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Big Data Processing Application on the Identification Method of the Dominant Channel in Polymer Flooding

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Abstract: Polymer flooding is a critical enhanced oil recovery technique; however, the development of polymer channeling along dominant channels during its later stages can adversely affect the process by increasing comprehensive water cut and dispersing remaining oil, thereby diminishing development benefits. This study aims to address this challenge by investigating the identification methods and distribution patterns of dominant channels in polymer flooding to inform and optimize the development strategy. Through a series of experiments, we analyzed how factors such as permeability, heterogeneity, reservoir thickness, and mineral composition influence the formation of dominant channels. We developed an identification method for dominant channels post-polymer flooding using a combination of reservoir engineering and mathematical analysis techniques. Our results highlight the significant role of rock and mineral composition, injection rate, and injection pressure in the formation of dominant channels. By integrating formation physical properties and production data from oil and water wells with the grey correlation method, we effectively identified dominant channels. This identification is crucial for guiding the development and adjustment of polymer flooding, enhancing oil recovery efficiency, and maximizing reservoir performance.

Keywords: polymer flooding; dominant channel; grey correlation; identification method; heterogeneity

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1. Introduction

In the later stages of polymer flooding development, the flow of polymers along dominant channels leads to an increase in comprehensive water cut and the high dispersion of remaining oil, thereby reducing development benefits. Therefore, studying the identification methods and distribution patterns of dominant channels in polymer flooding is crucial for guiding the development and adjustment of polymer flooding. Numerical simulation, as an important tool in modern reservoir engineering, has been widely used to predict and optimize the polymer flooding process [1]. By simulating subsurface fluid flow, these models can reveal the mechanisms of dominant channel formation, thereby providing decision support for reservoir management. Thus, numerical models play a key role in assessing the efficiency of oil displacement and identifying dominant flow paths in the reservoir [2].

In 1973, MartinFelsenthal took the injection well and the production well as the source and sink terms, respectively, and established a simple calculation method [3,4] of dominant channel permeability by using the plane radial flow formula. In 1982, Abbaszade [5–7] calculated the thickness, permeability, porosity, and other parameters of the superior channel by fitting the tracer output curve between Wells. In 1994, R.K. Bane [8] proposed to conduct production logging of the water absorption profile, and the surface swept coefficient of injected water [9] could be obtained by combining the gamma-gamma logging with the injection volume, and then the distribution diagram of dominant channels could be drawn. In 2009, C.S. Krabir [10] proposed an improved Hall curve that can be used for the identification of dominant channels. In 2009, J.A. Vargas-Guzman [11] et al. used the streamlined numerical simulation method to invert the production dynamic data under the geological model [12] that had not been roughed up to achieve the purpose of identifying the dominant channel. In 2014, Rashmanlou et al. [13] proposed the concept of interval-valued fuzzy sets, which is a generalization based on fuzzy mathematics. In 2021, Li et al. [14] introduced the research progress of several commonly used polymer flooding agents, including biopolymers, temperature- and salt-resistant monomer polymers, hydrophobic associating polymers, cross-linked polymers, comb polymers, and star polymers. In 2024, Khlaifat et al. [15] assessed the factors affecting polymer flooding in hydrocarbon reservoirs and applied them on both laboratory and field scales, providing experimental data for understanding the identification of dominant channels in polymer flooding.

There are many studies on the recognition of dominant channels in water flooding but few on the recognition methods of polymer flooding.

Conventional water flooding and polymer flooding are key techniques for enhancing oil recovery and have been widely applied in oil fields around the world. However, while these technologies improve recovery rates, they also present a series of reservoir engineering challenges. For instance, water channeling during water flooding and polymer channeling in polymer flooding [16] severely impact the economic benefits of oil fields. Although existing studies have addressed these issues through reservoir engineering methods and mathematical analysis methods, there is still a deficiency in the literature regarding the integration of these methods to optimize oil displacement strategies. This study aims to systematically analyze the impacts of conventional water flooding and polymer flooding [17], combining the latest reservoir engineering and mathematical analysis techniques to propose a new integrated approach to enhance oil displacement efficiency and oil field recovery rates.

