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Analysis of Inter-Layer Interference in Multi-Layer Reservoir Commingled Production Wells

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Abstract: During the operation of commingled production wells, inter-layer interference is a key factor affecting the recovery rate and flooding extraction efficiency. This study proposes a well deliverability equation that is characterized by a multi-parameter coupled inter-layer interference coefficient, which is applied to quantify the commingled production wells in a multi-layer reservoir. This study used principal component analysis (PCA) to study the combined effects of correlation parameters for inter-layer interference. The results show that the starting pressure gradient and the crude oil viscosity contrast have the most significant impact on inter-layer interference. Changes in these two parameters directly enhance the heterogeneity between different oil layers, thereby intensifying inter-layer interference. Additionally, the positive correlation between permeability and permeability contrast also highlights the contribution of physical property differences in the oil layers to the interference. The sensitivity analysis shows the main influencing factors of inter-layer interference in commingled production wells. providing references for subsequent improvements and optimization of the exploitation schemes and adjustments in reservoir management measures. The results not only enhance the understanding of the mechanisms of inter-layer interference in the exploitation of multi-layer oil reservoirs but also provide scientific evidence and technical support for oilfield development.

Keywords: multi-layer reservoir; inter-layer interference; sensitivity analysis; principal component analysis; multi-parameter coupling

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1. Introduction

The inter-layer interference phenomenon refers to the changes in oil and gas flow and pressure distribution caused by differences in physical properties (such as permeability and porosity) and development techniques (such as water injection and fracturing) between layers during the development of multi-layer oil reservoirs, thereby affecting the effective extraction of oil and gas. In the field of reservoir engineering, the following key factors are usually considered for inter-layer interference: permeability, porosity, and pore structure, differences in oil–water properties, formation pressure and pressure decay phenomena, extraction measures, fracture development, heterogeneity in reservoir physical properties, boundary conditions, and reservoir size [1,2].

Early studies on inter-layer interference focused mainly on the impact of single parameters (such as pressure and temperature) on oil and gas flow [3,4]. However, as research deepened, scholars found that the geological conditions and development processes of oil and gas reservoirs are extremely complex, and a single parameter is insufficient to fully represent the real situation of inter-layer interference. Therefore, we designed a multi-parameter coupling research method that comprehensively considered the effects

of physical properties (porosity, permeability), chemical properties (such as fluid composition), operating conditions (such as injection pressure, oil production speed), and other factors, and judged the impact of these factors on the inter-layer interference coefficient by the relationship between them.

The southern region of the Bohai Sea is dominated by thin interbedded oil reservoirs [5], and multi-layer joint exploitation is mainly used in reservoir development. There are significant physical property differences between layers vertically and severe heterogeneity [6–12], with some oil fields experiencing rapid production decline [13–15]. Li et al. [16,17] analyzed production data from seven heavy oil fields in the Bohai Sea and found severe inter-layer interference phenomena during joint injection and extraction of multi-layer heavy oil reservoirs, resulting in significant production losses compared to stratified exploitation. In the current context of prominent inter-layer interference conflicts, accurate evaluation of inter-layer interference is very important. However, in the current oilfield development schemes, the inter-layer interference coefficient is still selected through analogy or empirical values [17–20], and related improvement methods still have limitations, leading to large differences between designed and actual production capacity after oilfield commissioning. If inter-layer interference cannot be correctly evaluated during oilfield development, it will also cause difficulties for subsequent production. Due to the specificity of offshore oilfield development, it is impossible to use a large amount of stratified production testing data to understand the degree of inter-layer interference [21–25].

