Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2025, 13(12), 201-211
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

A Method for Adjusting Balanced Water Flooding in Irregular Well Patterns of Conventional Heavy Oil Reservoirs

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How to cite this paper: Sun, Q., Zhao, J. S., Xu, Y. N., Zhang, L. L., & Zhang, Y. C. (2025). A Method for Adjusting Balanced Water Flooding in Irregular Well Patterns of Conventional Heavy Oil Reservoirs. *Journal of Geoscience and Environment Protection, 13,* 201-211.
https://doi.org/10.4236/gep.2025.1312011

Received: November 7, 2025
Accepted: December 5, 2025
Published: December 8, 2025

Abstract

Offshore heterogeneous conventional heavy oil reservoirs are mostly developed with irregular area injection-production well patterns. During the high water-cut stage, the problem of uneven planar water flooding becomes prominent. Adjusting the injection-production pressure difference to achieve planar balanced displacement is a key approach to improve the degree of reserve utilization and reservoir recovery efficiency. Based on streamline numerical simulation, this paper divides the irregular area injection-production well pattern into several injection-production seepage units, with each unit accounting for planar heterogeneity. A calculation method for planar sweep efficiency, considering the starting pressure gradient of heavy oil and non-piston water flooding characteristics, is established using the flow pipe method. By optimizing the injection-production pressure difference of different production wells, the areal sweep efficiency of each injection-production seepage unit tends to be consistent, thereby realizing planar balanced water flooding. Applying this method to the injection-production structure adjustment of Bohai Oilfield B achieves significant effects in water control and oil increment. This method can provide a theoretical basis for the optimization of initial injection-production pressure difference and the adjustment of injection-production structure during the high water-cut stage in heterogeneous conventional heavy oil reservoirs.

Keywords

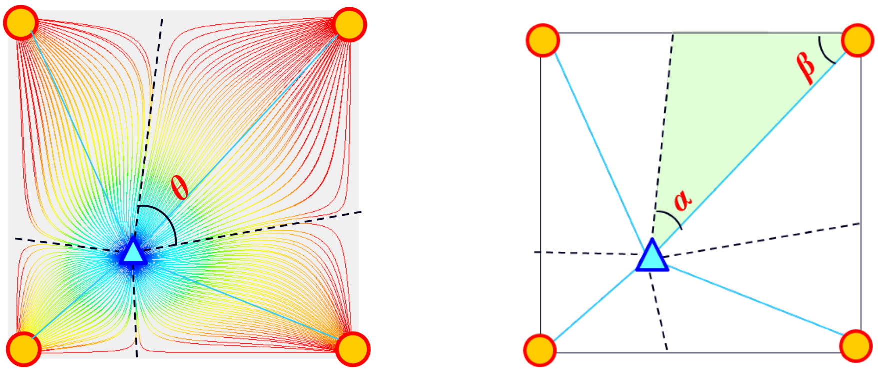
Planar Sweep Efficiency, Starting Pressure Gradient, Irregular Well Pattern, Flow Pipe Method, Balanced Displacement