2. Overview of Research Architecture and Methodology

In this study, we are committed to an in-depth analysis of the identification methods for dominant channels during polymer flooding and exploring their potential applications in oilfield development practices. To ensure the systematic and organized nature of the research, the following research architecture has been meticulously constructed:

(1) Introduction of Experimental Exploration and Grey Correlation Analysis

We begin by conducting meticulously designed laboratory experiments to comprehensively test the key geological and engineering parameters that influence the formation of dominant channels. These experiments not only provide us with empirical data but also lay the groundwork for the introduction of grey correlation analysis. As a powerful tool for assessing the impact of multiple variables and identifying dominant channels, grey correlation analysis will play a central role in this paper.

(2) Construction of Grey Correlation Analysis and Dominant Channel Discrimination Model

In the third chapter, we will delve into the theoretical foundations of grey correlation analysis and elaborate on how to use this method to construct a discrimination model for dominant channels. This model can precisely quantify the contribution of various factors to the formation of dominant channels, providing a scientific basis for the development of oilfield development strategies. We will present the model construction process, including key steps such as data preprocessing, correlation degree calculation, and model validation.

(3) Identification of Actual Oilfield Channels and Application of Strategies

Based on the aforementioned discrimination model, this paper will further demonstrate how to apply it to the identification of dominant channels in actual oilfields. We will describe in detail the application process of the model, interpretation of results, and potential impacts on oilfield development strategies, thus achieving an organic combination of theory and practice. In addition, we will discuss the applicability and limitations of the model in different oilfield environments, as well as how to adjust model parameters according to specific situations to optimize identification effects.

3. Laboratory Experimental Study on the Cause of Polymer Flooding Dominant Channel

Through laboratory [18] experiments, the causes of the dominant channel in polymer flooding are analyzed.

(1) Influence of reservoir permeability on formation of dominant channel

The grain diameter of reservoir sandstone and the porosity of the concrete together form the underground geological information, affecting the measure of concrete permeability being observed in this experiment. As shown in Figure 1, the permeability of the reservoir measured by macroscopic throat formation has a directivity effect; greater permeability suggests a water flooding [19] effect, where greater permeability creates more opportunities for macroscopic throats to appear.

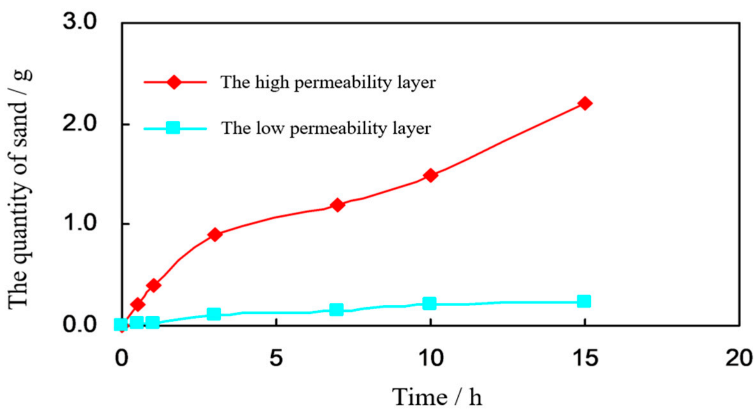

Figure 1. Relation curve of different permeability and sand production.

(2) Influence of reservoir variation coefficient on formation of dominant channel

The permeability of different reservoirs in underground oil wells is different, and water injection in areas with high permeability is more effective. According to the results of previous laboratory experiments and the investigation and analysis of relevant data, as shown in Figure 2, the maximum response characteristic of high permeability is the amount of sand production, and higher sand production will increase the probability of the occurrence of advantageous channels.