At present, research methods for inter-layer interference mainly fall into two categories: physical experimental methods and reservoir engineering methods. The mechanism of inter-layer interference is complex, with many influencing factors, and the majority of laboratory experiments only focus on single factors, which often leads to significant deviations [22–26]. Wu et al. [27] established a heterogeneous experimental model for emulsion drive and, based on experimental research, introduced the concept of diversion rate and diversion rate change coefficient to quantitatively characterize the tuning performance of emulsion. Huang et al. [28] used physical experiments and oilfield production data to quantitatively describe the inter-layer interference phenomenon at different water cut stages, proposing a production prediction method for common heavy oil reservoirs with multi-layer joint exploitation. In terms of theoretical research, Cai et al. [29] analyzed the relationship between resistivity and relative oil production index in the Kenli area of the Bohai oilfield and, using reservoir engineering methods, established a theoretical calculation model for the inter-layer interference coefficient, quantitatively characterizing the inter-layer interference coefficient. Sun et al. [30] used the multi-relaxation lattice Boltzmann method to quantitatively evaluate the co-exploitation effects of reservoirs with different pore–fracture–cavity configurations, pointing out that an increase in production pressure contrast is beneficial for the production of low-permeability gas layers. Zhang et al. [25] established a production fluid interference formula, and verified it using numerical simulation methods, quantitatively characterizing the change in the degree of inter-layer interference in heavy oil reservoirs through the oil production index multiplier ratio. Cui et al. [31] used the enumeration method to exhaustively list various layer recombination schemes and, based on technical and economic considerations, optimized the enumerated schemes to maximize the mobilization of reservoir resources and oilfield economic benefits. Chen et al. [32] comprehensively used the Buckley–Leverett equation and water phase diversion equation and adopted modified permeability parameters to fit production testing data, forming a new method of production splitting based on historical production data and providing guidance for production splitting in edge water reservoirs. The physical experiment method can find the phenomenon of inter-layer interference but cannot find the essential reason for the inter-layer interference mechanism.

Current reservoir engineering methods are mainly based on a series of assumptions to simplify actual reservoirs and establish mathematical models. These methods have not effectively considered key parameter information such as underground pore throat connectivity and fluid difference levels in multi-layer reservoirs. These methods use oil

groups as the research unit, not refined to small layers, with too large a research scale, and only consider the effect of inter-layer permeability differences on inter-layer interference. The considered factors are not comprehensive. The research results are not suitable for offshore thin inter-layer sandstone reservoirs with large vertical spans, multiple thin layers, minimal thickness, and a small sand body distribution range [17,33]. The research results have limited guidance for on-site production.

Based on the above, we conducted research on a typical thin offshore sandstone reservoir with a thin inter-layer. Our research considered factors such as starting pressure gradient, crude oil viscosity, crude oil viscosity contrast, permeability, permeability contrast, thickness, and fluid extraction speed to explore the mechanism of inter-layer interference. Based on the reservoir engineering theory, we established the inter-layer interference coefficient calculation formula. Through the principal component analysis model, we can obtain the main controlling factors of inter-layer interference. This study can provide a basis for revealing the principle of inter-layer interference and reasonably dividing the developmental layers of such reservoirs.

2. Materials and Methods

2.1. The Inter-Layer Interference Coefficient

Multi-layered oil and gas reservoirs commonly exhibit vertical heterogeneity. This leads to issues such as rapid increases in water cut, uneven reservoir utilization, and low recovery rates, all of which are due to inter-layer interference. The inter-layer interference coefficient quantifies how much the overall oil (or fluid) production capacity of a well decreases under co-production compared to separate injection and production. The physical meaning of the inter-layer interference coefficient is the extent to which the actual production capacity under co-production falls compared to the total production capacity under separate production at a given water cut. A higher interference coefficient indicates more severe inter-layer interference, meaning a stronger suppression effect on non-dominant layers and poorer outcomes from commingled production. The multi-layer reservoir inter-layer interference coefficient's definition is:

$$\alpha = \left(\sum_{i=1}^{n} J_{doi} - J_o \right) / \sum_{i=1}^{n} J_{doi} \quad (1)$$

In the formula:

α is the inter-layer interference coefficient of daily production, without dimensionality;

J_{doi} is the production of each layer at the i single mining, m^3/d;

J_o is the production of multi-layer combined production, m^3/d.

The interzonal interference coefficient is the difference between the sum of the oil production index of each layer during separate production and the oil production index of multiple layers during combined production under the same working system divided by the sum of the oil production index of each layer during separate production, that is, the decrease of the productivity phase during combined production compared with the total production capacity during recovery [34,35]. The inter-layer interference coefficient shown in Equation (1) can be used to quantitatively characterize the inter-layer interference effect, but it cannot capture the physical parameters that affect the inter-layer interference. In order to determine the interference factors more accurately, the subsequent section establishes a mathematical model of inter-layer interference coefficient with multi-parameter coupling.

