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The Effect of Well Patterns on Surfactant/Polymer Flooding

Kang Zhou*, Jian Hou, Xiaoning Li

School of Petroleum Engineering, China University of Petroleum, Qingdao, China

Email address:
zhoukang_upc@163.com (Kang Zhou)
*Corresponding author

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Abstract: Surfactant/polymer flooding enhances oil recovery by increasing water viscosity and decreasing water/oil interfacial tension. Researches have proved that well pattern has a significant effect on the development performance of surfactant/polymer flooding. Based on reservoir numerical simulation method, the paper studies the development performance of surfactant/polymer flooding using line drive well pattern, five-spot well pattern, nine-spot well pattern, inverse nine-spot and inverse seven-spot well pattern. Results show that the line drive method and five-spot method achieve the highest oil recovery while that of the inverse seven-spot well pattern is the lowest. Mechanism analysis indicates that the displacement efficiency is the dominate factor behind the result. So when determining which well pattern should be used for surfactant/polymer flooding, the displacement efficiency have to be increased as much as possible. Besides, the well pattern should be reasonably designed so that the injection and production wells can be perpendicular with the high permeability channels in order to reduce channelling flow of chemicals. When the heterogeneity of an actual large-scale oilfield is strong and complex, several well patterns may be used together.

Keywords: Surfactant/Polymer Flooding, Well Pattern, Enhanced Oil Recovery, Streamline Analysis

1. Introduction

Most waterflooding oilfields in China have reached the stage of high water cut. The channelling flow along the vertical direction as well as the horizontal direction becomes very severe, and the remaining oil is highly disperse after long time of water flooding. As a result, the enhanced oil recovery methods have attracted increasingly attention all over the world to maintain stable oil production and economic growth. Surfactant/polymer flooding is one of the most important enhanced oil recovery method because it can improve the mobility ratio and decrease interfacial tension between water and oil. Many researches have conducted on the optimization of surfactant/polymer concentration, slug size and injection amount. Besides, the well pattern should also be paid more attention, because the well pattern controls the oil displacement direction and has a significant effect on displacement efficiency.

The researches on reasonable well pattern for an oilfield started from Daqing Oilfield in China. In the early 1980s, Tong studied the relationship between the total seepage resistance and the number ratio of injection to production wells under the conditions of injection-production balance and constant oil production index. The results show that the five-spot well pattern is better than the other well patterns and it is more convenient for later development and adjustment. Zhang et al. [1] determine the number ratio of injection to production wells in order to obtain the maximum amount of liquid production, and then determine the best well pattern. Yang et al. [2] gave a quantitative description of the relationship between fluidity, fracture parameters of artificial fracturing, heterogeneity within the reservoir and the injection-production well pattern. Shi [3] used reservoir engineering methods such as numerical simulation and driving pressure gradient to study the effect of three well patterns on the development effect of water flooding. Yue et al. [4] studied the control ability on sand body of different well patterns, and the relationship between injection rate and well spacing. Liu et al. [5] proposed the principle of optimal combination of well pattern for high water cut oilfields according to the current distribution characteristic and potential stype of remaining oil in order to deal with the inadaptability of the present well patterns. According to the development characteristics of Daqing Oilfield, Han et al. [6] presented a comprehensive method for high water cut oilfields, including combination of encryption and injection-production adjustment, and reduction of well spacing. The determination of well pattern and well spacing in surfactant/polymer flooding should ensure great development effect and also avoidance of chemicals channelling flow. Li et al. [7] optimized the well pattern and well spacing for chemical flooding on the basis of fine geological modeling and reservoir numerical simulation technology. Zhang et al. [8] simulated the development effect of surfactant/polymer flooding using four-spot, five-spot, nine-spot and line drive well pattern, respectively. Ai et al. [9] studied the synergistic effect of well pattern adjustment and surfactant/polymer flooding. Wen et al. [10] carried out optimization study on well pattern, well column direction and well spacing of surfactant/polymer flooding from various aspects such as sand control factors, the degree of chemical flooding control, the perfection of center well group, injection and production capacity, injection rate, recovery rate and economic benefit. Wu et al. [11] took a western low permeability oilfield as an example, and optimized the mode and density of well pattern.