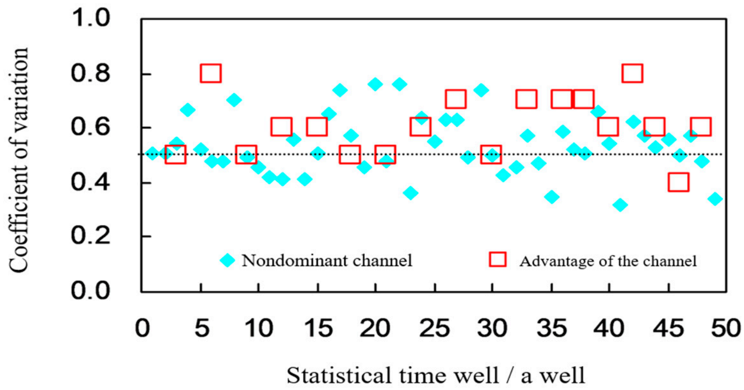

Figure 2. Relation between permeability variation coefficient and dominant channel.

In this study, we conducted a detailed analysis of the formation mechanism of dominant channels during polymer flooding through laboratory experiments. Figures 1 and 2 illustrate the impact of different permeabilities and permeability variation coefficients on sand production. Sand production here refers to the phenomenon where formation sand and stones enter the wellbore due to the decrease in reservoir pressure during oil extraction, which is an important indicator for assessing the risk of dominant channel formation. As shown in Figure 1, we observed that sand production increases with the increase in permeability, indicating that high-permeability areas are more likely to form dominant channels. Figure 2 further reveals the relationship between the permeability variation coefficient and the formation of dominant channels, where the increase in sand production is positively correlated with the increase in the permeability variation coefficient, indicating that the probability of dominant channel formation is higher in areas with greater permeability variation.

(3) The influence of single-layer thickness on the formation of dominant channel

As shown in Figure 3, the better the reservoir conditions are, the larger the water absorption profile will be after water injection, which will ultimately increase the possibility of the advantageous channel.

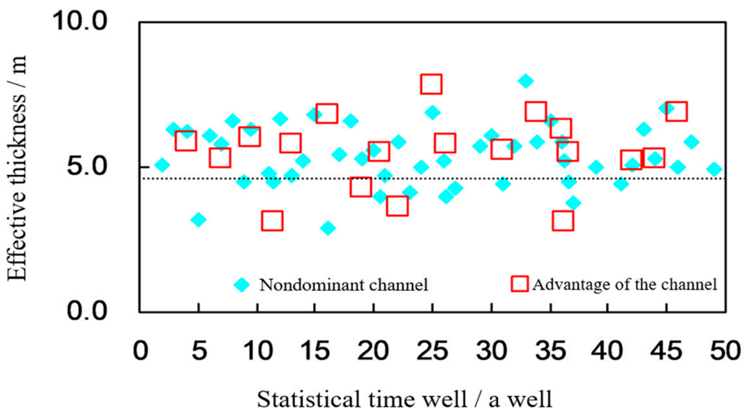

Figure 3. Relation between sandstone thickness and dominant channel.

The term "effective thickness" is chosen because it more comprehensively reflects the flow characteristics of the reservoir, rather than just the physical thickness. In porous media, fluid flow is not only influenced by the physical properties of the rock but also by the combined effects of the pore structure and fluid properties. Therefore, effective thickness provides a more integrated parameter for assessing the efficiency of fluid flow and the likelihood of dominant channel formation within the reservoir.

(4) The influence of rock cementation degree on the formation of dominant channel

Reservoir rock cementation species and quantity and mode of cementation effect are the determinants of reservoir sand, and because of the characteristics of this kind of complex structure, it contain a large amount of clay cement, but this kind of clay cement can very easily lose its adhesive viscosity and particle size and shape, and separation of sex can also affect the cementation strength of the rock.

At present, different cementation forms have been used. Under the same hydrodynamic force and the same simulated oil carrying effect (oil flooding speed LM/min), the influence of different cementation strengths on the formation [20] and development of large pore channels has been studied, and the relation curve of sand production with time change under different cementation degree has been obtained, as shown in Figure 4.