1. Introduction

Bohai Oilfield B is a conventional heavy oil reservoir, featuring a relatively single main oil layer, strong planar heterogeneity, and an irregular injection-production well pattern. Currently, the oilfield has entered the high water-cut stage. Affected by reservoir physical properties, fluid properties, well pattern type and other factors, the problem of uneven planar water flooding has become increasingly prominent, resulting in low well group recovery (Bai et al., 2024; Wang et al., 2024; Hou et al., 2022; Guo et al., 2024). To improve the planar water flooding effect, some scholars have conducted research on adjustment methods of injection-production pressure difference or oil well liquid production rate, with the goal of achieving planar balanced displacement (Yan et al., 2015; Feng et al., 2016; Chang et al., 2019; Wang et al., 2011; Cui et al., 2016; Yang et al., 2019; Cui et al., 2015; Sun et al., 2020). However, these studies mainly focus on regular area injection-production well patterns and fail to consider the influence of the starting pressure gradient of heavy oil and strong non-piston displacement on water flooding. Building on previous research, this paper divides the irregular area injection-production well pattern into different injection-production seepage units, and each unit can be further subdivided into two triangular seepage units. Meanwhile, by comprehensively accounting for the planar heterogeneity of the reservoir, the starting pressure gradient of heavy oil, and the strong non-piston characteristics of water flooding, a calculation method for the planar sweep efficiency of injection-production seepage units is established based on the multi-flow pipe division method. By optimizing the injection-production pressure difference of each injection-production seepage unit, the area sweep efficiency of all units tends to be consistent, thereby achieving planar balanced displacement. Planar balanced displacement refers to a displacement mode in oilfield development where technical measures are adopted to enable uniform advancement of displacement agents across the reservoir plane and to align the development indicators of each injection-production zone, thereby enhancing oil recovery and development efficiency.

2. Division of Injection-Production Seepage Units

An injection-production seepage unit refers to the seepage area controlled by each pair of injection and production wells within a well group, which is significantly affected by the shape of the injection-production well pattern. Based on streamline numerical simulation, the irregular injection-production well pattern is divided into different injection-production seepage units, which means the division of the initial well pattern (Feng et al., 2014; Chen et al., 2018). The included angle of an injection-production seepage unit is basically consistent with the angle between the bisectors of the lines connecting two adjacent groups of injection and production wells, as shown in **Figure 1**. Additionally, any injection-production seepage unit can be further divided into two triangular seepage units. Actual reservoirs usually have strong planar heterogeneity, which is one of the key factors affecting the water flooding development effect. To account for planar heterogeneity while simplifying calculations, it is necessary to take the average value of the physical parameters of each planar injection-production seepage unit. Considering that the water flooding development effect of an oilfield is most affected by the reservoir physical properties along the main flow line, the physical parameters of each injection-production seepage unit can be simplified to the average physical parameters along the line connecting the injection and production wells. The main flow line is the "dominant channel" for fluid flow within the seepage unit, and its physical properties determine the seepage resistance and flow distribution of the entire unit, thus being able to represent the overall average physical properties of the unit.



a) Streamline simulation b) Division of injection production seepage unit

Figure 1. Division of injection production seepage unit.

3. Calculation of Areal Sweep Efficiency

On the basis of dividing injection-production seepage units, a flow pipe model is established. The Buckley-Leverett two-phase oil-water displacement theory is used to calculate the flow rate and water flooding front position of each flow pipe at different times. Furthermore, the areal sweep efficiency of each flow pipe and each injection-production seepage unit is derived from these calculations.

The basic assumptions of the model are as follows:

1) The injection-production pressure difference between injection wells and production wells remains constant.

2) The reservoir is a rigid porous medium, and the fluid is incompressible.

3) Oil displacement follows a non-piston water flooding pattern, with an oil-water two-phase zone existing.

4) The starting pressure gradient of heavy oil is considered.

5) The planar heterogeneity of the reservoir is considered.

3.1. Establishment of the Stream-Tube Model

For any triangular seepage unit, the included angles corresponding to the injection well point and production well point can be equally divided into m parts respectively, forming m flow pipes (Guo et al., 2011; Guo et al., 2010; Liu et al., 2014;

He et al., 2015; Hu et al., 2022; Sun et al., 2018), as shown in **Figure 2**.

According to geometric relationships, the length between the injection well (Point A) and the inflection point (Point C) in any stream tube is calculated by:

$$L_1 = \frac{d \sin \beta_0}{\sin(\alpha_0 + \beta_0)} \tag{1}$$

in the formula: d is the distance between injection and production wells, in meters (m); α_0 is the included angle between any flow pipe starting from the injection well and the line connecting the injection and production wells, in degrees (˚); β_0 is the included angle between any flow pipe starting from the production well and the line connecting the injection and production wells, in degrees (˚).