2.2. Fluid Flow Mechanism Model

The goal of studying inter-layer interference is to explore the disturbances caused by the injected water to other layers during the underground seepage process in the actual water injection development of oil reservoirs. Darcy's Law is the fundamental equation used to describe the flow of a single fluid through a porous medium. This process is Darcian

flow, conforming to Darcy's law of fluid dynamics. Darcy's theorem uses the following key parameters to establish a mathematical model:

(1) Reservoir physical properties: These include porosity, permeability, and the mechanical properties of the rock. These physical parameters directly affect the fluid flow and pressure distribution within the reservoir.
(2) Fluid dynamics characteristics: Such as the viscosity of the fluid, its compressibility, and its behavior under different pressures and temperatures.
(3) Pressure and pressure difference: The pressure interactions between layers, especially during high-pressure water injection or gas extraction processes, where pressure differences between layers can significantly impact overall extraction efficiency.

To study the phenomenon of inter-layer interference in the commingled production wells, it is necessary to consider the two-phase flow of oil and water. The basic form of Darcy's Law is:

$$q = -\frac{kA}{\mu}\frac{\Delta P}{L} \tag{2}$$

In the formula:
q is the volumetric flow rate of the fluid through the medium;
k is the permeability of the medium;
A is the cross-sectional area of fluid flow;
μ is the viscosity of the fluid;
ΔP is the pressure difference;
L is the distance over which the fluid flows.

In multiphase flow, the effective permeability of each phase is reduced due to the presence of other phases, so Darcy's formula needs to be modified as follows:

$$q_i = -\frac{kk_{ri}A}{\mu_i}\frac{\Delta P}{L} \tag{3}$$

In the formula:
k_{ri} is the relative permeability of phase i;
μ_i is the viscosity of the fluid.

2.3. Modification of the Mathematical Model of Inter-Layer Interference Characterization

Considering the following parameters, we constructed a mathematical model for inter-layer interference in the commingled production wells.

(1) Considering Relative Permeability, Volume Factors and Viscosity Changes:

Relative permeability k_{ri} is the ratio of actual permeability k to the maximum possible permeability and is a function of saturation. For two-phase flow, we typically have two relative permeabilities k_{rok} and k_{rwk}, corresponding to the oil and water phases, respectively. Under reservoir conditions, the volume of a fluid may differ from its volume at surface conditions due to compression or expansion, represented by volume factors B_o and B_w. Viscosity μ_i may also vary with temperature, pressure, and chemical composition.

(2) Integration of Flow Equations:

For inter-layer interference, the flow equation for each phase needs to include the pressure differences across the formation pressure, bottom-hole flowing pressure, and fluid gravitational pressures, along with the flow characteristics of each phase, combining with the flow balance equations of each phase to adjust the overall production.

(3) Start-up Pressure Gradient:

In multiphase flow, fluids often encounter additional resistance, known as the start-up pressure gradient (SPPG). In practical applications, this resistance needs to be overcome for the fluid phases to start flowing, indicating capillary forces or other effects. This correction term reflects the additional pressure that needs to be overcome before fluid flow can start.

The introduction of the start-up pressure gradient modifies the traditional single-phase Darcy's formula to more accurately describe the complex multiphase flow phenomena in porous media. Therefore, the traditional pressure gradient ΔP in Darcy's formula needs to include the start-up pressure gradient term, transforming to $\left(P_{ek} - P_{wf} - G_{ok}\right)$, indicating the additional pressure that must be overcome before fluid movement begins.

Based on the above multi-parameter content, modifying the phase Darcy formula can yield a defined production formula as follows:

$$q_{pk} = \frac{542.87 K_k h_k}{ln\frac{R_{ev}}{R_w} + S_k} \cdot \left[\frac{k_{rok}\left(P_{ek} - P_{wf} - G_{ok}\right)}{B_o \mu_o} + \frac{k_{rwk}\left(P_{ek} - P_{wf} - G_{wk}\right)}{B_w \mu_w} \right] \tag{4}$$

In the formula:

q_{pk} is the production rate of the oil well;

k_{rok} and k_{rwk} are the relative permeabilities of the oil and water phases, respectively;

K_k is the absolute permeability;

h_k is the thickness of the formation;

P_{ek} is the formation pressure;

P_{wf} is the bottom hole flowing pressure;

G_{ok} is the gravity of the oil phase;

G_{wk} is the gravity of the water phase;

B_o and B_w are the volume factors for oil and water, respectively;

μ_o and μ_w are the viscosities of oil and water, respectively;

S_k is the skin factor;

R_{ev} and R_w are the effective radius of the oil well and the radius of the wellbore, respectively.

