [29] employed chemical slug injection during the WAG process to diminish oil–water interfacial tension. This approach led to a 26 percent enhancement in oil recovery when compared to traditional WAG flooding methods. Wang et al. [30] explored an innovative approach utilizing flue gas–water-alternating flue gas (flue Gas-WAG) injection technology after water flooding to achieve multi-component flue gas storage. This enhanced both the ultimate oil recovery rate and flue gas storage capacity of the reservoir. However, because of the multiple interactions of dynamic and static factors involved in WAG flooding, the evaluation of its development effect is encountering the challenges of complexity and lack of adaptability. A systematic and comprehensive evaluation system and methodology for this technology has yet to be established.

The evaluation system consists of the model and the method, as illustrated in Figure 1. It plays a crucial role in the accuracy and reliability of the evaluation results. Early evaluation systems majorly include the experimental method [31], the Delphi method [32–34], and the analogy method [35]. Nonetheless, these methods only belong to qualitative analysis and cannot be quantitatively characterized. The advantages and disadvantages of these systems are detailed in Table 1. Among them, the experimental method is time-consuming and expensive and cannot promptly meet the application needs on site. The Delphi method is too subjective, rendering it difficult to guarantee the accuracy and reliability of the results, and the analogical method has a restricted scope of application. Multi-criteria decision-making issues are evaluated by mathematical methods based on known dynamic and static parameters and dynamic development indexes to achieve efficient, accurate quantitative evaluation [36,37].

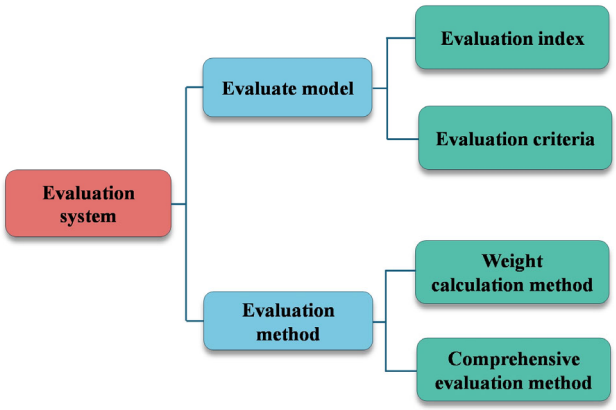


Figure 1. The structure of the evaluation system.

Table 1. Characteristics of the early evaluation system.

Evaluation System	Advantages	Disadvantages
Experimental method	Visual presentation of reservoir characteristics and development effect, providing a reliable basis.	A cumbersome process, a long cycle, requires a large input of manpower and material resources, costly.
Delphi method	Easy to operate, can quickly gather experts' wisdom to form a judgment.	Relying on experts' subjective opinions may lead to biased results, and requires multiple rounds of feedback, which consumes time and energy.
Analogical method	Using the data of developed reservoirs to infer the potential and trend of undeveloped reservoirs.	Difficult to be applied in the absence of similar reservoir cases, and limited scope of application.

The evaluation model consists of indexes and criteria. The evaluation criteria are clear regulations based on the specific requirements and determination scales of the evaluation indexes. Concerning water flooding development, Liu et al. [38] proposed a development index system based on parameters such as effective porosity, air permeability, and producer/injector ratio, and conducted qualitative analysis. Factor analysis was performed to simplify indexes and revealed the internal structure, so as to accurately evaluate the effect of water flooding development and the scientific formulation of the development strategy. Huang et al. [39] employed recoverable reserves, recovery degree, and cumulative water storage rate to build a quantitative reference standard for the effect of water flooding development. Wen et al. [40] constructed a system of indexes such as water cut growth rate, injection–production ratio, recoverable reserves and EOR. Their results lay a foundation for evaluating the development effect of water flooding in the ultra-high water cut stage and optimizing the development strategy. Regarding the development of unconventional oil and gas reservoirs, especially shale gas reservoirs in the ocean, Jiang et al. [41] conducted an adaptive analysis of evaluation criteria based on crucial indexes such as reservoir thickness, porosity, single well gas production, and net cash flow. It contributes to promoting the advancement of the marine shale gas development technology. With factors such as the relative density of crude oil, original oil saturation, porosity, reservoir temperature, and average formation pressure, Zheng et al. [42] compared the importance of each factor and established evaluation criteria. Nonetheless, the evaluation model failed to consider the influence of formation thickness. Rui et al. [43] tackled the lack of a quantitative evaluation system for oil and gas reservoir development and established a comprehensive

quantitative evaluation system with vital indexes such as porosity, permeability, and cumulative production. It aims to improve the design accuracy of the development plan. In the current research, qualitative, quantitative, and comprehensive development effect evaluations of different development methods or development stages have been conducted based on reservoir characteristic indexes, development dynamic indexes, and economic evaluation indexes.

Evaluation methods primarily include weight calculation methods and comprehensive evaluation methods. Generally, weight calculation methods can be divided into subjective weight methods and objective weight methods. Subjective weight methods assign weights to indexes following the experience or judgment of experts. Objective weight methods are based on the objective information reflected by index values themselves. In the research of subjective weights, Fu et al. [44] established an evaluation system for water flooding reservoirs based on the division of development stages and optimized the water injection development strategy. Fuzzy comprehensive evaluation, a quantitative evaluation method based on fuzzy mathematics, essentially quantifies the uncertainty and fuzziness in complex systems through affiliation functions and evaluation models. It combined with multiple index weights to ultimately achieve a comprehensive evaluation of the system or object. Practical research has revealed [45–47] that this method can decompose the complex water injection effect into specific quantifiable indexes for quantitative evaluation by constructing a multi-level index system. Hence, it can effectively overcome the limitations of traditional evaluation methods in multi-factor processing. Lu et al. [48] evaluated the application effect of CO_2 flooding technology by constructing a fuzzy mathematical method under the consideration of both the technical economy and environmental friendliness. In the research of objective weights, Geng et al. [49] adopted principal component analysis (PCA) to simplify complex indexes and extract crucial indexes to comprehensively evaluate the water injection effect of the edge and bottom water reservoir. Ju et al. [50] introduced the entropy weight method (EWM) to establish an evaluation model through the analysis of six influencing factors and quantify the brittleness and ductility of tight reservoir rocks. Su et al. [51] scientifically assessed the water injection development effect for the carbonate fracture–vuggy reservoir through Fuzzy Measure Theory and Martens distance method.