The length of any flow pipe between injection well A and production well B is calculated by:

$$L_2 = \frac{d(\sin \alpha_0 + \sin \beta_0)}{\sin(\alpha_0 + \beta_0)} \tag{2}$$

At any point in the stream tube, the cross-sectional area of the stream tube is:

$$A_s(\xi) = \begin{cases} 2h\xi \tan \dfrac{\Delta\alpha_0}{2}, & r_w < \xi < L_1 \\ 2h(L_2 - r_w - \xi) \tan \dfrac{\Delta\beta_0}{2}, & L_1 < \xi < L_2 - r_w \end{cases} \tag{3}$$

in the formula: h is the oil layer thickness, in meters (m); $\Delta\alpha$ is the included angle of any stream tube starting from the injection well, in degrees (˚); $\Delta\beta$ is the included angle of any stream tube starting from the production well, in degrees (˚).

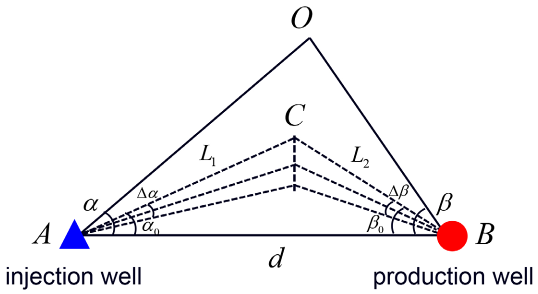


Figure 2. Flow pipe dissection of triangular seepage unit.

3.2. Derivation of the Flow Rate Equation

Laboratory experiments have shown that a start-up pressure gradient exists in ordinary heavy oil reservoirs, and thus the oil-phase flow rate equation no longer conforms to the linear Darcy's law (Cheng, 2011):

$$q_o = -\frac{KK_{ro}}{\mu_o} A_s(\xi)\left(\frac{\mathrm{d}p}{\mathrm{d}x} + G_o\right) \tag{4}$$

in the formula: q_0 is the oil-phase flow rate, in cubic meters per second (m^3/s); μ_0 is the oil-phase viscosity, in millipascal-seconds (mPa·s); Kro is the oil-phase relative permeability; K is the reservoir permeability, 10^{-3} μm^2; ξ is the distance from any position in the stream tube to the injection well, m; A_s is the seepage cross-sectional area at the position ξ in the stream tube, m^2; G_o is the start-up pressure gradient of heavy oil, MPa/m; p is the pressure along the displacement direction, MPa.

The water-phase flow rate equation is:

$$q_w = -\frac{KK_{rw}}{\mu_w} A_s(\xi)\frac{\mathrm{d}p}{\mathrm{d}x} \tag{5}$$

in the formula: q_w is the water-phase flow rate, m^3/s; μ_w is the water-phase viscosity, mPa·s; K_{rw} is the water-phase relative permeability.

The expression for the start-up pressure gradient is (Luo et al., 2009):

$$G_o = 0.1231 \times \left(\frac{k}{\mu_o}\right)^{-0.8688} \tag{6}$$

By combining Equations (4) and (5), the flow rate expression for any stream tube is derived as:

$$q_t = 0.0864 \cdot \frac{\Delta p - \int_{r_w}^{\xi_f} \left(\frac{K_{ro}}{\mu_o} G_o\right) \Big/ \left(\frac{K_{ro}}{\mu_o} + \frac{K_{rw}}{\mu_w}\right) \mathrm{d}\xi - G_o\left(L_2 - \xi_f\right)}{\frac{1}{K}\left[\int_{r_w}^{\xi_f} \frac{\mathrm{d}\xi}{A_s(\xi)\left(\frac{K_{ro}}{\mu_o} + \frac{K_{rw}}{\mu_w}\right)} + \int_{\xi_f}^{L_2 - r_w} \frac{\mathrm{d}\xi}{A_s(\xi)\frac{1}{\mu_o}}\right]} \tag{7}$$

in the formula: q_t is the stream tube flow rate, m^3/d; Δp is the injection-production pressure difference, MPa; ξ_f is the distance from the water flooding front in the stream tube to the injection well, m; r_w is the wellbore radius, m.

