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A Design and Optimization Method of Performing Layer Combinations in Separate-Layer CO_2 Flooding to Improve Oil Recovery

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Abstract: Separate-layer CO_2 flooding has increasingly been used to improve the overall development of multi-layer heterogeneous reservoirs. Due to their field technical limitations, layer combinations have to be carried out to reduce the number of layer-groups required for the separate injection of CO_2. Currently there are few studies of the method of designing layer combinations. In field practice, the layer combinations are often made based on the permeability ratio of the layers to be developed, but it is not possible to accurately obtain the optimal scheme in many cases. Therefore, in this paper, a new design and optimization method based on the weighted standard deviation of permeability is proposed, which comprehensively considers the effects of multiple geological and fluid properties in different layers. The new method is applied to study the layer combination schemes in separate-layer CO_2 flooding in H block, Daqingzijing Oilfield, Jilin, China. The prioritization of all of the schemes is obtained via the method, and a related numerical model is also established to perform verification and quantitative analysis. The results show that designing layer combinations using the new proposed method can achieve better development effect than using the conventional permeability ratio based method. It can achieve a more uniform interlayer CO_2 displacement with an obvious improvement in the CO_2 swept volume in low permeability layers and a higher overall oil recovery. According to the numerical simulation results, using the optimal layer combination scheme designed via the new proposed method, the ten-year swept volume of CO_2 in the low permeability layer can be increased by 16.2%, and the ten-year overall oil recovery efficiency can be increased by 3.3%, with both measures showing a remarkable improvement. The work can provide a significant reference point for the field design of layer combinations in separate-layer CO_2 flooding.

Keywords: CO_2-EOR; separate-layer gas injection; layer combination optimization; expanding swept volume; interlayer uniform displacement

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1. Introduction

CO_2-EOR has been widely used in the development of low permeability oil reservoirs [1]. Currently, commingled injection is often adopted in field cases of CO_2 flooding, which involves injecting CO_2 into all perforated layers using the same downhole pressure system without packers between the layers and the flow distributor in each layer. Commingled injection is relatively low cost and feasible for the development of reservoirs with similar properties between the layers [2]. However, a large number of studies and field cases show that the commingled injection may cause serious interlayer interference and poor overall oil recovery in the development of multi-layer heterogeneous reservoirs with obviously different properties between the layers [3–5]. In the case of the commingled injection of CO_2 flooding by water-alternating-gas (WAG), the injected gas and water more rapidly advance in the high permeability layer and reach the producer first, while the injected gas and water in the low permeability layer have not reached the producer, causing the displacement effect to vary greatly between the different layers, as well as a fast increase in the water cut and gas oil ratio in the producer, which makes the overall development unsatisfactory [6].

Separate-layer injection allows the injected gas or water to evenly advance in different layers by giving a specific rate of injection of fluid into each layer, as well as making the injected fluid in different layers reach to the producer at the same time to the maximum possible extent. As a result, all layers can be uniformly recovered with an improved overall development effect [7–9]. In the field, separate-layer CO_2 injection is mainly achieved using two methods, namely concentric double-pipe injection and single-pipe injection. For the single-pipe separate layer injection, the packer is used to separate the injection layers, and the rate of injection into each layer can be controlled by adjusting the nozzle of the flow distributor in each layer. For the concentric double-pipe separate layer injection, the fluid is injected into the upper layers through the annulus between the outer pipe and the center pipe, and it is injected into the lower layers through the center pipe [2]. Based on current technology, due to asphaltene precipitation, the difficulty in gas injection measurement and adjustment, the limitation in the size of casings in old wells, and other field limitations, the maximum number of layers available to make effective separate layer injections of CO_2 is 2~3. Therefore, when there are a large number of layers that need to be developed, the layers should be reasonably combined to create layer-groups to reduce the number of layers for separate injections. After completing layer combination, all of the layer-groups are separately injected from each other, while the layers within each layer-group are still commingly injected. It is essential to carry out reasonable design and optimization to identify the optimal layer combination scheme, which is used to obtain a relatively uniform displacement among the layers within each layer-group to the maximum possible extent. In this vein, the overall development can be improved.

There are few past works on the method of carrying out layer combination design and optimization. According to the Darcy's law, during flooding, the advancing speed of the injected phase is expressed as follows [10]:

$$v_i = \frac{KK_{ri}}{\mu_i} \nabla P_i \tag{1}$$

In order to achieve an interlayer uniform displacement in CO_2 flooding, the advancing speed of the injected CO_2 should be kept as similar as possible between the different layers, ensuring that the gas breakthrough in the producer can be delayed as far as possible to achieve longer-term stable production. For example, assuming there are n layers with distinct characteristics, if the interlayer uniform displacement is to be achieved, the following conditions should be met:

$$\frac{K_1 K_{rg\_1}}{\mu_{g\_1}} \nabla P_{g\_1} = \frac{K_2 K_{rg\_2}}{\mu_{g\_2}} \nabla P_{g\_2} = \cdots = \frac{K_n K_{rg\_n}}{\mu_{g\_n}} \nabla P_{g\_n} \tag{2}$$

The above equation can be simplified in some cases. Firstly, during commingled injection and production of the layers within each layer-group, based on the pressure balance inside of both the injection well and the production well, as well as the same displacement distance, the displacement pressure gradient of gas ∇P_g can be considered to be approximately equal in the different layers. Secondly, the relative permeability of gas K_{rg} is closely related to the gas saturation, and the gas saturation in different layers should be similar during an interlayer uniform displacement process within each layer-group. Moreover, the layers within the same layer-group should be close in their formation depth, pressure and temperature, and, thus, the viscosity of the injected gas μ_g should be similar in the different layers. Then, the above equation is simplified to give the following expression:

$$K_1 = K_2 = \cdots = K_n \tag{3}$$

This equation means that the permeability is the key factor controlling the advance of the injected fluid in each layer during commingled injection within each layer-group. To develop reservoirs with a large number of layers and obvious differences between their permeabilities, the layers with a smaller permeability distinction should be combined together as a layer-group to make the displacement within the layer-group as uniform as possible. Therefore, the key step is understanding how to design the layer combination scheme to make the permeability distinction of the layers within each layer-group as small as possible under a limited number of groups.