Combining Equations (1) and (4) leads to:

$$\alpha_o = \frac{\sum_{i=1}^{m} \frac{K_i k_{roi} h_i \left(P_{ei} - P_{iwf} - G_i\right)}{\left(P_{ei} - P_{iwf}\right) B_{oi} \mu_{oi} \left(ln\frac{R_{ei}}{R_w} + s_i\right)} - \sum_{i=1}^{m} \frac{K_i k_{roi} h_i \left(P_e - P_{iwf} - G_i\right)}{\left(P_e - P_{iwf}\right) B_{oi} \mu_{oi} \left(ln\frac{R_{ei}}{R_w} + s_i\right)}}{\sum_{i=1}^{m} \frac{K_i k_{roi} h \left(P_{ei} - P_{iwf} - G_i\right)}{\left(P_{ei} - P_{iwf}\right) B_{oi} \mu_{oi} \left(ln\frac{R_{ei}}{R_w} + s_i\right)}} \tag{5}$$

After constructing the mathematical model, we can gather data on the physical and chemical properties of the reservoir, as well as production history data, to explore the patterns of inter-layer interference under different conditions. Analyzing the main factors affecting inter-layer interference and identifying the patterns of various influencing factors, we can ensure that this multi-parameter coupled inter-layer interference coefficient characterization mathematical model can help developers optimize production plans and enhance the economic benefits of oil and gas fields. This mathematical model can also play a significant role in environmental protection and the rational use of resources.

2.4. Sensitivity Analysis Model

In the commingled production wells, inter-layer interference is one of the major factors affecting the productivity and ultimate recovery rate of oil and gas wells. Principal component analysis (PCA) has significant advantages in handling high-dimensional data and revealing key influencing factors.

In the exploitation of multi-layer reservoirs, it is necessary to consider many parameters, such as permeability, pressure gradient, and viscosity differential, to form high-dimensional data sets. PCA can identify the main directions and patterns of changes in the data, which is particularly useful for understanding how different parameters interact. By analyzing the relationship between the principal component and the original variable (factor load), the parameters have the greatest influence on the inter-layer interference,

and the parameters have potential correlation, so as to guide the optimization of the extraction strategy.

Principal component analysis (PCA) is a statistical analysis technique primarily used for data dimensionality reduction and pattern recognition. By reducing dimensions, it transforms multiple variables into a few principal components so that these principal components can reflect most of the information in the original data. The basic principles and detailed steps of PCA are as follows:

(1) Before applying PCA, it is usually necessary to normalize each variable in the dataset:

$$X_{norm} = \frac{X - min(X)}{max(X) - min(X)} \tag{6}$$

In the formula:
X is the original data value.
$max(X)$ is the maximum value of X in the dataset.
$min(X)$ is the minimum value of X in the dataset.
X_{norm} is the normalized data value, which ranges from 0 to 1.

(2) Inter-layer interference parameters have different dimensions, and the dataset contains variables with units; thus, normalization is a more appropriate choice. Calculate the covariance matrix After normalization, calculate the covariance matrix for the data affecting inter-layer interference in the commingled production wells.

$$\begin{aligned} Cov(X,Y) &= E[(X - E(X))(Y - E(Y))] \\ &= \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y}) \end{aligned} \tag{7}$$

In the formula:
$E(X)$ is the expected value of sample X;
$E(Y)$ is the expected value of sample Y;
x_i is the value of the ith x parameter;
$\overline{x}$ is the sample mean of parameter x;
y_i is the value of the ith y parameter;
$\overline{y}$ is the sample mean of parameter y.

Positive covariance indicates that X and Y have a positive correlation; negative covariance indicates a negative correlation. When the covariance is zero, X and Y are independent. Cov(X,X) is the variance of X. When the sample consists of n-dimensional data, their covariance is actually a covariance matrix (a symmetric matrix). For three-dimensional data (X,Y,Z), the calculation of its covariance would be:

$$Cov(X,Y,Z) = \begin{bmatrix} Cov(x,x) & Cov(x,y) & Cov(x,z) \\ Cov(y,x) & Cov(y,y) & Cov(y,z) \\ Cov(z,x) & Cov(z,y) & Cov(z,z) \end{bmatrix} \tag{8}$$

(3) Eigenvalue Decomposition

Eigenvalue decomposition is performed on the covariance matrix to find its eigenvalues and corresponding eigenvectors. The eigenvectors represent different directions in the data, while the eigenvalues indicate the variance magnitude in each direction, that is, the spread of the data along these directions.