It can be seen from Equation (7) that after considering the start-up pressure gradient in heavy oil reservoirs, there is an additional pressure drop caused by the start-up pressure gradient of heavy oil in both the oil-water two-phase zone and the pure oil zone. During the water flooding process, as the water flooding front in the stream tube advances, the oil-water two-phase zone gradually expands, while the pure oil zone gradually shrinks. This leads to continuous changes in the seepage resistance within the stream tube and the additional pressure drop caused by the start-up pressure gradient. Therefore, a reasonable injection-production pressure difference is required to overcome the additional pressure drop in the stream tube and achieve effective displacement.

3.3. Determination of the Water Flooding Front Position

The water saturation at the position ξ (distance from the injection well) in the stream tube and the position ξ_f of the water flooding front can be determined using Equation (8):

$$\int_{r_w}^{\xi} A_s(\xi)\mathrm{d}\xi = \frac{f_w'(S_w)}{\phi}\int_0^t q_t \mathrm{d}t \tag{8}$$

in the formula: S_w is the water saturation; $f_w'(S_w)$ is the derivative of the water cut with respect to water saturation; ϕ is the porosity.

The position of the oil-water front before the water flooding front in the stream tube reaches the inflection point (Point C) is:

$$\xi_f^2 = \frac{f'_w\left(S_{wf}\right)\int_0^t q_t \mathrm{d}t}{\phi h \tan\frac{\Delta\alpha_0}{2}} \tag{9}$$

The position of the oil-water front after the water flooding front in the stream tube reaches the inflection point (Point C) but before it reaches the production well (Point B) is:

$$\xi_f = L_2 - \sqrt{\left(L_2 - L_1\right)^2 - \frac{f'_w\left(S_{wf}\right)\int_0^t q_t \mathrm{d}t}{\phi h \tan\frac{\Delta\beta_0}{2}} + \frac{\tan\frac{\Delta\alpha_0}{2}}{\tan\frac{\Delta\beta_0}{2}} \cdot L_1^2} \tag{10}$$

3.4. Calculation of Water Flooding Sweep Efficiency

At different times, the water flooding sweep area in each stream tube can be obtained based on the water flooding front in each stream tube of the triangular seepage unit.

Before the water flooding front reaches the inflection point (Point C), the water flooding sweep area of the stream tube is:

$$s_i = \frac{1}{2}\xi_f^2 \Delta\alpha_0 \tag{11}$$

After the water flooding front reaches the inflection point (Point C) but before it reaches the production well (Point B), the water flooding sweep area of the stream tube is:

$$s_i = \frac{1}{2}L_1^2\Delta\alpha_0 + \frac{1}{2}\left[\left(L_2 - L_1\right)^2 - \left(L_2 - \xi_{\mathrm{f}}\right)^2\right]\Delta\beta_0 \tag{12}$$

After the water flooding front reaches the production well (Point B), the water flooding sweep area of the stream tube is:

$$s_i = \frac{1}{2}L_1^2\Delta\alpha_0 + \frac{1}{2}\left(L_2 - L_1\right)^2 \Delta\beta_0 \tag{13}$$

Based on the water flooding sweep area of each stream tube, the areal sweep efficiency of the triangular seepage unit at different times is calculated as:

$$E_{\Delta AOB} = \frac{\sum_{i=1}^{m} s_i}{S_{\Delta AOB}} \tag{14}$$

in the formula: $S_{\Delta AOB}$ is the area of the triangular seepage unit.

For the irregular areal injection-production well pattern, each injection-production seepage unit is divided into two triangular seepage units. By calculating the water flooding sweep area of each triangular seepage unit, the areal sweep efficiency of each injection-production seepage unit can be obtained.