For more accurate and reliable evaluation results, more researchers have investigated comprehensive evaluation methods. Gu et al. [52] considered the reservoir fracture characteristics comprehensively through a combination of qualitative and quantitative evaluation methods, supporting decision-making for the water injection in this type of reservoir. The hierarchical analysis method (AHP), a multi-objective weighting method combining qualitative and quantitative methods, has been proposed and widely applied to some evaluations, such as estimating the permeability of fault zones [53] and improving the decision-making of heavy oil projects [54]. Wang et al. [55] performed AHP and fuzzy comprehensive judgment to determine the subjective and objective weights of each index. They presented a simple and fast evaluation method suitable for the effect of water flooding of ultra-high water cut reservoirs in the later stage, guiding the adjustment of the oilfield development. With the Overlapping Advantage Method and PCA, Li et al. [56] quantified the weights of five influencing factors, unveiling that the thickness of carbonate rocks in the study area determines the development of high-quality reservoirs. The brittleness index and fracture density can significantly elevate the development efficiency of the reservoir. Song et al. [57] quantified the correlation between initial production capacity and high-pressure mercury injection parameters (Q1) and pore morphology parameters (Q2) through gray correlation analysis. They constructed a comprehensive weight model by integrating subjective weights of AHP and objective weights of EWM and built a double-coupled quantitative classification system based on the micro-pore structure to specify that the

Northwestern underwater distributary channel area is the favorable zone for high-quality reservoir development.

At present, the evaluation of the development effect of producers for WAG flooding is missing. Under this consideration, a closed-loop optimization system is established in this study to evaluate the development effect and potential of producers in the existing research block, the WAG pilot area. It aims to fill the gap in the field of evaluating the development effect of producers for WAG flooding and provide the theoretical foundation and practical paradigm for relevant operations in the field. Specifically, various kinds of dynamic and static data are collected and collated upon the actual situation in the field. New evaluation criteria are defined with the proposed evaluation method to form an evaluation model with independent and reasonable evaluation indexes. Then, it is necessary to determine the contribution weight of each producer to the production of the well group in the process of development effect evaluation. Hence, the EWM is used to determine its weight. Meanwhile, the traditional AHP is innovatively improved to enhance the objectivity of its method, namely, IAHP. Additionally, the EWM–IAHP coupled evaluation model is constructed by combining the weights to obtain coupled weights that are more in line with the actual development effect to attenuate the dominant index effect. Finally, producers with different development effects are categorized, and targeted development adjustment measures are proposed under the principle of technical economy. In this way, a closed-loop optimization system is formed based on the evaluation of the development effect and potential of producers with WAG flooding.

2. Methodology

2.1. Data Pre-Processing

Positive, negative, and extreme indexes usually coexist in the process of constructing an evaluation index system. The data of various types of indexes considerably differ in scale and order of magnitude, and each has a clear data range. Consequently, they may be improperly influenced by the data size itself in the evaluation process, affecting the accuracy of the evaluation results. With the purpose of managing this headache, the data are standardized with respect to extreme deviation. The value range of the data will be standardized in the interval [0, 1] through this treatment, thereby unifying scales and eliminating biases caused by different scales and orders of magnitude. This improves the rationality of the role of indexes in the evaluation process while further strengthening the scientificity and reliability of the entire evaluation system. Thus, it can be guaranteed that evaluation results accurately reflect the actual situation and lay a solid foundation for subsequent research and decision-making.

The formula for the positive index is

$$X_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{1}$$

The formula for the negative index is

$$X_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}} \tag{2}$$

The formula for the extreme index is

$$X_{ij} = 1 - \frac{\left|x_0 - x_{ij}\right|}{x_{max} - x_{min}} \tag{3}$$

where X_{ij} denotes the normalized data, x_{ij} represents the original data for a particular index, x_0 indicates the best value for the extreme index, x_{min} embodies the minimum value in the original data, and x_{max} designates the maximum value in the original data.

2.2. Entropy Weight Method (EWM)

Information entropy, an index of the degree of chaos in information systems, is a crucial metric for quantifying the uncertainty of random variables and has been widely applied in many fields. Since its concept was proposed, it has essentially functioned in the assessment of suitability or risks such as engineering disasters and multi-criteria decision analysis. The reason lies in that it can objectively evaluate the distribution of each evaluation factor and to some extent exclude the interference of evaluator's subjective factors on evaluation results. In this study, the information entropy theory is introduced to reflect the development effect of each producer by evaluating the degree of disorder of its evaluation indexes and selecting indexes such as injection–production ratio as the basis for measuring the development effect. When these indexes are more dispersed, the information entropy value is smaller, and the corresponding weight is larger, and vice versa. Therefore, the contribution weights of producers in the well group can be determined by analyzing the degree of dispersion in indexes of each producer. Specifically, the EWM is employed to derive the entropy weight of each evaluation index based on the degree of differentiation of evaluation index values for each producer. Subsequently, the entropy weight of each evaluation index is weighted for all producers to obtain objective evaluation results. The evaluation process is depicted in Figure 2. The basic steps of the EWM are described as follows:

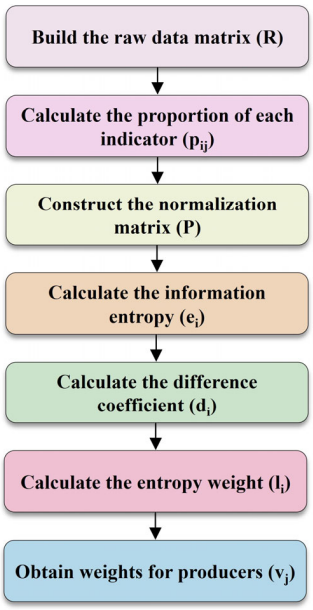


Figure 2. The EWM evaluation process.