In most of the field practices and studies, the permeability ratio is used as an indicator to characterize and quantify the degree of permeability distinction between the layers [11–14]. To carry out layer combination design and optimization based on the permeability ratio method, firstly, all of the potential layer combination schemes are enumerated, and the permeability ratio is calculated for each layer-group under each layer combination scheme, which can be expressed as follows:

$$R_j = K_{max,j} / K_{min,j} \tag{4}$$

where j is the serial number of the layer-groups divided, R_j is the permeability ratio of the layer-group j, and $K_{max,j}$ and $K_{min,j}$ are the permeability of the highest permeability layer and the permeability of the lowest permeability layer within layer-group j, respectively.

Then, the averaged permeability ratio of the layer-groups is calculated under each of the different schemes, and they are compared to each other to make the choice. The smaller the averaged permeability ratio, the better the scheme.

Although this conventional method mentioned above is relatively easy to use, it actually has some defects, since it (1) only considers the permeabilities of the highest permeability layer and the lowest permeability layer within the layer-group, neglecting the influence of the permeabilities of the other layers on the layer-group's overall displacement effect, and (2) only considers the permeability to be a single parameter, neglecting the relevant factors, namely the effective thickness and porosity, that can affect the importance of each layer in terms of its contribution to the layer-group's overall oil recovery.

In many field cases of CO_2 flooding, the number of layers to be developed is usually large (more than 5 or even more than 10), and the effective thickness of the layers greatly varies, which amplifies the defects of the conventional method and greatly reduces the accuracy of performing layer combination scheme optimization through the conventional method. As a result, using the scheme obtained via the conventional method may have a development effect far different to that expected of it.

In order to resolve the defects of the conventional method based on the permeability ratio and more reasonably and accurately design an optimal layer combination scheme for the target formation, in this work, a new design and optimization method was proposed. As a commonly used mathematical parameter, the standard deviation can reflect the degree of dispersion of a set of data. It was, thus, applied and extended to be used to quantify the distinction of the permeabilities between all of the layers within the layer-group, via which method the permeability values of all of the layers within the layer-group can be involved in the evaluations. Moreover, the effective thickness and porosity were introduced to apply a weight to the permeability value of each layer and, thus, create a new parameter known as the "weighted standard deviation of permeability". This newly proposed parameter well resolved the defects of the conventional method and can be used to much more reasonably and accurately evaluate the level of interlayer uniform displacement than using the commonly used permeability ratio via the conventional method.

2. Principles and Procedures Involved in the New Method

The purpose of applying separate-layer injection and layer-combination is to practically achieve a uniform displacement between the layers to the greatest possible extent. For a target block with a large number of layers to be developed and a specific number of groups to be divided, there are many different selectable layer combination schemes, with the principle of the new method being to find the prioritization of all of those different schemes to perform the optimization by comparing the weighted standard deviation of permeability calculated under each different scheme.

As shown in the schematic diagram (Figure 1), assuming that there are N layers to be developed and they have to be divided and combined into n layer-groups due to field limitations, all of the different potential layer combination schemes are enumerated before making calculations and comparisons.

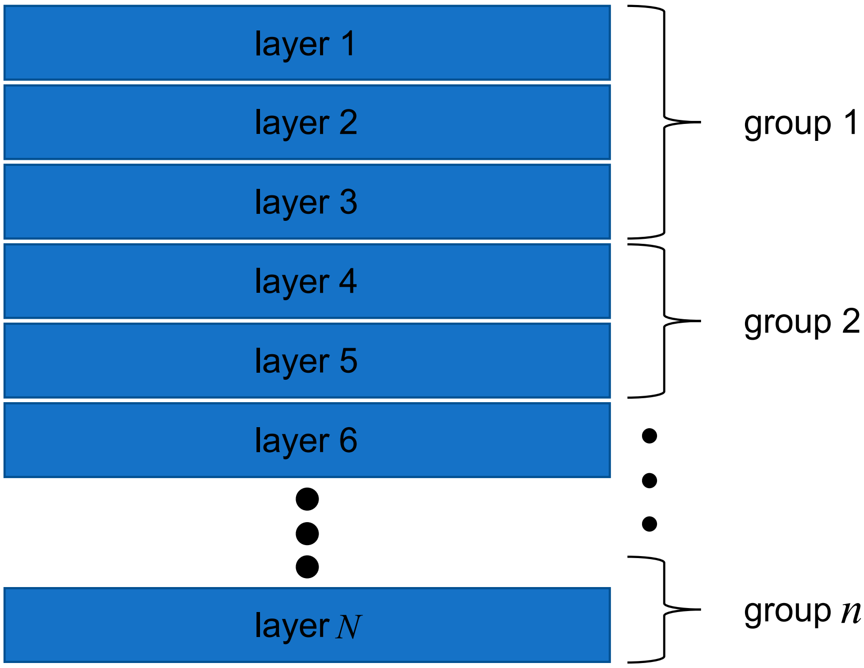

Figure 1. Schematic diagram of layer combination used to perform separate-layer injection.

For the first step, the weight index of each layer is determined. In order to achieve a uniform displacement between the layers, the flow rate in each layer has to be proportional to its cross-sectional area, and the cross-sectional area is affected by the effective thickness and porosity of the layer. As a result, the contribution of the layer to the layer-group's overall production depends on the effective thickness and porosity of the layer. This finding means that the evaluation of permeability values in different layers has to be of different levels of importance in terms of the layer's contribution to the overall production of the layer-group. In order to characterize it, M_i (i = 1~N) is introduced as a weight index of the ith layer in the calculation of the weighted standard deviation of permeability, which is expressed as follows:

$$M_i = H_i \times \varnothing_i \tag{5}$$

where H_i and $\varnothing_i$ are the effective thickness and porosity of the ith layer, respectively.