The current studies on well pattern mostly focus on late adjustment for high water cut oilfields and the synergistic effect between surfactant/polymer flooding and well pattern adjustment. However, relatively few papers pay enough attention to the reasons why one well pattern is better than the other for surfactant/polymer flooding. So this paper tried to provide a simple explanation behind this fact based on reservoir numerical simulation method.

2. Reservoir Simulation Model

The surfactant/polymer flooding has been successfully used in China, such as Daqing and Shengli oilfields. Based on the geological properties of a typical reservoir in Shengli, a basic reservoir numerical simulation model is built. The model is discretized into 53×53×3=8427 grids. Each grid is 10.6m in the horizontal directions. Figure 1 shows the 3D map of the reservoir model with five-spot well pattern. Table 1 summaries the geological parameters used in this study.

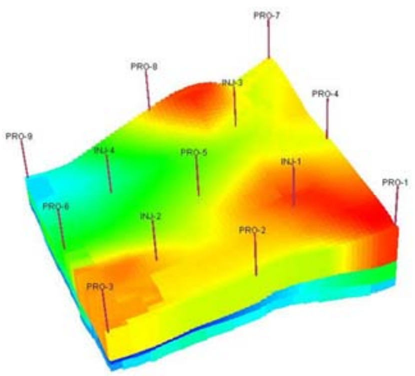
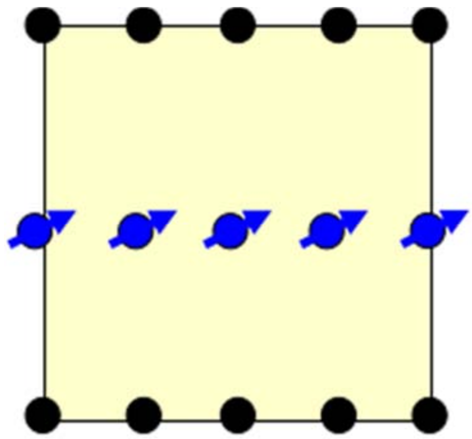


***Figure 1.** The reservoir numerical simulation model.*

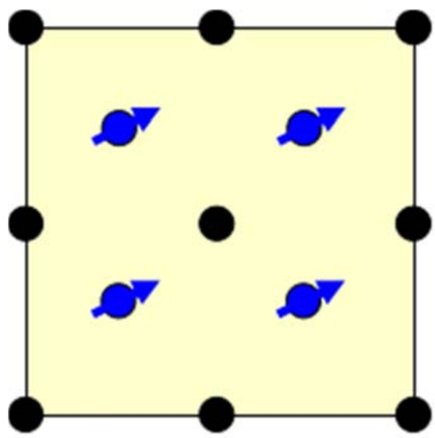
***Table 1.** The geological parameters of the reservoir simulation model.*

Parameters	Values
Oil-bearing area, km^2	0.31
Geological reserves, $10^4 m^3$	90
Pore volume, $10^4 m^3$	129
Depth, m	1261-1294
Average permeability, $10^{-3} \mu m^2$	1500
Heterogeneity coefficient	0.6
Initial oil saturation, %	72
Initial pressure, MPa	12.4
Saturation pressure, MPa	10.2
Oil viscosity, mPa•s	45
Effective thickness, m	12
Relative density	0.953
Reservoir temperature, °C	68
Average porosity, %	34

In accordance with the development characteristic of the typical oilfield, the production and injection data of the reservoir model is approximated based on the ratio of pore volume between the two reservoirs. And it produces from July 1986 to February 2010. In order to study the effect of well pattern on surfactant/polymer flooding, five kinds of well patterns are studied including line drive method, five-spot method, nine-spot method, inverse nine-spot method and inverse seven-spot method. Figure 2 details the distribution of production and injection wells in the five well patterns, respectively.