Assuming that there are m producers and n evaluation indexes, the raw data matrix $R = (r_{ij})_{n \times m}$ of the corresponding evaluation indexes of producers is formed as

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}_{n \times m} \tag{4}$$

where r_{ij} denotes the index value of jth producer under ith evaluation index.

The proportion p_{ij} of the index value for jth producer is calculated under ith evaluation index:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} (i = 1, \cdots, n;\ j = 1, \cdots, m) \tag{5}$$

Thus, the normalization matrix $P = (p_{ij})_{n\times m}$ is constructed for each producer.

The information entropy e_i for ith index is calculated:

$$e_i = -\left(\frac{1}{\ln n}\right)\sum_{i=1}^{n} p_{ij}\ln p_{ij}(i = 1, 2, \cdots, n) \quad (6)$$

where e_i embodies the information entropy of the index, $e_i > 0$. If $p_{ij} = 0$, define $e_i = 0$.

The difference coefficient d_i for ith index is calculated:

$$d_i = 1 - e_i \quad (7)$$

The entropy weight l_i for ith index is calculated:

$$l_i = \frac{d_i}{\sum d_i}(i = 1, \cdots, n) \quad (8)$$

The contribution weight of each producer to the well group is calculated:

$$v_j = \frac{p_{ij} \times l_i}{\sum p_{ij} \times l_i}(i = 1, \cdots, n;\ j = 1, \cdots, m) \quad (9)$$

2.3. Improved Analytic Hierarchy Process (IAHP)

Analytic Hierarchy Process (AHP), proposed in 1971 by Thomas L. Satie, is a multi-criteria decision-making tool. It transforms subjective judgments of decision-makers into quantitative analyses through an ordered hierarchical structure and thus effectively integrates qualitative and quantitative indexes in complex system evaluations. The universality of the method is reflected in three aspects as follows. First, the structured characterization of complex systems is achieved by constructing a hierarchical model with a strict mathematical foundation. Second, the pairwise comparison method is adopted to convert expert experience into a computable judgment matrix. Third, the weighting system based on the eigenvector method is equipped with a strict consistency-checking mechanism. Consequently, the AHP method has demonstrated strong decision support capabilities in over 30 disciplines, primarily involving resource allocation, risk evaluation, and engineering preference.

The core of the AHP evaluation model follows a three-stage systematic process. First, a structured analysis is conducted based on the intrinsic logical relationship of decision-making objectives to construct a multi-level architecture consisting of the objective layer, the criterion layer and the solution layer. Concerning complex decision-making issues, the key elements are decomposed, and the hierarchical relationships are reorganized, so as to form an evaluation system with a tree structure. This ensures that the dominant relationships between elements are consistent with the logical hierarchy. In concrete implementation, the decision-making problem is disassembled into non-overlapping sets of elements, which are hierarchically categorized in accordance with their affiliation to form a top-down control chain structure. Second, the proportional scaling method is employed to compare elements at the same level pairwise. Meanwhile, the weight coefficients of each element relative to the upper factors are derived by constructing a judgment matrix that satisfies the mathematical requirements. Finally, the weights of each layer are progressively synthesized by the recursive algorithm to obtain the global priority of the bottom layer scheme relative to the top layer target.

The standard implementation procedure of the method comprises four key steps: (1) designing the hierarchical architecture; (2) constructing the judgment matrix; (3) performing hierarchical single ranking and consistency validation to solve the eigenvector and calculate the maximum eigenvalue; (4) hierarchical total ranking and consistency

validation. The evaluation flow is exhibited in Figure 3. The steps are described in detail as follows.

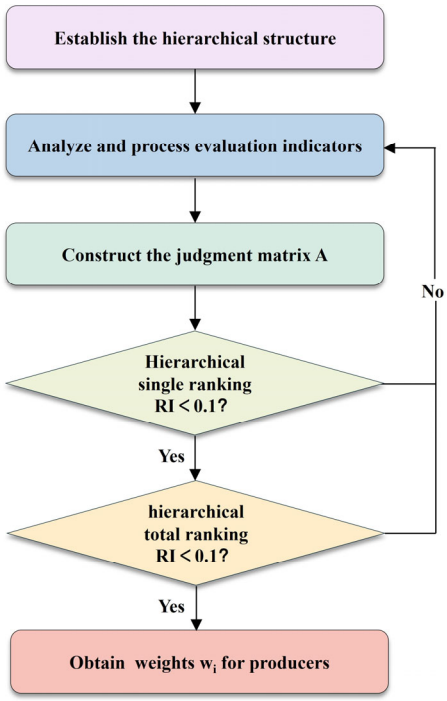


Figure 3. The improved AHP evaluation process.

2.3.1. Design the Hierarchical Architecture

After an in-depth and comprehensive analysis of the specific problem, various elements of the problem are accurately decomposed and categorized into a hierarchical architecture with strict affiliation upon their intrinsic logical connections and hierarchical attributes, including the objective layer, the criterion layer, and the solution layer. The hierarchical architecture of the hierarchies and relationships between elements is accurately visualized and depicted by a block diagram. If the number of elements in a particular layer is large, it will be decomposed into several sub-layers to optimize the clarity and logical coherence of the hierarchical architecture. In the constructed hierarchical model, the elements of the same layer are both dominated and constrained by the elements at the previous layer. Meanwhile, they exert influence and regulation on elements at the next layer. The top of the hierarchical architecture is the objective layer, which generally contains only one core element, and the bottom of the architecture is the solution layer. Between the objective and solution layers are one or more criterion layers, which are essentially composed of indexes or guideline layers, as exhibited in Figure 4.

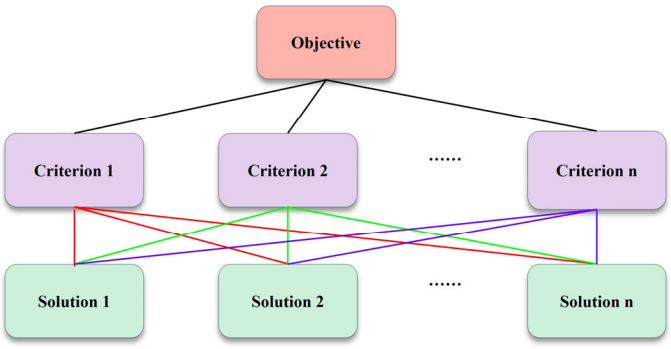


Figure 4. The hierarchical model of AHP.