For the second step, under each of the different potential layer combination schemes, the weighted standard deviation of permeability in each of the n layer-groups, σ_j (j = 1~n), is calculated, which quantifies the extent of the permeability difference between the layers within each layer-group. Furthermore, it reflects the extent of the interlayer uniform displacement of each layer-group under the scheme.

$$\sigma_j = \sqrt{\frac{\sum_{i=N_{bot}}^{i=N_{top}} \left[(K_i - \mu_j)^2 \times M_i \right]}{\sum_{i=N_{bot}}^{i=N_{top}} M_i}} \tag{6}$$

where N_{top} and N_{bot} are the serial numbers of the top layer and the bottom layer of the jth layer-group, respectively; K_i is the permeability of the ith layer; and μ_j is the weighted average permeability of the layers in the jth layer-group.

As there are n layer-groups divided under each of the different layer combination schemes, in order to perform a further comprehensive evaluation of the displacement effects of all of the layer-groups, the weighted standard deviation of permeability of all of the n layer-groups, namely $\sigma_1 \sim \sigma_n$, should be comprehensively considered and calculated to obtain an averaged value of interlayer permeability difference to perform an overall evaluation of the displacement effect under each of the different schemes.

In order to characterize the difference in the contribution of each layer-group to the overall production of the whole formation, M_j (j = 1~n) is introduced as a weight index of the jth layer-group, which is expressed as follows:

$$M_j = \sum_{i=N_{bot}}^{i=N_{top}} M_i \tag{7}$$

For the final step, the weighted average of $\sigma_1 \sim \sigma_n$ under each of the different layer combination schemes, recorded as $\overline{\sigma}$, can be calculated via Equation (8). $\overline{\sigma}$ is used to evaluate the overall extent of interlayer uniform displacement under each scheme. The smaller the $\overline{\sigma}$, the more uniform the displacement is expected to be. By comparing $\overline{\sigma}$ calculated under the different schemes, the prioritization of the schemes can be obtained.

$$\overline{\sigma} = \frac{\sum_{j=1}^{n}\left[\sigma_j \times M_j\right]}{\sum_{j=1}^{n} M_j} \tag{8}$$

3. Application of the New Method

There are six major layers (#1~#6, from top to bottom) to be developed in H block, Daqingzijing Oilfield, Jilin, China. The averaged initial oil saturation and viscosity are 0.6 and 1.81 cp, respectively. Table 1 shows the averaged permeability, effective thickness, and porosity of each layer.

Table 1. Geological properties of the major layers to be developed in H block.

Layer	Permeability (mD)	Effective Thickness (m)	Porosity (%)
layer 1	2.9	2.5	12.4
layer 2	3.3	2.2	12.9
layer 3	1.0	1.6	11.4
layer 4	5.4	5.3	13.9
layer 5	2.2	2.6	12.6
layer 6	2.4	2.6	12.4

Depending on the technical conditions of the practice of separate-layer CO_2 injection in Daqingzijing Oilfield, the six layers (#1~#6 from top to bottom) were divided and combined into two layer-groups. As shown in Table 2, a total of five different potential layer combination schemes were enumerated for selection. The interlayer permeability difference under each of the five different schemes was evaluated through the new layer combination design and optimization method proposed in this paper and the conventional method based on permeability ratio, respectively. These results are shown in Tables 3 and 4, respectively.

Table 2. Potential layer combination schemes.

Combination Scheme	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Layer-Group 1	layer 1	layer 1–2	layer 1–3	layer 1–4	Layer 1–5
Layer-Group 2	layer 2–6	layer 3–6	layer 4–6	layer 5–6	layer 6

Table 3. Calculation results under different schemes (through the new method).

Combination Scheme	Weighted-Standard-Deviation of Permeability Layer-Group 1	Weighted-Standard-Deviation of Permeability Layer-Group 2	Weighted Average of Two Layer-Groups
Scheme 1	0.000	1.601	1.371
Scheme 2	0.200	1.736	1.314
Scheme 3	0.904	1.549	1.317
Scheme 4	1.542	0.100	1.109
Scheme 5	1.552	0.000	1.321

Note: the weighted standard deviations of permeability in layer-group 1 and layer-group 2 (i.e., σ_1 & σ_2) were calculated using Equation (6), and the weighted average of the two layer-groups (i.e., $\overline{\sigma}$) was calculated using Equation (8).

Table 4. Calculation results under different schemes (through the conventional method).

Combination Scheme	Permeability Ratio Layer-Group 1	Permeability Ratio Layer-Group 2	Average of Two Layer-Groups (Unweighted)	Average of Two Layer-Groups (Weighted)
Scheme 1	1.000	5.400	3.200	4.769
Scheme 2	1.138	5.400	3.269	4.230
Scheme 3	3.300	2.455	2.877	2.758
Scheme 4	5.400	1.091	3.245	4.105
Scheme 5	5.400	1.000	3.200	4.744

Note: the permeability ratios in layer-group 1 and layer-group 2 were calculated via the ratio of the permeability of the highest permeability layer to the permeability of the lowest permeability layer within each of their layer-groups (i.e., K_{max}/K_{min} within each layer-group).

According to the calculation results obtained using the conventional method based on the permeability ratio (Table 4), Scheme 3 was evaluated to be the optimal scheme because it yielded the lowest averaged permeability ratio among all of the different schemes. However, according to the calculation results obtained using the new method proposed in this work (Table 3), Scheme 4 was evaluated to be the optimal scheme because it yielded the lowest $\overline{\sigma}$ among all of the different schemes, and, thus, can be considered to achieve the most uniform displacement between the layers and the best overall development among all of the different schemes.

When there are more than two layers within a layer-group, the permeability values of the middle permeability layers within the layer-group may have a wide range, which cannot be characterized or accurately reflected only using the highest and the lowest permeability values within the layer-group. For example, under Scheme 3 (treating Layers 1~3 as the 1st layer-group and layers 4~6 as the 2nd layer-group), in the 1st layer-group, the permeability of the median permeability layer (Layer 1) was closer to the permeability of the highest permeability layer (Layer 2), but in the 2nd layer-group, the permeability of the median permeability layer (Layer 6) was closer to the permeability of the lowest permeability layer (Layer 5). In addition, for each of the layer-groups, the median permeability layer gave considerable weight to the layer-group's overall production based on the effective thickness and porosity (Table 1). Therefore, the permeability values of the middle permeability layers should play important roles in the evaluation of the interlayer permeability difference, as well as the extent of interlayer uniform displacement, within each of the layer-groups.