Eigenvalues and Eigenvectors

If a vector v is an eigenvector of a matrix A, it can certainly be represented in the following form:

$$Av = \lambda v \tag{9}$$

where λ is the eigenvalue corresponding to the eigenvector v, and a set of eigenvectors of a matrix forms a set of orthogonal vectors.

Eigenvalue Decomposition Matrix

For matrix A, having a set of eigenvectors v, orthogonalizing and normalizing this set of vectors obtains a set of orthogonal unit vectors. Eigenvalue decomposition involves breaking down matrix A as follows:

$$A = Q\Sigma Q^{-1} \tag{10}$$

where Q is a matrix composed of the eigenvectors of matrix A, and Σ is a diagonal matrix with eigenvalues on its diagonal.

(4) Selection of Principal Components

Based on the magnitude of the eigenvalues, the largest eigenvalues and their corresponding eigenvectors are selected during the calculation process. These eigenvectors, known as principal components, are orthogonal axes representing the most significant structural directions in the data. In principal component analysis, the cumulative contribution rate is used as a criterion for selecting principal components, that is, the sum of the selected eigenvalues reaches a certain percentage (such as 85%, 90%) of the total eigenvalues.

Calculation of Variance Explained Ratio

The variance contribution of each principal component can be calculated by comparing its eigenvalue with the sum of all eigenvalues. For the k-th principal component, its variance explained ratio e_k can be represented by the following formula:

$$e_k = \frac{\lambda_k}{\sum_{i=1}^{p} \lambda_i} \tag{11}$$

In the formula:

λ_k is the eigenvalue of the k-th principal component;

P is the total number of eigenvalues (i.e., the number of variables), indicating the proportion of the k-th principal component in the total variance of the data.

Calculating cumulative variance explained involves summing the variance explained ratios of the first m principal components:

$$E_m = \sum_{k=1}^{m} e_k \tag{12}$$

This cumulative value indicates how much of the total variance is explained by the first m principal components.

(5) Factor loadings retrieval and spatial transformation using the selected eigenvectors, the original data are transformed into a new coordinate system. This is achieved by multiplying the data by each selected eigenvector. The result is a new dataset where each row now represents the projection of the original data in the direction of the principal components. Using previously obtained eigenvectors and eigenvalues, factor loadings coefficients are calculated from the data's covariance matrix or correlation matrix Σ through eigenvalue decomposition to obtain eigenvalues λ_i and corresponding eigenvectors (principal component directions) v. Calculation of factor loadings coefficients: Factor loadings coefficients L can be obtained by multiplying each eigenvector v_i by the square root of its corresponding eigenvalue λ_i For each principal component k in the principal component analysis, its loadings coefficient L_k can be calculated using the following formula:

$$L_k = v_k \times \sqrt{\lambda_k} \tag{13}$$

In the formula:

L_k represents the loadings vector of the k-th principal component;
v_k is the eigenvector of the k-th principal component;
λ_k is the corresponding eigenvalue.

If there are "p" eigenvectors and corresponding eigenvalues, the entire factor loadings matrix "L" can be represented by combining all loading vectors into a matrix, where each column represents a principal component's loadings vector:

$$L = \left[v_1\sqrt{\lambda_1}, v_2\sqrt{\lambda_2}, \ldots, v_p\sqrt{\lambda_p}\right] \quad (14)$$

The formed factor loadings matrix provides a comprehensive view, showing the contribution of each original variable to each principal component.

(6) In this study, physical properties of multi-layer oil reservoirs (such as permeability, permeability gradient, initial pressure, sub-layer thickness), fluid properties (such as viscosity, viscosity contrast), extraction conditions (such as liquid extraction speed), and historical production data were first collected. Then, by entering these parameters into Equation (5), the relationships between the inter-layer interference coefficient and each parameter were obtained, and then the relationships between various parameters and the inter-layer interference coefficient were judged using the principal component analysis model.

3. Results and Discussion

Based on the geological mechanism model of comingled wells in multi-layer reservoirs (Figure 1), we use the principal component analysis method, processing the data in Table 1. Then we evaluate the inter-layer interference parameters of commingled production wells. At last, the results are displayed in Table 2.