2.3.2. Construct the Judgment Matrix

After the establishment of the hierarchical model, the affiliation between the upper and lower layers is determined. Concurrently, a judgment matrix is constructed by comparing the importance of each factor in the same layer relative to the previous layer pairwise with the 1–9 scale method (Table 2). If factor A in the previous layer is taken as the criterion, b_1, b_2, …, b_n are the factors in the next layer dominated by A, and the importance of b_i and b_j are evaluated relative to the criterion A. The nth order matrix $A = (a_{ij})_{n\times n}$, where a_{ij} represents the degree of importance (or unimportance) of the factor b_i over b_j relative to criterion A.

Table 2. The judgment matrix.

Criterion	Index 1	Index 2	…	Index *n*
Index 1	a_{11}	a_{12}	…	a_{1n}
Index 2	a_{21}	a_{22}	…	a_{2n}
⋮	⋮	⋮	⋱	⋮

Considering that comparisons and judgments between two factors commonly depend on the experience of experts, they involve more human factors and are highly subjective. In this study, the intrinsic attributes of factors are first determined, and different factors are classified according to positive, negative, and extreme indexes. Following the size of the data range, the dynamic nine-level scaling algorithm is innovatively used for splitting (Equation (10)), and measurements and comparisons are based on the distance between factors. This method realizes the precise quantification of the differences between factors while establishing robust theoretical support for AHP through data-driven objective comparison. Thus, it effectively improves the objectivity and scientificity of the decision-making process, offering a new perspective and methodology for related research fields.

$$S_k = x_{min} + \left(\frac{x_{max} - x_{min}}{9}\right) k \ (k = 1, 2, \ldots, 9) \tag{10}$$

All judgment matrices must satisfy $a_{ii} = 1$, $a_{ii} = 1/a_{ji}$ (where i, j = 1, 2, …, n). The meanings of the judgment matrix scales are presented in Table 3.

Table 3. Scale 1–9 and meaning.

Criterion	Index 1	Index 2	Index *n*
9	b_i is extremely important than b_j	1/9	b_i is extremely less important than b_j
7	b_i is significantly more important than b_j	1/7	b_i is significantly less important than b_j
5	b_i is more important than b_j	1/5	b_i is not as important as b_j
3	b_i is slightly more important than b_j	1/3	b_i is slightly less important than b_j
1	b_i is equally important as b_j	1	b_i is equally important as b_j

If the importance level of b_i is between two adjacent levels compared to b_j, then the value of a_{ij} is taken as 2, 4, 6, 8 and 1/2, 1/4, 1/6, 1/8.

2.3.3. Hierarchical Single Ranking and Consistency Validation

The hierarchical single ranking aims to determine the weight of the importance order of a factor in the previous layer to factors in the next layer that it dominates. First of all,

the eigenvector and the maximum eigenvalue of the judgment matrix A are calculated, namely, the equation $AW = \lambda_{max}W$. Among them, W represents the regularized eigenvector corresponding to λ_{max}, λ_{max} denotes the maximum eigenvalue of the judgment matrix A, and the component W_i of W embodies the single ranking weight value of the corresponding factor, reflecting the ranking weights of factors at the same layer regarding their importance to a certain factor at the previous layer.

Each column of the judgment matrix is normalized:

$$\overline{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} (i, j = 1, 2, \cdots, n) \tag{11}$$

The normalized judgment matrix is summed by row:

$$\overline{w}_i = \sum_{j=l}^{n} \overline{a}_{ij} \ (i, j = 1, 2, \cdots, n) \tag{12}$$

The vector $\overline{w} = [\overline{w}_1, \overline{w}_2, \ldots, \overline{w}_n]^T$ is normalized:

$$w_i = \frac{\overline{w}_i}{\sum_{i=1}^{n} \overline{w}_i} (i = 1, 2, \cdots, n) \tag{13}$$

Then $w = [w_1, w_2, \ldots, w_n]^T$ is the desired eigenvector.

The maximum eigenvalue of the judgment matrix is computed:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{14}$$

where $(AW)_i$ denotes the ith component of the vector AW.

If the judgment matrix A has full consistency, then $\lambda_{max} = n$. However, this situation is relatively rare. Thus, the consistency index $CI = (\lambda_{max} - n)/(n - 1)$ must be calculated to perform consistency validation for hierarchical single ranking. When $CI = 0$, the judgment matrix has full consistency; the smaller the value of CI, the better the consistency of the judgment matrix. Additionally, the random consistency ratio $CR = CI/RI$ of the judgment matrix, that is, the ratio of CI to the average random consistency index RI of the same order, should be calculated to judge whether the consistency of the matrix is satisfactory or not. If $CR < 0.10$, the result of hierarchical single ranking has satisfactory consistency, otherwise it is necessary to adjust the value of the judgment matrix factors. The values of the average random consistency index RI are listed in Table 4.

Table 4. The value of RI.

Matrix Order	1	2	3	4	5	6	7	8	9
RI value	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.3.4. Hierarchical Total Ranking and Consistency Validation

The hierarchical total ranking is performed to quantify the relative importance ranking weights of factors at the same layer relative to the highest layer. The process follows the principle of progressive calculation from the highest to the lowest layer. Notably, the hierarchical single ranking result of the highest layer is equivalent to its hierarchical total ranking result. With the purpose of ensuring the reliability of the total hierarchical ranking result, consistency validation is conducted to verify the consistency of its result. Therefore, the random consistency ratio $R = CI/RI$ of hierarchical total ranking is calculated, where CI denotes the consistency index of hierarchical total ranking $CI = \sum_{j=1}^{m} a_j CI_j$, CI_j represents

the consistency index of the judgment matrix of the B layer corresponding to a_j; RI indicates the random consistency index of hierarchical total sorting $RI = \sum_{j=1}^{m} a_j RI_j$; RI_j embodies the random consistency index of the judgment matrix of B layer corresponding to a_j. If $CR < 0.10$, the hierarchical total ranking has satisfactory consistency calculation results; if $CR \geq 0.10$, each judgment matrix must be adjusted until the random consistency ratio CR of the hierarchical total ranking is less than 0.10.