However, the conventional method based on permeability ratio only considers the effects of the highest permeability layer and the lowest permeability layer within the layer-group, neglecting the effects of the other layers on the displacement process within the layer-group, as well as the weight parameters of the layers. As a result, using the conventional method to perform layer combination optimization is not reliable in many cases, and, thus, the Scheme 3 that selected via the conventional method (Table 4), may not be the true optimal scheme. In contrast, the new method based on the weighted standard deviation of permeability comprehensively considers the permeability difference between all of the layers and introduces the weight parameters, such as the effective thickness and porosity, to characterize the contribution of each layer to the layer-group's overall production, meaning that it can more accurately prioritize the layer combination schemes, with Scheme 4 being selected to be the optimal scheme (Table 3).

4. Verification via Numerical Simulation

4.1. Model Establishment

A related multi-layer theoretical model (Figure 2) was established using Eclipse based on the geological and reservoir properties, as well as the injection and production parameters in H block. A typical inverted nine-spot rhombus flooding unit with displacement spacing of 150 m × 600 m was built to act as the simulation area. The plane grid spacing was set as 20 m × 10 m, and the vertical grid spacing was set based on the effective thickness of each layer. Both water flooding and CO_2 flooding by WAG were simulated. Based on the field data, for the injection well, the rate of injection was set at 40 m^3/d for water and 20,000 m^3/d for CO_2 (under standard conditions), with the maximum bottom hole pressure set at 40 MPa. For the production wells, the minimum bottom hole pressure was set at 14 MPa, with the maximum liquid production rate per well being 20 m^3/d. The upper limit of water cut was set at 0.98, and the upper limit of produced GOR was set at 1500.

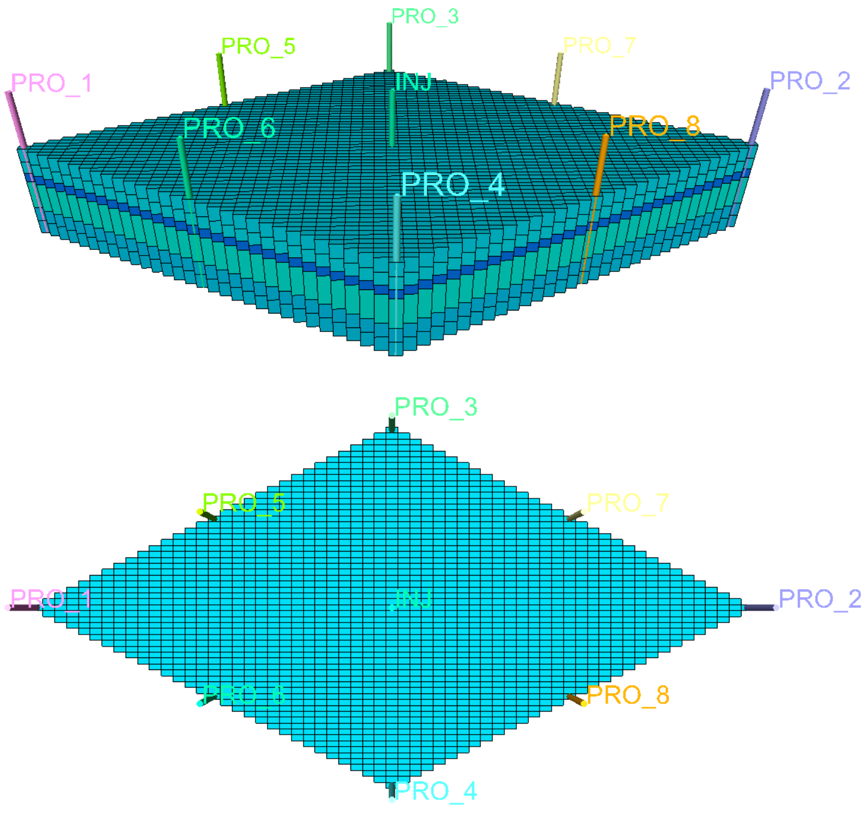

Figure 2. Multi-layer theoretical model of a typical flooding unit in H block (the variable shown in the grid is the permeability in the horizontal direction).

4.2. Determination of the Rate of Injection for Each Layer-Group

Through the model, all of the five different layer combination schemes for separate-layer injection (Table 2) were simulated in cases of water flooding and CO_2 flooding by WAG. In addition, the scheme of overall commingled injection for all of the layers was simulated as a reference. As stated, under every layer combination scheme, the 1st layer-group and the 2nd layer-group were separately injected (i.e., separate layer-group injection), and the layers within each layer-group were still commingled injected. For both water flooding and CO_2 flooding by WAG, in each of the different schemes, the total volume injected into the flooding unit was kept equal, i.e., the sums of the daily volume of injection into the 1st layer-group and the 2nd layer-group were the same for different schemes.

To realize a uniform advancement of the injected fluid between the layers, the expected rate of injection into each layer should be proportional to the flow cross-sectional area of the layer.

$$Q_i = \frac{H_i \times \varnothing_i}{\sum_{i=1}^{N} H_i \times \varnothing_i} \times Q_t \quad (9)$$

$$Q_j = \sum_{i=N_{bot}}^{i=N_{top}} Q_i \quad (10)$$

where Q_t is the total rate of injection into the flooding unit based on the field data, Q_i is the expected rate of injection into the ith layer to achieve a uniform fluid advancement between the layers, Q_j is the rate of injection into the jth layer-group to be set in the simulation, H_i is the effective thickness of the ith layer, $\varnothing_i$ is the porosity of the ith layer, N is the total number of layers to be developed in the flooding unit, and N_{top} and N_{bot} are the serial numbers of the top layer and the bottom layer of the jth layer-group, respectively.

According to the above equations, the daily volume of injection of water and CO_2 into each of the layer-groups were determined under the different schemes for both the case of water flooding and the case of CO_2 flooding by WAG (Table 5).

Table 5. Daily volume of injection into each layer-group under different schemes.