(a) line drive



(b) five-spot

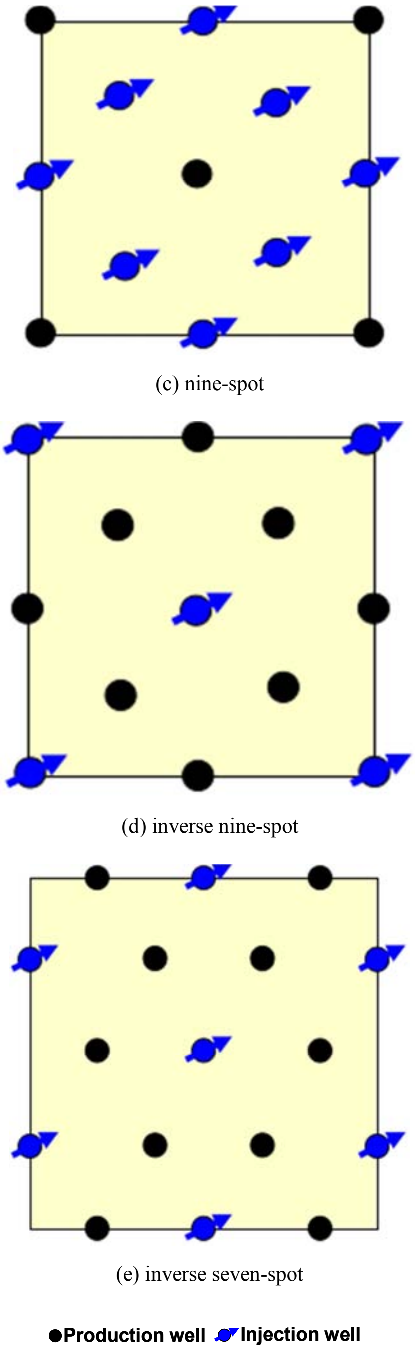


Figure 2. Comparison of different well pattern.

3. Results and Analyses

3.1. Enhanced Oil Recovery

In this study, the injection concentration of polymer and surfactant is set as 2000mg/L and 0.4wt% respectively. The injection rate of water flooding and the later chemical slug is set to be 0.1PV/a. However, the injection rate of water slug after chemical injection are set to be 0.08PV/a, 0.09PV/a, 0.10PV/a,0.11PV/a and 0.12PV/a respectively. The injection or production rates of each well are allocated based on the location of every injector or producer. After the simulation, the oil recovery as well as the enhanced value than water flooding when the water cut moves back to 98% are collected, as shown in Figure 3 and Figure 4. Obviously, the oil recovery of line drive well pattern, five-spot well pattern, and the inverse nine-spot pattern have much higher oil recovery than that of the nine-spot well pattern and inverse seven-spot well pattern no matter how much the injection rate is. Similarly, the enhanced oil recovery by surfactant/polymer flooding than water flooding is much higher in Line drive, five-spot and inverse nine-spot than that of the other two well patterns. We can conclude that, the water flooding rate after chemicals slug has little effect on the final oil recovery of surfactant/polymer flooding with different well patterns.

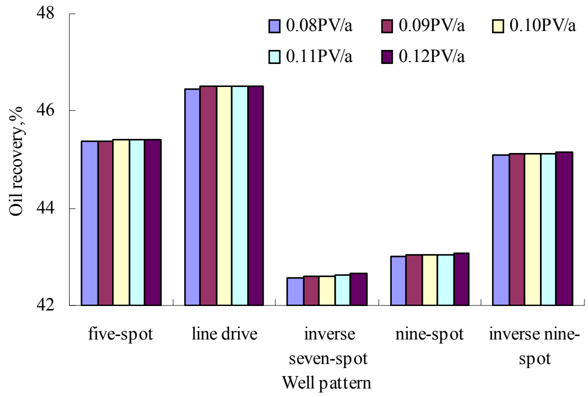


Figure 3. Oil recovery by surfactant/polymer flooding.