2.4. Coupled EWM–IAHP Evaluation Model

AHP and EWM are two common methods of determining weights in the field of multi-index comprehensive evaluation. By constructing a structured hierarchical model, AHP assigns weights to the evaluation indexes based on the subjective judgment of experts on the relative importance of indexes. From another perspective, the EWM is determined by the entropy value of the index data. It objectively reflects the information contained in indexes, mines inherent rules of the data, and makes the evaluation more objective. However, it fails to incorporate the experience of experts and opinions of decision-makers, and the weight values sometimes deviate from the actual importance of indexes.

The single use of AHP or EWM can easily induce a preference for a certain method in the evaluation results. Evaluation results should converge to create a unified method to be more in line with the actual situation. Innovatively, weights v_i obtained by EWM are coupled with weights w_i obtained by IAHP in this study to construct coupled weights u_i, expressed as

$$u_i = \alpha v_i + (1 - \alpha) w_i (i = 1, 2, \cdots, n) \quad (15)$$

where $0 \leq \alpha \leq 1$.

This coupling approach aims to integrate the advantages of the two methods, balance the effects of dominant indexes, and enhance the objectivity of the weight determination.

Specifically, v_i and w_i represent weights of the EWM and IAHP model, respectively, and α denotes the proportional coefficient. This study takes $\alpha = 0.5$, which is the arithmetic mean of weights of two models [58], to objectively present the respective advantages of the two methods and provide strong support for accurate evaluation.

3. Case Study

In this section, high-quality dynamic and static data are collected and screened for the WAG development test area in a low-permeability carbonate reservoir in the Middle East. Based on the processed field data, an evaluation system for the effect and potential of WAG development of producers is established from the EWM evaluation process, the IAHP evaluation process, and lastly the coupled model evaluation process.

3.1. Raw Data Description

The object of this study is a short-axis anticline and low-amplitude structural reservoir located in the Middle East. The pore type of this reservoir is medium-high porosity (4–28%) and the permeability is 0.1–16 mD. It is a typical low-permeability reservoir. Following rock type classification, the reservoir is divided into three categories: gas top zone at the top, pure oil zone at the waist, and oil–water transition zone at the edge.

The reservoir is developed with gas injection and area well patterns. Due to the long-term injection of a large amount of hydrocarbon gas and some CO_2, the field development benefits are constrained by high GOR and declining production. Therefore, a WAG pilot test area (four injectors and four producers) is performed in the region to evaluate the field production effect and demonstrate the feasibility of its implementation to develop the oil–water transition zone at scale. In order to save economic costs, the extracted hydrocarbon gas and CO_2 are reinjected as the injection gas for the development of the pilot test area.

Additionally, static and dynamic data of the well group are collected and collated from the oilfield site with various factors taken into account to fully characterize the WAG development effect of producers in the test area. Attributed to the short production time and in the experimental stage, the dataset contains information collected from four horizontal producers at the oilfield site one year before and six months after the test, including well ID, porosity (φ), permeability (K), horizontal length of the producer (L), average monthly oil production (AMOP), gas–oil ratio (GOR), water cut (WCT), and injection–production ratio (VRR). Specifically, there are signs of gas breakthrough, and GOR is high, owing to the injection of a large amount of gas before the implementation of the test area. Hence, the data after six months of the test are screened to weaken the residual effect of gas injection. After logical analysis from three dimensions of geology, engineering, and development, redundant parameters or indexes are eliminated. Meanwhile, we select evaluation indexes that can accurately reflect the development effect of producers with WAG flooding by combining the actual data sources in the field, as detailed in Tables 5 and 6.

Table 5. Status of production before the implementation of the pilot area.

Time	Well ID	φ/%	K/mD	L/ft	AMOP/bbl	GOR/(scf/bbl)	WCT/%	VRR
2022.06 – 2023.06	P-89	14	5.07	3668	1671.9	1868.6	5.0	1.39
	P-119	12	1.93	3480	2677.7	4999.3	6.8	1.05
	P-120	13	5.66	3713	3232.6	4261.6	1.4	0.98
	P-124	15	6.35	2593	2308.4	4280.9	1.0	0.94

Table 6. Status of production after the implementation of the pilot area.

Time	Well ID	φ/%	K/mD	L/ft	AMOP/bbl	GOR/(scf/bbl)	WCT/%	VRR
2024.01 – 2024.12	P-89	14	5.07	3668	1431.2	2291.9	5.4	2.59
	P-119	12	1.93	3480	2683.0	4968.3	8.5	0.49
	P-120	13	5.66	3713	2998.4	5127.5	2.3	0.41
	P-124	15	6.35	2593	2676.9	4139.5	3.8	1.77

3.2. Evaluation of Development Effect Using EWM

Following the EWM process in Section 2.2, the standardized data are input into corresponding Equations (5)–(7) to calculate evaluation index values of producers (Table 7). GOR has the greatest influence on the development effect of producers, accounting for 28.9% among seven categories of indexes; the porosity is second, accounting for 16.1%; and the influence of VRR is the smallest, with a value of only 2.7%, as illustrated in Figure 5. The weights of other indexes are not significantly different, suggesting that development indexes have the greatest influence, followed by geology indexes and engineering indexes have the smallest influence. This result is consistent with the empirical knowledge during the development process.

Table 7. Index information for EWM.

Index	e_i	d_i
φ	0.729	0.271
K	0.785	0.215
L	0.789	0.211
AMOP	0.788	0.212
GOR	0.517	0.483
WCT	0.765	0.235
VRR	0.956	0.044

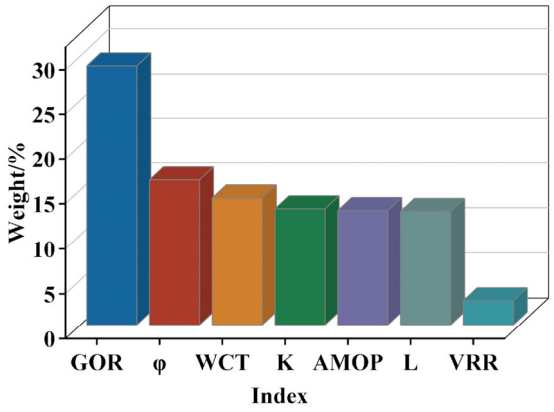


Figure 5. Entropy ranking of indexes.