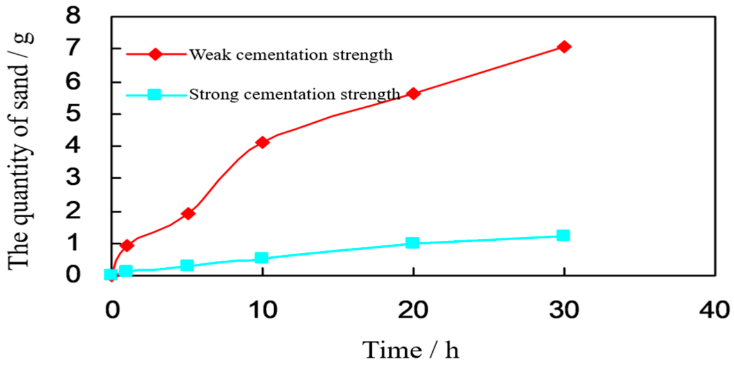

Figure 4. Relationship between crude oil viscosity and sand production.

(5) Influence of formation fluid viscosity on formation of dominant channel

The sand production volume ofgravel was studied for carrying crude oil in the advantage channel, sinceoil viscosity will affect the quantity of sand, and gravel will average distribution among them, and as a result, the viscous crude oil of gravel sinks, so the viscosity is more advantageous for channel probability. The previous experimental results shows that, as shown in Figure 5, regarding crude oil viscosity, greater sand production leads to a more advantageous channel.

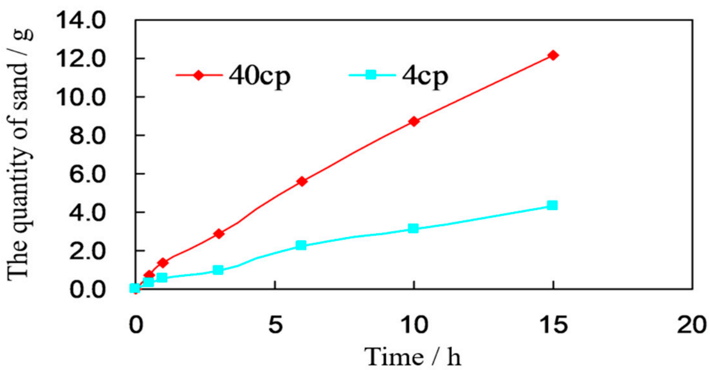

Figure 5. Relation curve between crude oil viscosity and sand production.

(6) Injection speed

Under the condition of a low injection parameter (1 mL/min), water injection can no longer fulfill the sand production requirement of the oilfield, but the injection speed can be increased to meet the target requirement. As can be seen in Figure 6, under other conditions, increasing the injection speed of water flow can increase sand production.

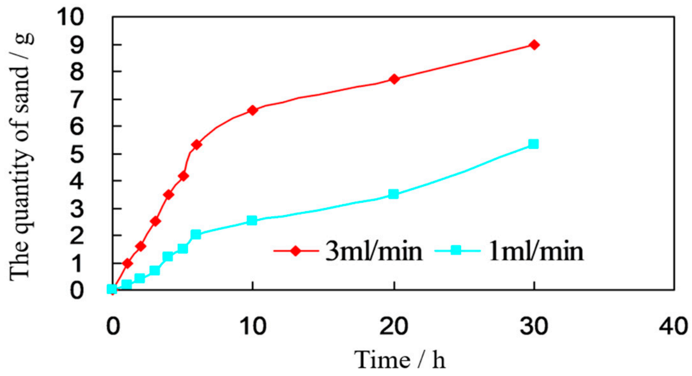

Figure 6. Relation of sand production and time under different oil-driven speeds.