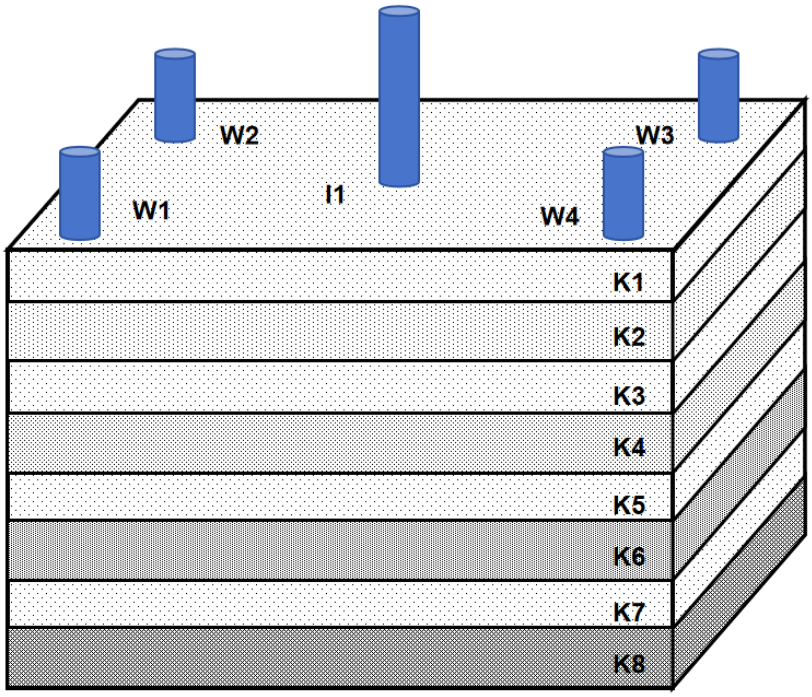

Figure 1. Comingled wells in a multilevel reservoir.

Table 1. Raw data of influencing factors.

Startup Pressure Gradient/(MPa/m)	Crude Oil Viscosity	Crude Oil Viscosity Contrast	Permeability	Permeability Contrast	Thickness	Production Rate
0	150	0.1	150	0.2	10	0.08
0.0005	100	0.15	250	0.3	8	0.07
0.001	80	0.1875	350	0.4	6	0.06
0.0025	50	0.3	450	0.6	5	0.05
0.005	30	0.5	550	1	4	0.04
0.01	15	1	650	2	3	0.03
0.02	10	1.5	750	3	2	0.02
0.05	5	3	850	4	1	0.01

Table 2. Normalized influence factors.

Startup Pressure Gradient	Crude Oil Viscosity	Crude Oil Viscosity Contrast	Permeability	Permeability Contrast	Thickness	Production Rate
0	1	0	0	0	1	1
0.01	0.655172414	0.017241379	0.142857143	0.026315789	0.777777778	0.857142857
0.02	0.517241379	0.030172414	0.285714286	0.052631579	0.555555556	0.714285714
0.05	0.310344828	0.068965517	0.428571429	0.105263158	0.444444444	0.571428571
0.1	0.172413793	0.137931034	0.571428571	0.210526316	0.333333333	0.428571429
0.2	0.068965517	0.310344828	0.714285714	0.473684211	0.222222222	0.285714286
0.4	0.034482759	0.482758621	0.857142857	0.736842105	0.111111111	0.142857143
1	0	1	1	1	0	0

Because different variables in the original data have different scales and units, normalizing the data here can ensure that each influencing factor has equal importance in the analysis. Through normalization, each variable is rescaled so that all variables contribute equally to the determination of the principal components, effectively avoiding biases caused by scale differences. This helps to more accurately capture the variability and structure in the data, making it an important preprocessing step before conducting principal component analysis of inter-layer interference in multi-layer oil reservoir joint exploitation.

From the correlation matrix (Figure 2), it can be seen that the viscosity contrast of crude oil has a high positive correlation with the startup pressure gradient, permeability, and permeability contrast. At the same time, crude oil viscosity also shows a high positive correlation with fluid production rate and thickness. High positive correlations between variables indicate that they may be influenced by the same or similar factors.