As revealed by comparing the actual situation of the current field development, high GOR is the primary constraint at present, and the development should be adjusted based on the main controlling factor; a large amount of gas is injected before the implementation of WAG development, resulting in gas channeling or potential risks. The high GOR has consistently been the main factor restricting producer production, in good agreement with the current on-site problems and reflecting the retention effect of previously injected gas in the subsurface. Simultaneously, weights of various indexes are favorable references for reservoir engineers' later dynamic analysis and development adjustment, allowing for the timely discovery of problems and prevention of hidden risks.

Producers are calculated by Equations (8) and (9) to obtain their respective production contribution weights in the well group. Specifically, the P-89 producer has the largest contribution to the production of the well group (32.4%) and exhibits the best production effect. The P-119 producer has the smallest contribution to the production of the well group (11.3%) and demonstrates the worst production effect, as depicted in Figure 6. The results are different from those obtained by measuring the production effect of a producer based on the single production index. The development effect of producers, influenced by various factors, is analyzed and judged from geology, development and engineering dimensions to objectively and quantitatively reflect the real production status of producers.

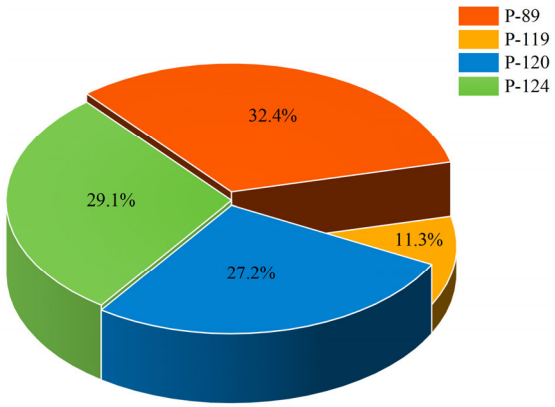


Figure 6. Contribution weights v_j of producers.

3.3. Evaluation of Development Effect Using IAHP

The hierarchical architecture of this study does not involve sub-layers in the criterion layer. This belongs to the problem of hierarchical single ranking and consistency validation. The framework of the evaluation of the WAG development effect of producers is illustrated in Figure 7. Following the IAHP in Section 2.3, the field data collected after the implementation of WAG development in the pilot test area (2024.01–2024.12) are adopted for the preliminary evaluation of the development effect, and scores are calculated, as listed in Table 8. As revealed from scores, the P-119 producer has the lowest score, implying that the production effect is still the worst. Upon scores of each producer, the dynamic nine-level scale method is performed to finely classify and accurately evaluate the difference in the level of development effect of producers (Figure 8). The judgment matrix is constructed, as detailed in Table 9.

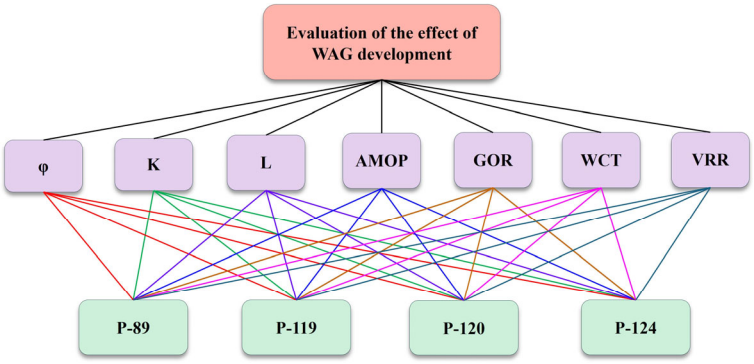


Figure 7. The framework of WAG development effect evaluation.

Table 8. Preliminary evaluation.

Well ID	φ/%	K/mD	L/ft	AMOP/bbl	GOR/(scf/bbl)	WCT/%	VRR	Score
P-89	3	2	3	1	4	2	1	16
P-119	1	1	2	3	2	1	4	14
P-120	2	3	4	4	1	4	3	21
P-124	4	4	1	2	3	3	2	19



Figure 8. The schematic diagram of production effect differences.

Table 9. The judgment matrix for producers.

Well ID	P-89	P-119	P-120	P-124
P-89	1	2	1/6	1/4
P-119	1/2	1	1/9	1/6
P-120	6	9	1	2
P-124	4	6	1/2	1

After the judgment matrix is normalized by Equations (11) and (12), the eigenvector and the maximum eigenvalue of producers are obtained according to Equations (13) and (14). In addition, the eigenvector (namely, weight values) and the weight w_i of each producer's contribution to the production of the well group are obtained, as presented in Table 10:

Table 10. Results of IAHP calculations.

Well ID	Eigenvector	Weight Value (%)	Maximum Eigenvalue	*RI*	*CR*	Consistency Validation Result
P-89	0.091	9.1%	4.238	0.90	0.088	Pass
P-119	0.053	5.3%				
P-120	0.543	54.3%				
P-124	0.313	31.3%				

Through the consistency validation and referencing Table 4, the average random consistency index RI of the judgment matrix is 0.90 and CR = 0.088 < 0.10 considering 4 producers in the well group, n = 4. In other words, the consistency validation is passed, validating the rationality and reliability of IAHP proposed in this study.

According to IAHP calculation, among the production contribution weights of each producer in the well group, the P-120 producer has the largest contribution to the production of the well group (54.3%) and exhibits the best production effect; the P-119 producer has the smallest contribution to the production of the well group (5.3%) and reveals the worst production effect, as illustrated in Figure 9. The analysis unveils that the P-120 producer has the highest score in the preliminary evaluation, benefitting from the best performance of K, L, AMOP, WCT, and VRR. Many indexes of 5/7 rank first, and production and engineering factors exert a significant impact on its development. Thus, its production contribution weight is over 50% in the evaluation of the method, with a large potential for development. The scores of φ, K, and WCT of the P-119 producer are the lowest, and GOR and VRR are high. Most of the indexes perform poorly, while geology and development factors have a greater impact on it. Its evaluation results are consistent with the weight in Section 3.2, the lowest in the well group. This further confirms that the well condition is very poor and it is difficult to develop it effectively.