In this study, we specifically chose a water flow rate of 3 mL/min for injection, a selection based on two main considerations. Firstly, according to previous studies, a rate of 3 mL/min is a common injection velocity in actual oilfield operations, representing the efficiency of water flooding under most reservoir conditions. Secondly, from the perspective of experimental design, a velocity of 3 mL/min allows us to capture the key dynamics of how water flow affects the formation of dominant channels in our simulation experiments while maintaining the controllability and repeatability of the experiments.

(7) Injection pressure

Injection pressure is a very important index in field development. The change in injection pressure can directly reflect the suction condition of the reservoir. According to the physical experiment, as shown in Figure 7, the actual direction of sand production will also produce sand from both sides because the mining process gradually moves to the later stage. However, the mainstream side will still accelerate and produce a high permeability zone; that is, the mainstream direction is prone to produce large pore channels. The injected pressure will increase under the oil displacement step, and the viscosity of the gravel will be unable to bond due to the increase in pressure, thus increasing the number of sand produced, leading to the creation of a dominant [21] channel.

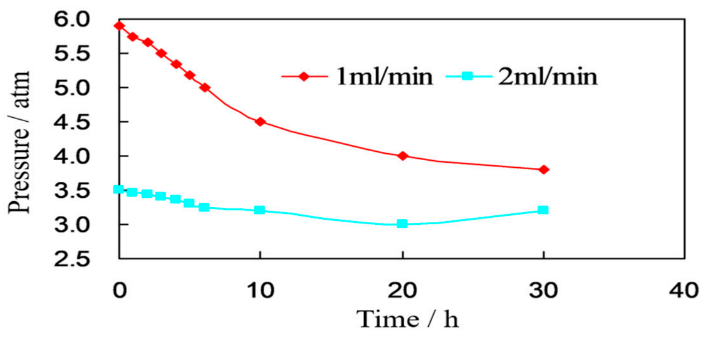

Figure 7. Relation of pressure and time under different oil drive speeds.

4. Recognition Method of Dominant Channel in Polymer Flooding

In order to complete the accurate description of the advantage channel, it is necessary to understand the specific scheme of identifying the advantage channel, which is to lay a foundation for the quantitative evaluation of the advantage channel. Now, there are many available identification methods of the advantage channel in the world, and the more commonly used methods are shown in Table 1.

Table 1. Common advantage channel identification methods.

Methods	Advantage	Disadvantage
Logging data method	The principle is simple and the development of dominant channels in different periods can be determined	The development direction of dominant channel cannot be determined
Dynamic data method	The principle is simple and the implementation is convenient	The dominant channel pore radius cannot be determined
Tracer method	The principle is simple, can determine the dominant channel	Long construction cycle, heavy workload, high cost
Well test data method	The principle is simple and the implementation is convenient	It can only qualitatively determine whether there is a dominant channel
Fuzzy mathematics	Take into account the most comprehensive factors	The pore radius of the dominant channel cannot be determined
Probabilistic model method	Can qualitatively and quantitatively estimate	A large amount of data is required and the direction of the dominant channel cannot be determined

Based on the analysis of the above research methods, this paper can effectively judge the trend of advantageous channels between oil and water wells by systematically analyzing the correlation degree of dynamic data between injection and production wells. By using the grey correlation method, dynamic data such as injection pressure, injection strength, and apparent water absorption index of the injection well, and dynamic data such as liquid yield, comprehensive water cut, visible concentration, and visible time of coalescence of the production well are converted into quantitative discriminant value, and the existence of advantageous channel is determined by a mathematical method.

4.1. Principle of Grey Relational Analysis

For variables in different systems, variables will change their correlation due to changes in given conditions. This indicates the relevance of the identified content: if the variables in the data differ because of synchronous change and the synergy degree is strong, then a strong correlation exists between them; on the other hand, if it is weak, then the changes will be in agreement. This analysis is called the gray correlation analysis method, also known as grey relevancy analysis, which is very suitable as the auxiliary method of dynamic analysis.