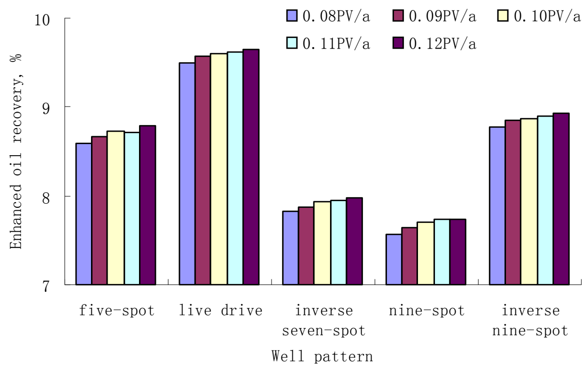


Figure 4. Enhanced oil recovery by surfactant/polymer flooding.

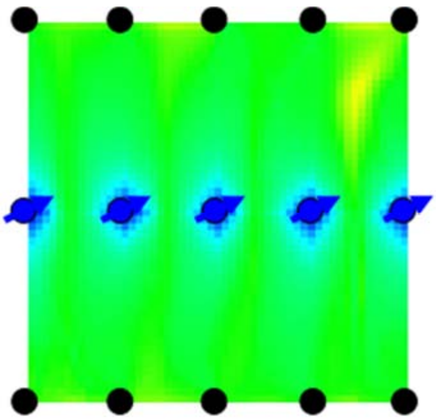
3.2. Remaining Oil Saturation

Figure 5 compares the distribution of remaining oil saturation at the water cut of 98% after surfactant/polymer flooding. As can be seen from the figure, the line drive well pattern achieves the lowest remaining oil saturation while that of the inverse seven-spot well pattern is the highest. In each figure, the region with high remaining oil saturation is generated because it is not well displaced by surfactant/polymer solution. From Figures 3-5 we can see that the line drive well pattern and five-spot well pattern is more suitable for surfactant/polymer flooding than the other well patterns. This conclusion is in accordance with the published papers. But what are the reasons behind this phenomena. This will be discussed in the next two sections.

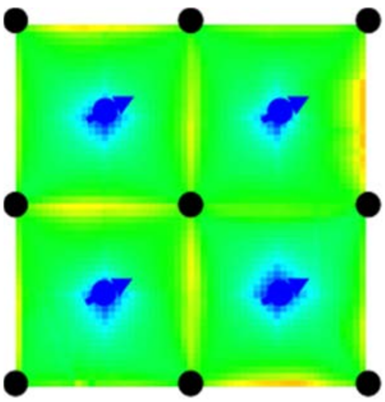
3.3. Sweep Efficiency and Displacement Efficiency

Surfactant/polymer flooding enhances oil recovery by increasing both the sweep efficiency and the displacement efficiency. The main controlling factor can be determined by investigating the variation principles of sweep efficiency and displacement efficiency under different well patterns. It can provide effective guidance for choosing the most suitable well pattern for a potential surfactant/polymer flooding project.

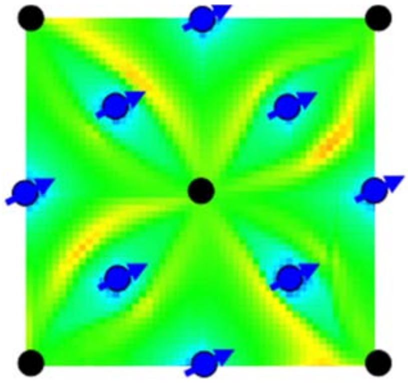
During reservoir simulation, the displacement efficiency can be calculated indirectly by the variation of oil saturation in each grid. Then, the sweep efficiency can be determined using Equation (1). As shown in Figure 6 and Figure 7, the diminishing order of the displacement efficiency of the five well patterns is the line drive well pattern, five-spot well pattern, inverse nine-spot well pattern, nine-spot well pattern and last the inverse seven-spot well pattern. The displacement efficiency from 0.4 to 0.5 of the line drive well pattern reaches about 50%. Figure 8 illustrates the sweep efficiency diminishing order of the five well patterns: line drive well pattern, five-spot well pattern, inverse nine-spot well pattern, nine-spot well pattern and inverse seven-spot well pattern. Compared the difference of Figure 7 with the difference of Figure 8, we can conclude that the displacement efficiency is the dominate factor resulting in the difference of surfactant/polymer flooding between different well patterns. Since the ultimate oil recovery of a reservoir is the product of sweep efficiency and displacement efficiency, the line drive well pattern and five-spot well pattern are suitable for surfactant/polymer flooding.