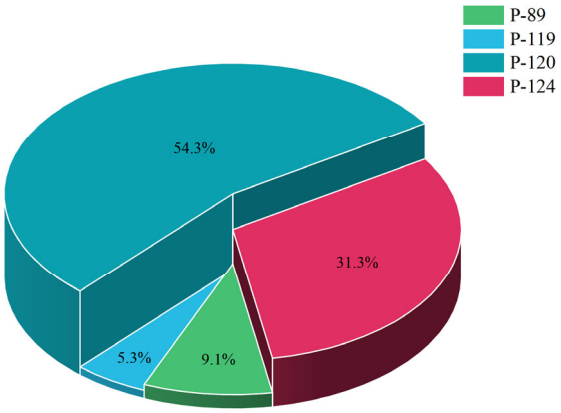


Figure 9. Contribution weights w_i for producers.

3.4. Evaluation of Development Effect Using Coupled Model

The two methods mentioned above have different ways of analyzing and processing the data, as well as capturing the main controlling factors affecting the development effect of producers in different directions. Therefore, the calculated weights of the two types above are weighted to obtain the evaluation results most in line with real well conditions. This contributes to further reducing the errors caused by the two methods themselves, balancing their dominant indexes, and achieving a more accurate evaluation of the production effect of each producer in the well group.

Coupled weights that best match the real well conditions for each producer are obtained by bringing v_i and w_i into the coupled weights Equation (15), as illustrated in Figure 10.

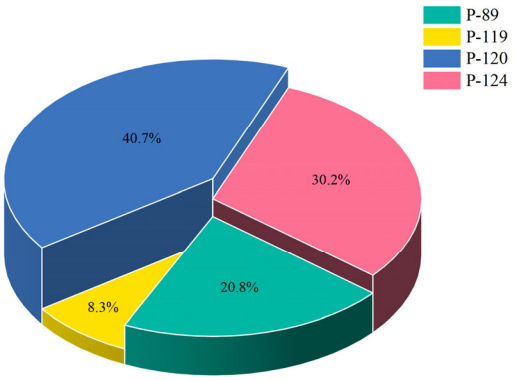


Figure 10. Contribution weights u_i for producers.

Lastly, the P-120 producer has the largest contribution weight to the well group (40.7%) and the best development effect. The P-119 producer has the smallest contribution weight to the well group (11.3%) and the worst development effect. Particularly, producers with better production effects should maintain the status quo or make local adjustments upon the concept of maximizing the whole life cycle to develop the residual oil in the reservoir in a balanced way while lessening the heterogeneity caused by the development. Meanwhile, producers with poorer development effects improve the reservoir condition and elevate the development efficiency by changing the well working system under the principle of engineering economy and considering the reservoir modification measures if necessary.

4. Results

In this study, production contribution weights of the well group are divided into five levels to provide clearer feedback to field reservoir engineers and other staff about the

current production status of producers. There are four producers in this well group, and the ideal production contribution weight for each producer should be 25%. However, the actual production performance is different attributed to different geology, development, and engineering factors of each producer, as well as the existence of inter-well interferences. Under the consideration of development effect and exploitation potential it is divided into five classification levels of high-efficiency well, medium-high-efficiency well, medium-efficiency well, low-efficiency well, and ultra-low-efficiency well with the threshold value of 25% as the boundary. This facilitates on-site staff in quickly analyzing and judging the current situation based on the historical production information of the well group, quantifying the degree of challenges faced by producers, and making dynamic adjustments to production systems promptly to avoid potential risks. The classification levels can be employed for early warning, elimination of risks and development optimization.

With the purpose of further assisting in guiding the practical development work, different development adjustment plans and engineering interventions for reservoir modification are provided for the potential issues of each class of producers. They are of reference and significance for engineers engaged in reservoir dynamic analysis and development adjustment. To date, the whole process of evaluating the effect of WAG development has formed a complete closed-loop optimization system, as depicted in Figure 11.

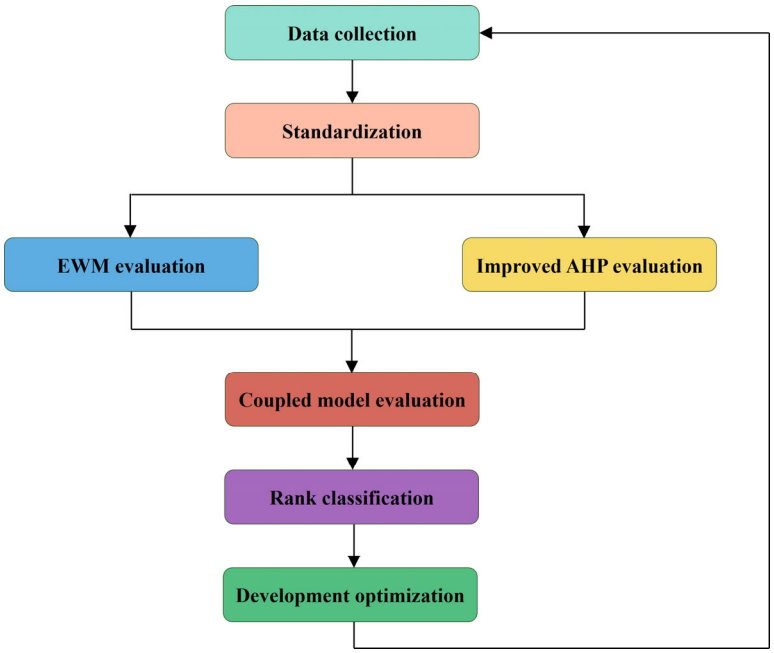


Figure 11. The closed-loop optimization system for evaluating WAG development effect and potential of producers.