The actual operation process is as follows:

(1) Determine the reference sequence

Sort out the research objects, subdivide the indicators contained in the experimental objects, collect and analyze data, and define the data combination that determines the system results. The data combination represents the system result. The reference data combination is a theoretical combination. In the practical application process, the optimal value of each index is optimized to form the reference data combination.

(2) Dimensionless data

Considering that the dimensionality of the value will represent different meanings in different systems, this situation can not be used as a condition, or it can be said that it is difficult to obtain an accurate answer through the grey correlation method, so dimensionless is the premise work of grey correlation analysis.

$$x_i' = \frac{x_i - \overline{x}}{s} \tag{1}$$

$$s = \sqrt{\frac{1}{n}\sum(x_i - \overline{x})^2} \tag{2}$$

x_i represents the *ii*th data point in the original dataset.

x_i' is the value of the *ii*th data point after dimensionless processing.

s is the standard deviation of the original dataset, which is a statistical measure of the dispersion of the data.

n is the total number of data points in the dataset.

$\overline{x}$ is the average value of the original dataset.

(3) Grey correlation coefficient of reference data combination.

① The difference between the corresponding parameter values of each evaluated object index combination and the reference combination is calculated one by one.

$$\Delta_i(k) = |x_1(k) - x_i(k)| \quad (i = 1, \cdots\cdots, n) \tag{3}$$

$$m = \min_i \min_k \Delta_i(k) \tag{4}$$

$$M = \max_i \max_k \Delta_i(k) \tag{5}$$

$\Delta_i(k)$ represents the difference between the i-th comparison sequence and the reference sequence at the kth data point.

n is the number of evaluated objects.

② Calculate the correlation coefficients of the corresponding elements of each comparison sequence and reference sequence, respectively (simplified version of formula).

$$\gamma_{1i}(k) = \frac{m + \xi M}{\Delta_i(k) + \xi M} \quad i = 1, \cdots\cdots, n \tag{6}$$

Among them, ξ is the resolution coefficient and $0 < \xi < 1$. If ξ is smaller, the greater the difference between correlation coefficients, the stronger the ability to distinguish. Often, ξ is 0.5.

min is the minimum difference between two levels and max is the biggest difference between the two levels.

$\gamma_{1i}(k)$ is the grey correlation coefficient.

4.2. Determination of Discriminant Parameters

Under the actual conditions of oilfield development, the apparent water absorption index (I′W) and water injection intensity (QWT) are key parameters for assessing the trend of dominant channels. Based on our dynamic analysis of injection/production well data from 7 target wells located in a certain region of eastern China, we have identified significant correlations among these parameters. Under actual conditions, the apparent water absorption index (I′W) typically varies within the range of 0.65 to 0.8 MPa, while the water injection intensity (QWT) is between 8 and 10 $m^3/m{\cdot}d$. These values are determined based on a systematic analysis of well group dynamic monitoring data and comparisons with typical blocks with similar geological characteristics.

For instance, in our study, the average value of the apparent water absorption index (I′W) is 0.75 MPa, indicating the oilfield's water absorption efficiency under moderate injection pressure. The average value of the water injection intensity (QWT) is 9 m^3/m·d, which reflects how to balance the risk of dominant channel formation while maintaining high injection efficiency. The results of grey correlation analysis are shown in Table 2. As can be seen from the table, PW and I′w can be used for trend judgment. The actual values of these parameters are crucial for guiding the oilfield's injection strategy and optimizing oil displacement effects.

Table 2. Dynamic indexes of wells and correlation degree of existing superior channels.

Injection Parameters	Relevance
PW (m^3/m·d)	0.889
QWT (m^3/MPa·d)	0.755
I′W (MPa)	0.620

Oil well indicators: QST, VFW, T polymerization, and other parameters, in which QST is the liquid yield strength, VFW is the rising rate of water cut, T polymerization is the visible concentration, and T polymerization is the visible polymerization time. The results of grey correlation analysis are shown in Table 3. It can be seen from the table that QWT and VFW can be used for trend judgment.