4. Adjustment Method for Planar Balanced Displacement

In offshore heavy oil reservoirs developed with irregular areal injection-production well patterns, factors such as the start-up pressure gradient of heavy oil, strong non-piston displacement characteristics, and planar heterogeneity of the reservoir lead to uneven displacement of injected water in different water flooding directions. Reserves in non-main streamline areas are difficult to exploit, and there is a large variation in the areal sweep efficiency among different injection-production seepage units. For injection-production seepage well groups with uneven water flooding, the injection-production pressure difference of different injection-production seepage units can be adjusted. Specifically, for injection-production seepage units with low planar sweep efficiency, the injection-production pressure difference needs to be increased to make the areal sweep efficiency of all injection-production seepage units converge, thereby achieving planar balanced displacement. For ordinary heavy oil reservoirs, the start-up pressure difference of each stream tube can be calculated based on the length of the stream tube and the start-up pressure gradient. Using this calculation, the injection-production pressure difference of each injection-production seepage unit can be optimized to achieve a higher planar sweep efficiency.

5. Case Application

Taking an injection-production well group in Bohai Oilfield B as an example, this well group adopts an irregular five-spot well pattern, and the production wells corresponding to the injection well are numbered P1, P2, P3, and P4. The permeability of each injection-production seepage unit, the injection-production well spacing, and the injection-production pressure difference of each production well are shown in **Table 1**. This well group has been in production for 15 years. In addition, the reservoir porosity of the target block is 0.25, the oil layer thickness is 10 m, the formation crude oil viscosity is 250 mPa·s, the formation water viscosity is 0.7 mPa·s, the residual oil saturation is 0.2, the irreducible water saturation is 0.25, and the relative permeability curve adopts the normalized relative permeability of the entire oilfield.

Table 1. Parameters of each injection production seepage unit.

Well Name	Injection-Production Well Spacing/m	Permeability/ $10^{-3}\ \mu m^2$	Injection-Production Pressure Difference/MPa
P1	360	2000	15.5
P2	250	1800	15.8
P3	390	800	15.8
P4	500	1500	15.0

Based on the method established in this study, the water flooding process of the well group was simulated, and the planar water flooding sweep efficiency of each injection-production seepage unit was calculated. The areal sweep efficiencies corresponding to production wells P1, P2, P3, and P4 are 0.49, 0.80, 0.67, and 0.28, respectively. To improve the planar water flooding effect and realize balanced displacement, the injection-production pressure differences of wells P1 and P4 (which have low sweep efficiencies) were optimized. The optimization period is set as a 10-year simulated operation after the adjustment of injection and production pressures, and after optimization, the injection-production pressure difference of wells P1 and P4 was adjusted to 21.0 MPa. After optimization, the daily oil increment of the well group reached 35 m^3. Model simulations show that after adjustment, the sweep efficiency of each injection-production seepage unit will reach approximately 0.80. The changes in the planar water flooding sweep efficiency of each injection-production seepage unit are shown in **Figure 3** and **Figure 4**. It can be observed from **Figure 4** that after considering the start-up pressure gradient of heavy oil, there are undevelopable areas in the non-main streamline parts. To exploit these areas, it is necessary to increase the injection-production pressure difference to overcome the additional pressure drop caused by the start-up pressure gradient of heavy oil, thereby achieving a higher planar sweep efficiency. Generally, in offshore oilfields, the purpose of adjusting the injection-production pressure difference is achieved by regulating the injection pressure of injection wells and controlling the bottom-hole flowing pressure of production wells.