We conducted a systematic analysis on the current situation in the early stage of the WAG development in such low-permeability complex carbonate reservoirs in the Middle East, where the production capacity of producers varies greatly, the stable production period is short, and the injection and production response is poor. Considering the economic feasibility of the development, the development effects of producers in the well group are classified into different levels based on the actual situation on site. Reasonable development adjustment suggestions are proposed, as presented in Table 11.

Table 11. Classification level of development effect and adjustment measures.

Weight	Classification Level	Development Adjustment Measures	Core Adjustment Direction
40%>	High-Efficiency Well	• Stable production operation (production fluctuation < ±5%) • Real-time monitoring (alerts for pressure/GOR/WCT anomalies) • Multi-cycle small-slug alternating injection to enhance displacement efficiency	Stabilize Production and Maintain Efficiency
40~30%	Moderate-High Efficiency Well	• Stepwise Water flooding (Reduce water slug by 0.1 PV When WCT Increases 2%) Stepwise waterflooding (reduce water slug by 0.1 PV when WCT increases 2%) • Priority gas injection into high-permeability zones for in-layer diversion, delaying water channeling • Pulsed gas injection to perturb pressure field and expand sweep efficiency	Water Control and Oil Stabilization
30~25%	Moderate-Efficiency Well	• Gas channeling plugging (intervention when GOR > 4000 scf/bbl) • Dynamic gas injection adjustment (intermittent pulse injection) • Gas flooding to waterflooding conversion	Gas Control and Oil Stabilization
25~15%	Low-Efficiency Well	• Differential gas injection by interval: WAG flooding (water-gas ratio 1:1) in low-perm zones; waterflooding in high-perm zones • Targeted plugging (selective plugging of high GOR/WCT layers to optimize injection–production ratio) • High-frequency pulsed injection–production (cycle $\leq$ 3 days)	Interval Management
<15%	Ultra-Low Efficiency Well	• Sidetracking of Existing Wells + Small-Slug Injection Sidetracking of existing wells + small-slug injection • Fracturing stimulation (fracture length > 100 m) • Fishbone completion ($\geq$4 branches)	Reservoir Stimulation

Given coupled weights calculated in Section 3.4 and the principle of development economy, the following development adjustment measures are provided for the pilot test area (Table 12); these measures are employed to optimize the current production situation, make producers in a healthy and virtuous full-life development cycle, and ultimately form a closed-loop optimization system for evaluating the effect and potential of WAG development.

Table 12. Proposed adjustment measures for producers in the pilot test area.

Well ID	Coupled Weight	Classification Level	Development Adjustment Measures
P-120	40.7%	High-Efficiency Well	• Stable production operation (production fluctuation < ±5%) • Real-time monitoring (alerts for pressure/GOR/WCT anomalies) • Multi-cycle small-slug alternating injection to enhance displacement efficiency
P-124	30.2%	Moderate-Efficiency Well	• Gas channeling plugging (intervention when GOR > 4000 scf/bbl) • Dynamic gas injection adjustment (intermittent pulse injection) • Gas flooding to waterflooding conversion
P-89	20.8%	Low-Efficiency Well	• Differential gas injection by interval: WAG flooding (water-gas ratio 1:1) in low-perm zones; waterflooding in high-perm zones • Targeted plugging (selective plugging of high GOR/WCT layers to optimize injection–production ratio) • High-frequency pulsed injection–production (cycle ≤ 3 days)
P-119	8.3%	Ultra-Low Efficiency Well	• Sidetracking of Existing Wells + Small-Slug Injection Sidetracking of existing wells + small-slug injection • Fracturing stimulation (fracture length > 100 m) • Fishbone completion (≥4 branches)

5. Discussion

There are still practical challenges and difficulties concerning this study, which require further improvement. First, the data sources collected from the field are partially limited. For example, the monitoring data of reservoir pressure and bottom hole flowing pressure have been scarce since producers are horizontal wells, triggering the difficulty of collection and the long interval between data points. The introduction of them into the evaluation model cannot effectively reflect the real well conditions of producers but rather increases the error. Second, the pilot test area has been encountering the headache of high GOR before implementation. There is the influence of the residual effect of the previous gas injection and the complexity of the development situation. Under the controlling of gas and stabilizing of oil, the periodicity of WAG is uncertain, and some of the characteristic indexes characterizing WAG development have not been introduced into the evaluation model. Finally, this research object at present is in the experimental exploration stage of WAG. The pilot test area size limits the diversity of the sample size, and the integration of more producers and multiple parameters is needed to continuously enrich the data system.

The next research work will focus on two aspects. On the one hand, the dynamic database will be updated in real time, more development indexes representing the characteristics of WAG development will be collected, and the key missing indexes will be reasonably processed by using the missing value interpolation method. The data system will be continuously enriched to evaluate the development effect more comprehensively and facilitate the rapid scale development of the pilot test area. On the other hand, the intelligent agent model has the advantages of high efficiency and is timesaving. Embedding

the evaluation process into the agent model will improve the efficiency of the evaluation work. After the further promotion of the pilot test area with continuous exploration and research, the establishment of a large-scale intelligent evaluation and optimization system will significantly save manpower, material, and financial resources while reinforcing the efficiency of oilfield development.

6. Conclusions

This study established a closed-loop optimization system for low-permeability carbonate reservoirs to evaluate the production effect and potential of WAG flooding. Our research team conducted a field case study using the evaluation system developed, achieving a comprehensive quantitative evaluation of the development effect and potential of producers. Finally, rationalized development adjustment measures for the next step were given based on the development effects of different producers. The conclusions of this study are drawn as follows.

(1) The improved AHP, which is based on intrinsic attributes of the factor data and does not rely on the opinions of experts, has been enhanced through innovative improvements to strengthen the objectivity and reliability of the method itself.
(2) The two evaluation methods demonstrate different focuses. The weights of producers are obtained through the coupled evaluation model to weaken the dominant index effect and make evaluation results more consistent with the real situation of production.
(3) Based on the contribution degree and classification levels of producers, the field staff have a clear understanding of the development situation and analyze possible risks faced by producers.
(4) Reasonable development adjustments are proposed to address the main development challenges combined with the principle of development and engineering economy to form a closed-loop optimization system. This system ensures that the condition of producers is always in a healthy and virtuous cycle, prolonging the entire life cycle of producers.

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