Table 3. Dynamic index of oil well and correlation degree of superior channels.

Production Parameters	Relevance
QST (m^3/m·d)	0.915
VFW (%/month)	0.795
T polymerization (day)	0.615

Thus, the discriminant parameters of the dynamic data method to determine whether there is a dominant channel trend in the oil and water well are shown in Table 4.

Table 4. Parameters of superior channel trend in oil wells identified by dynamic data method.

Injection Well		Production Well	
I′W	QWT	VFW	QWT

4.3. There Exists Dominant Channel Trend Discrimination in Wells

Based on the empirical data of typical blocks with similar formation features and advantageous channels, and combined with the development parameters of the study block, the discriminant method of injection wells is clarified, as shown in Table 5.

Table 5. Identification method of wells with dominant channel trend.

Strong		Weak		None	
QWT (m^3/m·d)	**I′W**	**QWT (m^3/m·d)**	**I′W**	**QWT (m^3/m·d)**	**I′W**
>10	<0.65	8–10	0.65–0.8	<8	>0.8
>10	0.65–0.8	8–10	>0.8		
8–10	<0.65	<8	0.65–0.8		

4.4. There Exists Dominant Channel Trend Discrimination in Oil Wells

According to the empirical data of typical blocks with similar formation features and advantageous channels, and combined with the development parameters of the study block, the discrimination method of producing wells is clarified, as shown in Table 6. The critical value of the rising speed of water cut in Table 6 can be referred to in Table 7. Table 7 summarizes various dominant channel identification methods and their advantages and disadvantages.

Table 6. The discriminant method for the trend of oil wells with superior channels.

Strong		Weak		None	
QST (m^3/m·d)	**VFW (%/Month)**	**QST (m^3/m·d)**	**VFW (%/Month)**	**QST (m^3/m·d)**	**VFW (%/Month)**
>10	Greater than critical value	5–10	Greater than critical value	<5	Less than critical value

Table 7. Critical value of water-cut rising speed of oil wells with superior channels (reference).

Water Interval	70–80		80–90		90–95	
VFW (%/month)	>0.66	<0.66	>0.67	<0.67	>1.25	<1.25

From Table 7, it can be seen that when the water interval is between 90 and 95, it is the main channel for fluid leak-off. The medium channels for fluid leak-off do not differ significantly and have a relatively smaller impact on development.

By combining these methods, a more comprehensive assessment of the formation and development trends of dominant channels can be achieved, thereby enhancing the accuracy of identification.

5. Polymer Flooding Advantage Channel Recognition Example

C and Y reservoirs have been in production since 1965, and there are now three types of well patterns: they are the basic well patterns of C and Y combined production. This includes the primary well pattern of exploiting the C, Y, and G thin differential reservoir and the polymer flooding well pattern of exploiting the Y layer. These oil reservoir areas are located in a certain region of eastern China, and they are low-permeability anticline reservoirs that have been under development for over a decade.

The basic well pattern put into development in 1965 adopts the line-and-line injection well pattern with the row spacing of injection and production of 600 m wells. The extraction objects are CI, CII, CIII, and YI reservoirs.

The primary infill well pattern put into development in 1986 adopted the 250 m $\times$ 250 m inverse nine-point method area well pattern, and the exploitation object was the low-permeability thin difference oil layer with poor and unutilized utilization in the base well pattern. In the well layout mode, the basic well pattern is adopted to carry out comprehensive pumping, and new wells are added between the basic well pattern and the well pattern.

A type of reservoir polymer flooding well pattern was put into development in 1995. The area of the good pattern was adopted by the 125 m $\times$ 125 m five-point method. The production object was a YI group oil layer injected with medium molecular weight polymer. However, in the late-stage project of oil field exploitation, because the water volume in the oil field will be too large for a long time to produce ineffective water circulation, which greatly increases the possibility of producing advantageous channels, it is particularly important to make clear the specific release of the advantageous channel in the oil field for the sake of the efficiency of exploitation in the future.