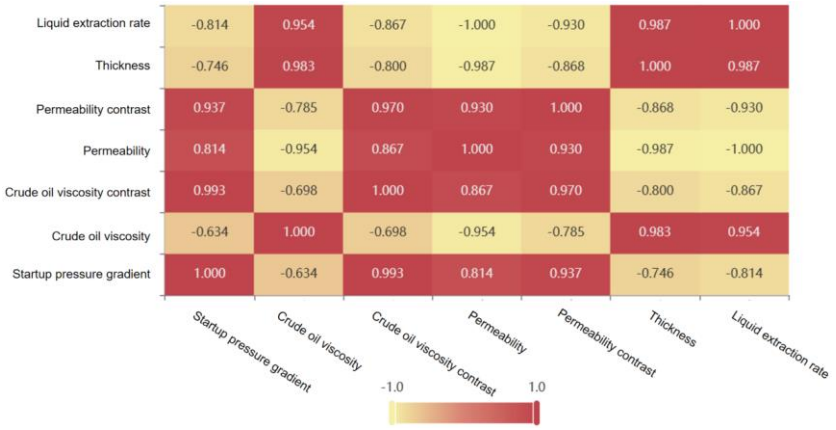

Figure 2. Heatmap of the correlation coefficients of seven parameters.

Through principal component analysis, we can get the variance interpretation for each parameter, and the components with the largest variance explanation rate are analyzed. We can filter out the relatively unimportant components (those related to noise). Then the main influencing factors of intermedium interference in joint production of multi-layer reservoirs can be revealed more clearly.

As can be seen from Table 3, principal component analysis constructs one principal component with an eigenvalue of 6.299, and the cumulative variance explained is 89.984%. The first principal component can explain 89.984% of the information content of the seven indicators to be reduced in dimension.

Table 3. Variance interpretation table.

Principal Component	Total Variance Interpretation		
	Characteristic Root Eigenvalue	Variance Interpretation Rate (%)	Cumulative Variance Explanation Rate (%)
1	6.299	89.984	89.984
2	0.65	9.285	99.269
3	0.042	0.601	99.871
4	0.005	0.077	99.948
5	0.003	0.043	99.991
6	0.001	0.009	100
7			100

The loading coefficients (Table 4) reflect the correlation between the principal components and the seven inter-layer interference influencing factors, and the communality generally reflects the explanatory capability of the principal components constructed. It can be seen that the communality index is high, which can effectively explain the issue of inter-layer interference. The first principal component is positively correlated with startup pressure gradient, crude oil viscosity contrast, permeability, and permeability contrast, and negatively correlated with crude oil viscosity, thickness, and liquid extraction speed. Through the calculation of factor loadings, a better understanding of the dynamics of inter-layer interference in multi-layer oil reservoirs can be achieved to facilitate further analysis.

Table 4. Table of factor load coefficients.

	Factor Load Coefficient			Communality (Common Factor Variance)
	Principal Component 1	Principal Component 2	Principal Component 3	
Startup pressure gradient	0.893	0.438	−0.104	1
Crude oil viscosity	−0.907	0.415	0.056	0.997
Crude oil viscosity contrast	0.932	0.36	−0.029	0.999
Permeability	0.988	−0.147	0.035	0.999
Permeability contrast	0.967	0.204	0.151	0.999
Thickness	−0.961	0.268	0.047	0.997
Production rate	−0.988	0.147	−0.035	0.999

Here, a comprehensive analysis of principal component analysis is conducted, considering the division into three principal components to fully explain the impact of inter-layer interference:

$$F1 = 0.142P_g - 0.144u + 0.148u_c + 0.157k + 0.154k_c - 0.153H - 0.157q \quad (15)$$

$$F2 = 0.674P_g + 0.638u + 0.554u_c - 0.226k + 0.313k_c + 0.412H + 0.226q \quad (16)$$

$$F3 = -2.464P_g + 1.326 \times u - 0.694 \times u_c + 0.837 \times k + 3.578 \times k_c + 1.11 \times H - 0.837 \times q \quad (17)$$

In the formula:
P_g: Startup pressure gradient, MPa/m;
u : Crude oil viscosity, mPa·s;
u_c: Crude oil viscosity contrast;
k: Permeability, D;
k_c: Permeability contrast;
H: Thickness, m;
q: Production rate, m^3/d.

From the above content, a multivariate fitting formula for the main controlling factors of inter-layer interference in the commingled production wells can be derived, which is $F = (0.9/0.999) \times F1+(0.093/0.999) \times F2+(0.006/0.999) \times F3$.