Scheme	Daily Water Injection (m^3)		Daily CO_2 Injection (m^3)	
	Group 1	Group 2	Group 1	Group 2
Combination Scheme 1	5.73	34.27	2867	17,133
Combination Scheme 2	10.98	29.02	5491	14,509
Combination Scheme 3	14.35	25.65	7177	12,823
Combination Scheme 4	27.98	12.02	13,990	6010
Combination Scheme 5	34.04	5.96	17,019	2981
Commingled injection for all layers	40		20,000	

4.3. Numerical Simulation Results and Analysis

The five different layer combination schemes of separate-layer injection and the scheme of overall commingled injection were simulated to obtain the curve of ten-year oil recovery efficiency in both the cases of water flooding (Figure 3) and CO_2 flooding by WAG (Figure 4), where the first subplot in each figure is the full curve of the ten years of simulation period, while the second subplot in each figure is the curve zoomed in on the last one year. By comparing the ten-year oil recovery efficiency under the different schemes (Table 6), Scheme 4 (layers 1~4 as the 1st layer-group and layers 5~6 as the 2nd layer-group) realized the best development effect with the highest ten-year oil recovery efficiency in both the case of water flooding and the case of CO_2 flooding by WAG. The five different layer combination schemes were prioritized as Scheme 4, Scheme 2, Scheme 3, Scheme 5, and Scheme 1 in a descending order of the ten-year oil recovery efficiency, which agreed well with the calculation results obtained via the new layer combination design and optimization method proposed in this paper (Table 3).

It was also found that the scheme of overall commingled injection for all layers yielded the worst development with the lowest ten-year oil recovery efficiency in both the case of water flooding and the case of CO_2 flooding by WAG, as was generally assumed. In case of water flooding, the ten-year oil recovery efficiency was 27.3% under overall commingled injection, 28.1% under separate-layer injection through Scheme 3 designed via the conventional layer combination optimization method, and 29.6% under separate-layer injection through Scheme 4 designed via the new layer combination optimization method proposed in this paper. Obviously, the ten-year oil recovery efficiency under the optimal scheme (Scheme 4) obtained via the new method was 2.3% higher than that under overall commingled injection and 1.5% higher than that under the scheme (Scheme 3) obtained via the conventional method. In the case of CO_2 flooding by WAG, the ten-year oil recovery efficiency was 38.1% under overall commingled injection, 39.6% under separate-layer injection through Scheme 3 designed via the conventional layer combination optimization method, and 41.4% under separate-layer injection through Scheme 4 designed via the new layer combination optimization method proposed in this paper. Obviously, the ten-year oil recovery efficiency under the optimal scheme (Scheme 4) obtained via the new method was 3.3% higher than that under overall commingled injection and 1.8% higher than that under the scheme (Scheme 3) obtained via the conventional method. Based on these results, using the new layer combination optimization method to design the separate-layer injection can give a better scheme with higher oil recovery efficiency, which showed a remarkable improvement compared to the conventional method. In addition, the results showed that the improvement of oil recovery efficiency through separate-layer injection in the case of CO_2 flooding by WAG was higher than that in the case of water flooding.

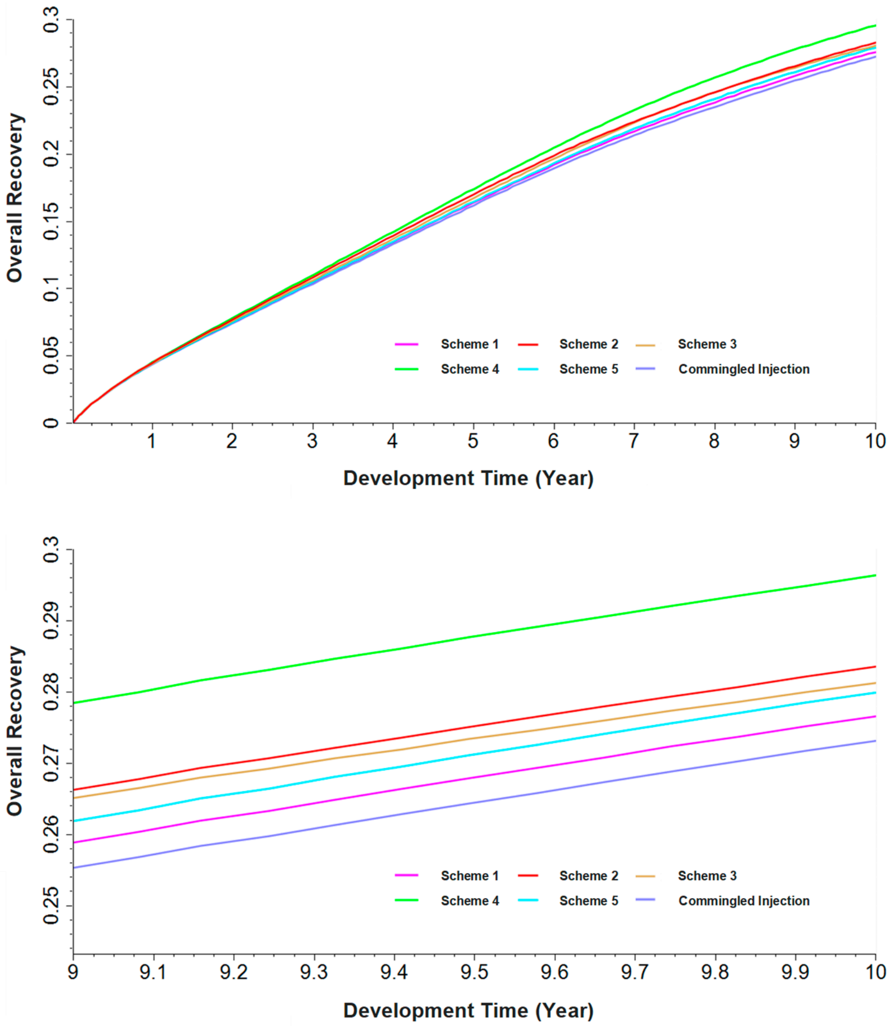

Figure 3. Ten-year oil recovery efficiency under different schemes (water flooding).