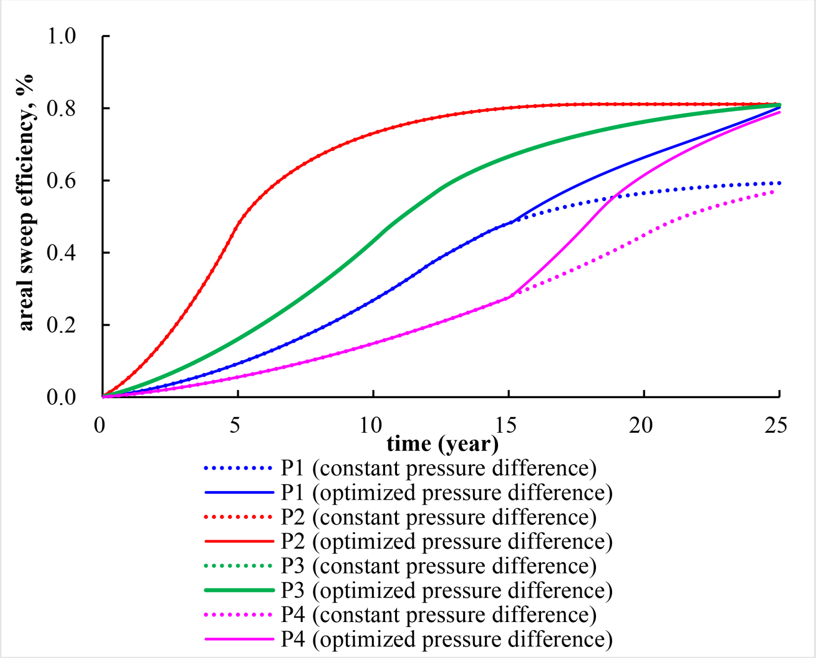


Figure 3. Sweep efficiency curve of different injection production seepage unit area.

This study only conducts analysis and calculation for the irregular five-spot well pattern. For other types of irregular areal injection-production well patterns, the same method can be used to divide the injection-production seepage units, and the areal sweep efficiency of each injection-production seepage unit can be calculated to guide the injection-production adjustment of well groups and realize planar balanced displacement in oilfields.

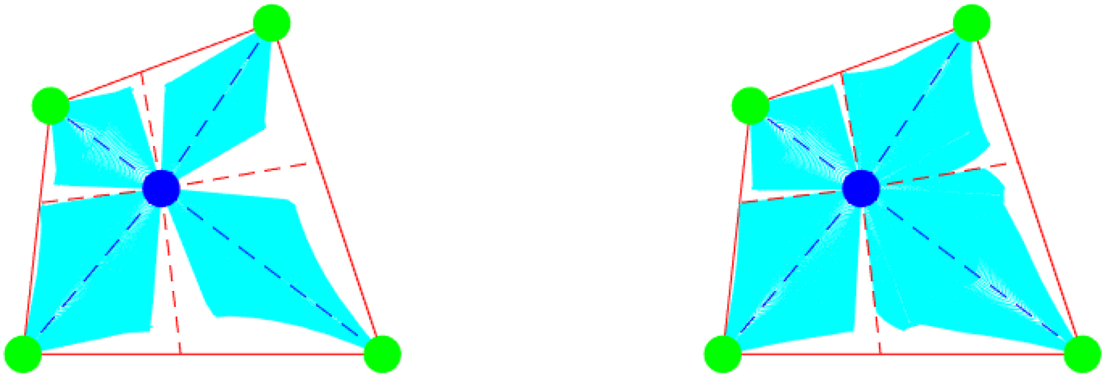

a) Non optimized injection production pressure difference (25a) b) Optimized injection production pressure difference (25a)

Figure 4. Plane water drive sweep diagram of irregular injection production well pattern.

6. Conclusions and Insights

1) For irregular areal injection-production well patterns, on the basis of dividing injection-production seepage units, a method for calculating the areal sweep efficiency is established using the stream-tube method, which takes into account the start-up pressure gradient of heavy oil and the characteristics of non-piston water flooding.

2) With the goal of planar balanced displacement, by optimizing the injection-production pressure difference of each production well, the impact of the start-up pressure gradient of heavy oil in non-main streamline areas is overcome, and the areal sweep efficiency of each injection-production seepage unit is made to converge, thus realizing balanced displacement.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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