Principal component analysis, based on loadings and other information, performs principal component weight analysis, which is calculated by the formula: variance explained ratio/cumulative variance explained ratio after rotation. By analyzing the weights(Table 5), it is possible to decide to retain principal component 1 and principal component 2, as they most effectively represent the information of the original data. The cumulative explained variance of these two components has reached a high proportion, and they are able to capture most of the data information content, effectively explaining the essential issues of inter-layer interference in commingled production wells.

Table 5. Results of principal component weights.

Principal Component	Variance Interpretation Rate (%)	Cumulative Variance Explanation Rate (%)	Weight (%)
Principal component 1	0.9	89.984	90.101
Principal component 2	0.093	99.269	9.297
Principal component 3	0.006	99.871	0.602

Through Table 4, it is found that inter-layer interference is a key factor in the commingled production wells, which affects the development efficiency and ultimate recovery rate of the reservoirs. The loadings and communality indices derived from the principal component analysis (PCA) reflect the correlation between the seven parameters and the inter-layer interference issue and the explanatory power of the principal components. Communality generally reflects the explanatory ability of the constructed principal components. All parameters have high communality indices, which can well explain the issue of inter-layer interference. Analyzing the factors of inter-layer interference in the commingled production wells, the role of startup pressure gradient, crude oil viscosity contrast, permeability, permeability contrast, crude oil viscosity, thickness, and liquid extraction speed in exploitation can be further understood from the following aspects:

Startup pressure gradient and crude oil viscosity contrast: The positive correlation of these two parameters indicates that when the startup pressure gradient and crude oil viscosity contrast are large, the impact of inter-layer interference is also significant. This is due to the physical property differences between layers causing uneven fluid displacement between production layers. This finding of high startup pressure gradients and viscosity contrasts means more energy is needed to overcome the resistance of these layers, thereby affecting the fluid dynamics and recovery efficiency.

Permeability and permeability contrast: The positive correlation of permeability and its contrast indicates that layers with large permeability differences are likely to produce more significant fluid dynamic differences, thereby amplify the inter-layer interference effect. In practice, special attention should be paid to the multi-layer wells with significant differences in permeability. Development strategies such as stratified water injection should be used to minimize the interference effect.

Crude oil viscosity, thickness, and production rate: The negative correlation of these parameters with the principal components suggests that high-viscosity crude oil, thicker oil layers, and lower liquid extraction speeds may help reduce inter-layer interference. This

is because high-viscosity crude oil presents greater resistance during displacement, thicker oil layers provide more stable flow channels, and lower liquid extraction speeds reduce the rapid expansion of inter-layer pressure differences.

Through the content of principal component analysis, we observed that startup pressure gradient, crude oil viscosity, permeability, permeability contrast, sub-layer thickness, production rate, and crude oil viscosity contrast are all major factors affecting the inter-layer interference in commingled production wells. To minimize the effect of inter-layer interference in the commingled production wells, we need to proceed with care on the design of the number of layers, liquid extraction speed, and water injection strategy, considering the startup pressure gradient, crude oil viscosity, permeability, and permeability contrast. The above achievements not only improve the understanding of the mechanisms of inter-layer interference in the exploitation of multi-layer oil reservoirs but also provide scientific evidence and technical support for oilfield development, helping to improve the development efficiency and economic benefits of oil and gas fields.

4. Conclusions

In order to more accurately determine the interference factors, a multi-parameter coupled inter-layer interference coefficient characterization mathematical model is established to determine the essential influencing factors of inter-layer interference in the commingled production wells.

Through principal component analysis, we can identify key factors influencing the extent of inter-layer interference in the commingled production wells. Startup pressure gradient, crude oil viscosity contrast, permeability, and permeability contrast all have a significant positive impact; these factors are important influencers of the behavior patterns of inter-layer interference in multi-layer oil reservoir joint exploitation. Crude oil viscosity, thickness, and liquid extraction speed are also influencing factors of inter-layer interference in multi-layer oil reservoir joint exploitation, but their positive impact is limited. The results of the principal component analysis could help us optimize reservoir management strategies and adjust exploitation plans, thereby improving the development efficiency and economic benefits of oil and gas fields.

The application of the multi-parameter coupled inter-layer interference coefficient characterization model allows for a more systematic handling of the complex interactions between layers in multi-layer combined exploitation, thereby achieving better results in oil and gas development projects.

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