The difference in the CO_2 swept volume between the layers under the overall commingled injection and the two schemes of separate-layer injection (obtained via the conventional method and the new method, respectively) were clearly demonstrated in the profiles of CO_2 molar concentration (Figure 5).

As the profiles show, the injected CO_2 rapidly advanced in the high permeability layers while slowly advancing in the low permeability layers under overall commingled injection, yielding a quick increase in the gas oil ratio in the producer and a high ineffective circulation rate for the injected CO_2. However, using separate-layer injection (both Scheme 3 and Scheme 4), the displacement effect became much better, as the advancement of the injected CO_2 in the high permeability layers was slowed down and the advancement of the injected CO_2 in the low permeability layers was accelerated, which yielded a more uniform displacement between layers than that obtained via overall commingled injection, as expected.

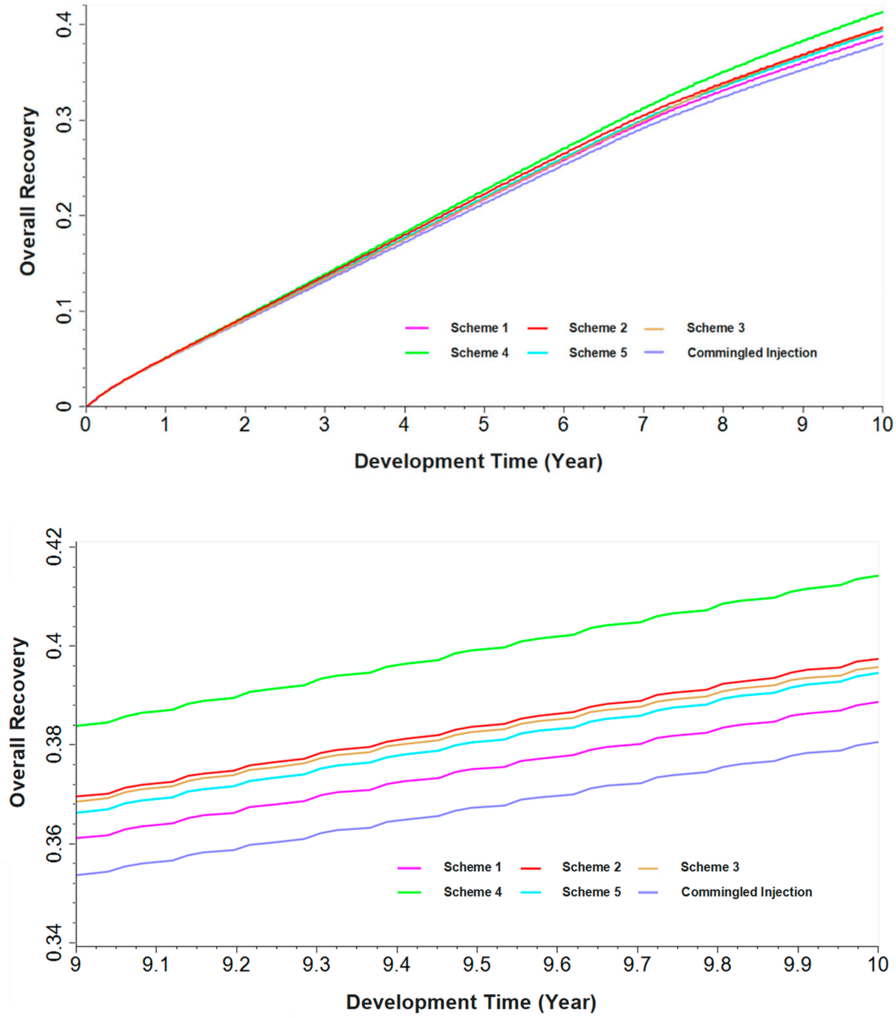

Figure 4. Ten-year oil recovery efficiency under different schemes (CO_2 flooding by WAG).

Table 6. Ten-year oil recovery efficiency under different schemes.

Scheme	Water Flooding	CO_2 Flooding by WAG
Combination Scheme 1	27.7	38.9
Combination Scheme 2	28.4	39.8
Combination Scheme 3	28.1	39.6
Combination Scheme 4	29.6	41.4
Combination Scheme 5	28.0	39.5
Commingled injection for all layers	27.3	38.1

In addition, by comparing the profiles under Scheme 3 and Scheme 4, it was found that using Scheme 4 (obtained via the new method) can achieve a better improvement in the displacement than using Scheme 3 (obtained via the conventional method). Compared to Scheme 3, the injected CO_2 more uniformly advanced between the layers under Scheme 4, as the swept volume in the low permeability but thicker layers (Layer 5 and Layer 6) significantly expanded. According to the field of CO_2 molar concentration after ten-year CO_2 flooding by WAG, the swept volume of the injected CO_2 in Layer 5 under Scheme 4 was 16.2% higher than that under Scheme 3 (Figure 6).