Firstly, the wells repeated by dynamic and mathematical methods are selected by comparison. Then, according to the inter-well identification basis, the trend well group is identified. Finally, the quadrants are used to determine the wells with strong and weak trends. See Table 8.

Table 8. Statistics of overlapping wells.

Identification Methods and Results	**Number of Injection Wells**			**Number of Production Wells**		
	Strong dominant channel	Weak dominant channel	Nondominant channel	Strong dominant channel	Weak dominant channel	Nondominant channel
Dynamic data method to identify the number of wells	13	11	3	13	12	4
Fuzzy mathematics method to identify the number of wells	14	10	3	14	9	6
Coincidence well number	11	8	3	12	7	4

In this study, we identified the dominant channels in the oilfield by combining dynamic data and the grey relational method. Figure 8 shows the connectivity map of the dominant channels, distinguishing between strong and weak dominant channels. In terms of error estimation, we found significant differences between the two.

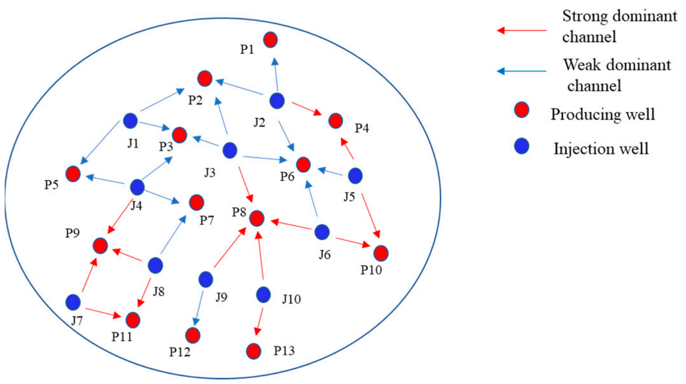

Figure 8. Connectivity diagram of well group of superior channels.

Specifically, the error estimation for strong dominant channels is typically lower, which may be due to their stronger consistency and predictability in geological physical properties and production data. According to our analysis, the average error estimation for strong dominant channels is 5%, while that for weak dominant channels is 10%. This difference is mainly attributed to the higher uncertainty of weak dominant channels in the reservoir and greater variability in the data collection and processing procedures.

In practical applications, this difference in error estimation is significant for formulating oilfield development strategies. The low error estimation for strong dominant channels provides more reliable development targets for the oilfield, while the high error estimation for weak dominant channels suggests the need for additional monitoring and adjustment measures to optimize oil displacement effects.

6. Conclusions

(1) Based on the experience of predecessors and the actual conditions of the fine block, from the point of view of geology and development factors, through the analysis of the formation physical properties and production data of oil and water wells, we can obtain the influencing factors of the dominant channel after the polymer flooding.
(2) The evaluation factor set determined by the grey correlation analysis method is scientifically rigorous and highly reliable, which is the first choice for dynamic analysis in a multi-factor linkage system.
(3) Using grey correlation methods, there are advantages for typical reservoir channel trend of oil and water Wells, which can identify the advantage channel injection well 27 mouths, failure of 29 mouths, through sedimentary facies, perforation, and well connected between data analysis and further identify existing advantage channel well group, strong advantage channel well group 40, weak dominant channel well group 29.
(4) This study successfully identified the dominant channels in polymer flooding using the grey relational method, providing a theoretical basis and practical guidance for oilfield development. The model results indicate that by adjusting injection strategies and optimizing well network layouts, it is possible to effectively control dominant channels and enhance oil displacement efficiency. In practical applications, these results can guide oilfield operations by monitoring changes in injection pressure and production to verify and optimize model predictions, achieving more efficient oilfield management.
(5) Future research can further explore the formation patterns of dominant channels under different geological conditions, as well as how to integrate the latest big data and artificial intelligence technologies to optimize polymer flooding strategies. Additionally, the field application and effectiveness evaluation of dominant channel identification methods are also important directions for future research.

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