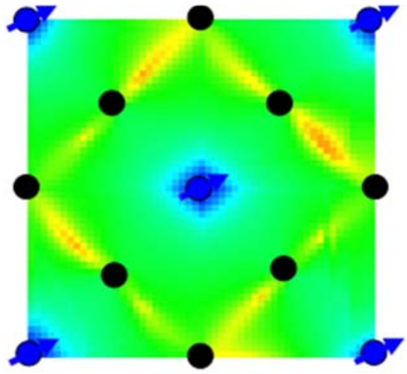
(a) line drive



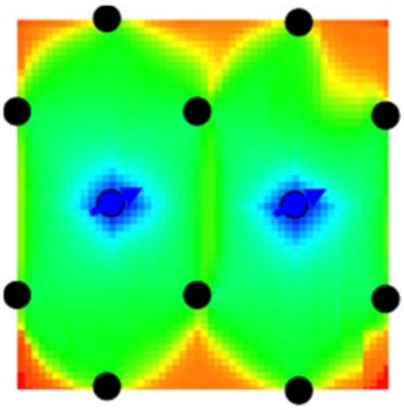
(b) five-spot



(c) nine-spot



(d) inverse nine-spot



(e) inverse seven-spot

Figure 5. *Remaining oil saturation of different well patterns.*

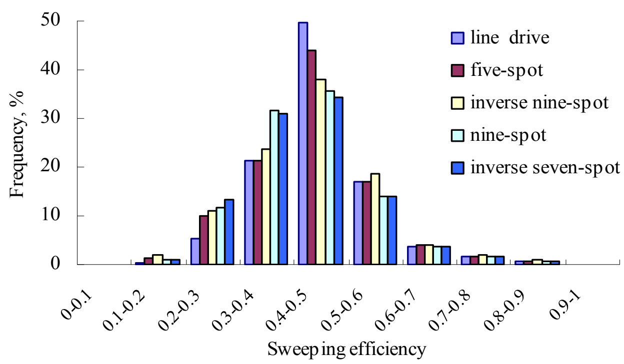


Figure 6. *Frequency of sweeping efficiency.*

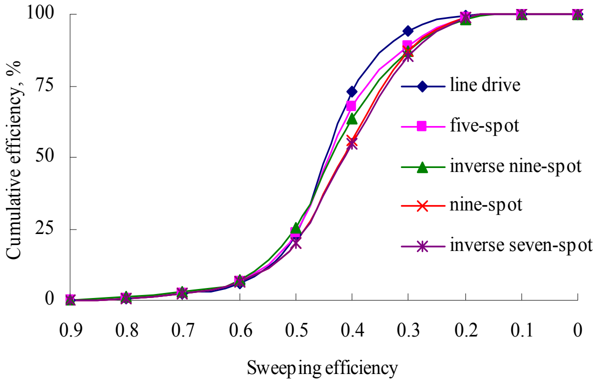


Figure 7. *Cumulative frequency of sweeping efficiency.*

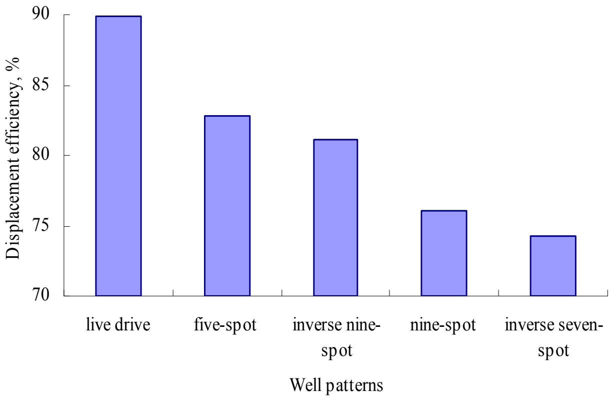
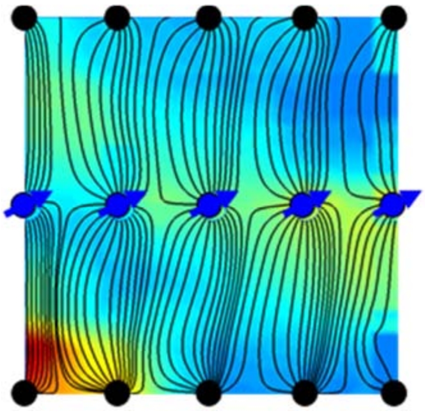


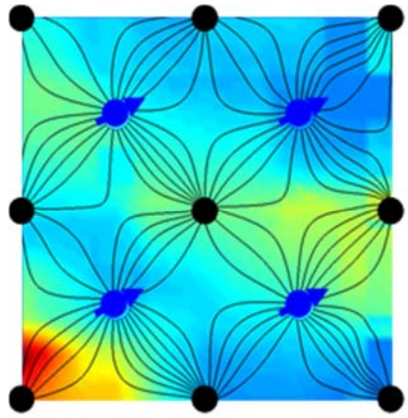
Figure 8. *Displacement efficiency of different well patterns.*

3.4. Streamline Analyses

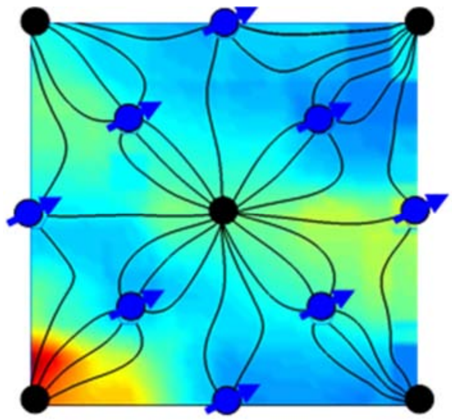
Streamline is the trajectory of fluid under a certain driving pressure. Based on reservoir numerical simulation method, the sreamline maps at the end of the surfactant/polymer flooding using different well patterns are drawn. So, we can anlyze clearly the situation of driving and sweeping. As can be seen from Figure 8, during the water-oil displacement process, the streamline shape formed between injection well and production well are totally different in each well pattern. The line drive well pattern has the densest streamline distribution compared with other well patterns. This indicates that the flow rate in line drive well pattern is the largest and its sweep efficiency is also the largest. Therefore, the development effect of surfactant/polymer flooding in the line drive well pattern is the best. Compared Figure 9(a) with 9(b), we can conclude that if there are high permeable channels in the reservoir, the well pattern should be reasonably selected in order to ensure that the flow direction of injection well and production well can be perpendicular with the high permeability zone. So the channelling flow along the high permeable channels can be reduced and thus the displacement efficiency can be increased. Sometimes, the heterogeneity of an actual large-scale oilfield is strong and complex. Several well patterns may be used together according to geological parameters.