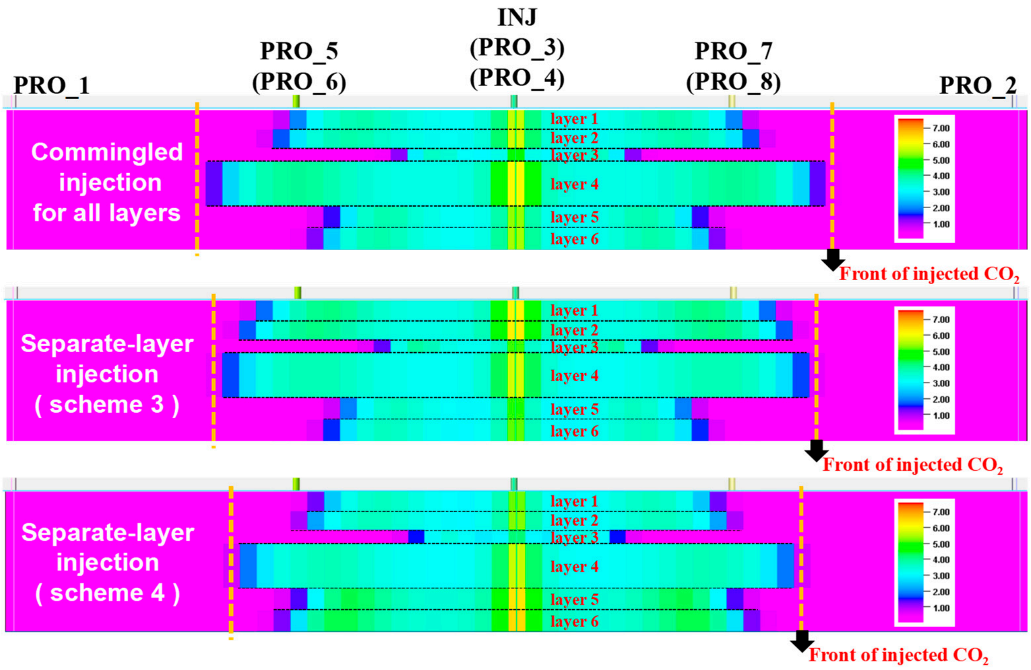

Figure 5. Profile of the CO_2 molar concentration of connection wells 'PRO_1—INJ—PRO_2' (kmol/rm^3) after ten years of injection in case of CO_2 flooding by WAG under the overall commingled injection and the two separate-layer injection schemes designed via the conventional method and the new method, respectively.

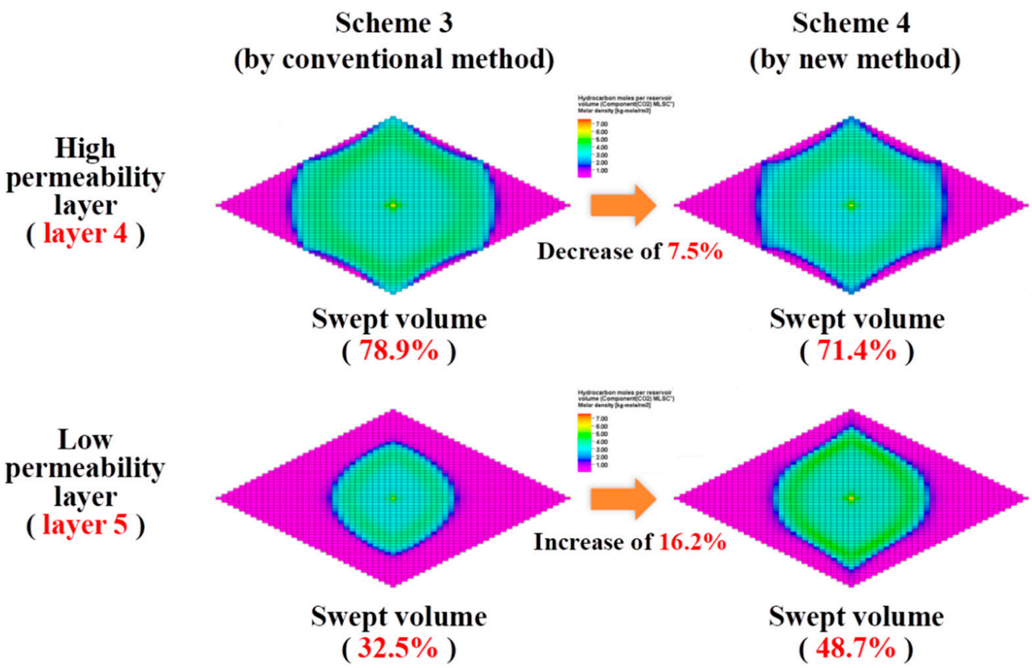

Figure 6. Field of CO_2 molar concentration (kmol/rm^3) after ten years of injection in the case of CO_2 flooding by WAG, with the difference in the CO_2 swept volume between Scheme 3 and Scheme 4 in both the high permeability layer and the low permeability layer shown.

The changes in the field producing gas–oil ratio and dynamic CO_2 storage in the formation under different schemes are shown in Figures 7 and 8, respectively, and the values at the end of ten years of development are compared in Table 7.

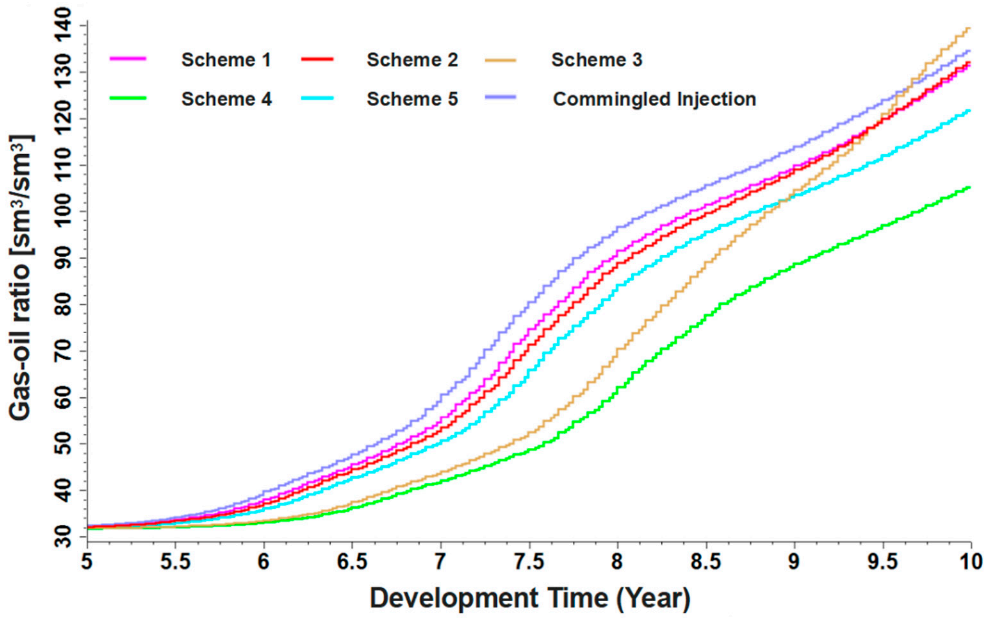

Figure 7. Change in the field producing gas–oil ratio under different schemes.

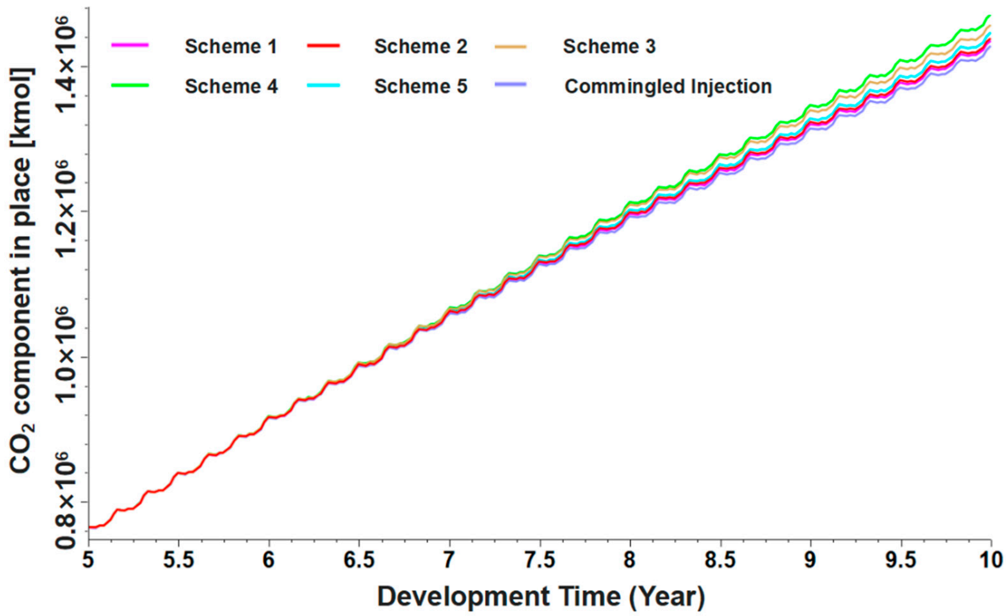

Figure 8. Change in the dynamic CO_2 storage in the formation under different schemes.

Table 7. Field gas–oil ratio and dynamic CO_2 storage in the formation after ten years of development under different schemes.

Scheme	Gas-Oil Ratio (sm^3/sm^3)	CO_2 Storage (10^6 kmol)
Combination Scheme 1	131.4	1.436
Combination Scheme 2	132.2	1.439
Combination Scheme 3	139.6	1.458
Combination Scheme 4	105.4	1.475
Combination Scheme 5	121.8	1.447
Commingled injection for all layers	134.7	1.427

Based on the simulation results, using Scheme 4 (obtained via the new method) can achieve the slowest rise in the gas–oil ratio, as well as the highest dynamic CO_2 storage in all of the different schemes, with these results being much better than those obtained using Scheme 3 (obtained via the conventional method).

Under Scheme 4, the gas channeling was delayed to the greatest extent. At the end of ten years of development, the gas–oil ratio under Scheme 4 was 29.3 sm^3/sm^3 lower than that under overall commingled injection and 34.2 sm^3/sm^3 lower than that under Scheme 3. Furthermore, the decline of ineffective circulation rate of the injected CO_2 also caused the increase in the dynamic CO_2 storage in the formation. At the end of ten years of development, the CO_2 storage in the formation under Scheme 4 was 48 $\times$ 10^3 kmol (i.e., 2.1 $\times$ 10^3 t) higher than that under overall commingled injection and 17 $\times$ 10^3 kmol (i.e., 0.75 $\times$ 10^3 t) higher than that under Scheme 3 (Table 7).

5. Discussion and Conclusions

(1) In the development of multi-layer heterogeneous reservoirs, using separate-layer injection can effectively solve the interlayer interference problem in overall commingled injection and lead to a more uniform displacement between the layers.

(2) Due to a series of field technical limitations, layer combinations have to be performed to achieve separate-layer CO_2 injection in practice. However, the commonly used conventional layer combination design and optimization method has lots of defects, due to which the real optimal scheme cannot be obtained in many cases.

(3) In this paper, a new layer combination design and optimization method, which is based on the calculation of the weighted standard deviation of permeability of the layers to be developed, was proposed and applied in the design of layer combination schemes in a typical field case. It was found that the new method could effectively solve the defects affecting the conventional method and improve the reliability of the optimization of the schemes.

(4) A related numerical simulation was performed, and the prioritization of the different layer combination schemes was obtained based on the simulated ten-year oil recovery efficiency. The simulation results showed good consistency with those calculated via the new method proposed in this paper, which verified the accuracy and reliability of the method.

(5) According to the simulation results, in the case of water flooding, the ten-year oil recovery efficiency under the optimal scheme obtained via the new method was 2.3% higher than that obtained under the scheme of overall commingled injection and 1.5% higher than that obtained under the scheme obtained via the conventional method; in the case of CO_2 flooding by WAG, the ten-year oil recovery efficiency under the optimal scheme obtained via the new method was 3.3% higher than that obtained under the scheme of overall commingled injection and 1.8% higher than that obtained under the scheme obtained via the conventional method, which showed a great improvement in terms of the overall oil recovery.

(6) Based on the profiles of CO_2 molar concentration after ten years of injection, the gas channeling can be effectively delayed by applying separate-layer injection with the layer combination scheme designed via the new method. The CO_2 swept volume in the low permeability layer can be expanded by 16.2% using the new method, which showed a remarkable improvement compared to the conventional method.

(7) Based on the simulation results of the changes in the gas–oil ratio and dynamic CO_2 storage in the formation under different schemes, using the scheme obtained via the new method can achieve the slowest rise in the field gas–oil ratio, as well as the highest dynamic CO_2 storage among all of the different schemes. It was much better than using the scheme obtained via the conventional method.

(8) According to the results identified in this work, using the new proposed method to perform the layer combination design and optimization is effective and reliable, and it can achieve an obvious improvement compared to the conventional method. This work is of great significance to the design of separate-layer CO_2 flooding and layer combination in multi-layer heterogeneous reservoirs. Also, in this work, the

applications of the new proposed method were mainly focused on the typical scenario of CO_2 flooding in Jilin Oilfield, China, meaning that a broader set of field case studies are needed in future work.

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