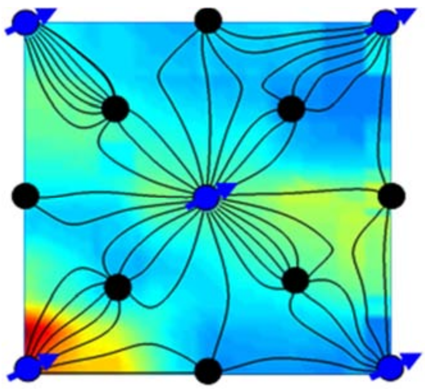
(a) line drive



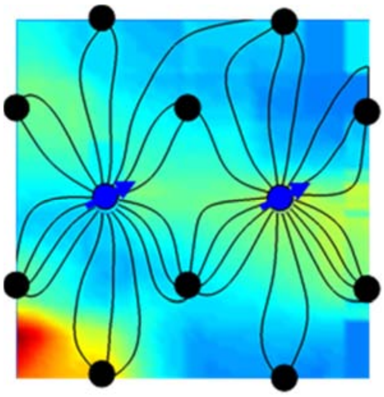
(b) five-spot



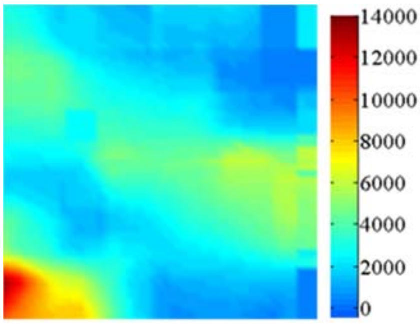
(c) nine-spot



(d) inverse nine-spot



(e) inverse seven-spot



(f) permeability, $10^{-3}\mu m^2$

Figure 9. *Streamline distribution of different well patterns.*

4. Field Validation

Oilfield A is developed by surfactant/polymer flooding using the line drive well pattern (like unregular five-spot well pattern) for many years. Figure 10 shows the reservoir simulation model of Oilfield A and the original well distribution. In order to validate the conclusion obtained by the simulation study based on the conceptual model, the paper designed four well patterns for the future development of Oilfield A based on its present development performance, including the original line drive well pattern (like unregular five-spot well pattern), nine-spot well pattern, inverse nine-spot well pattern and inverse seven-spot well pattern. The total number of wells and the amount of injection and production rares are kept the same in all of the four well patterns. In fact, there are 143 wells in total. The total injection rate in all of the four well patterns is 5592.48m^3/d and the total production rate is 5699.59m^3/d, which is in accordance with the development history. Table 2 details the number of injection wells and production wells, and also the injection rate and production rate of each well pattern.

The four development designs with different well patterns are simulated using reservoir numerical simulation software. The development performance of each well pattern are collected, including the water cut after 15 years since injecting chemicals and the oil recovery when the water cut reaches 98%. On the basis, the paper studies the effect of well patterns on surfactant/polymer flooding in Oilfield A.

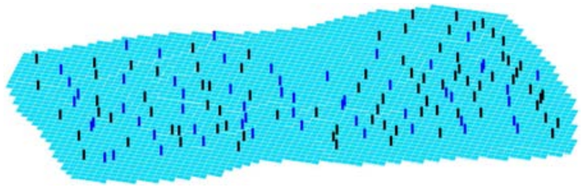


Figure 10. *The reservoir model and original well distribution of Oilfield A.*

Table 2. *The parameters of the four well patterns.*

Well pattern	Parameters	Values
Line drive well pattern	Number of producers	85
	Production rate, m^3/d	67.05
	Number of injectors	58
	Injection rate, m^3/d	96.42
Inverse nine-spot well pattern	Number of producers	103
	Production rate, m^3/d	55.34
	Number of injectors	40
	Injection rate, m^3/d	139.81
Nine-spot well pattern	Number of producers	46
	Production rate, m^3/d	123.90
	Number of injectors	97
	Injection rate, m^3/d	57.65
Inverse seven-spot well pattern	Number of producers	94
	Production rate, m^3/d	60.63
	Number of injectors	49
	Injection rate, m^3/d	114.13

Figure 11 shows the water cut of the four well patterns after 15 years since the chemical injection. As can be seen, the water cut of nine-spot well pattern is the highest. The original line drive well pattern, inverse nine-spot well pattern and inverse seven-spot well pattern have relatively low water cut values.

Figure 12 shows the oil recovery of the four well patterns when the water cut reaches 98%. As we can see from the figure, the original live drive well pattern achieves the highest oil recovery value. Then, the oil recovery decreases in the sequence of line drive well pattern, inverse nine-spot well pattern, nine-spot well pattern and last the inverse seven-spot well pattern. This result is in accordance with that obtained by the conceptual model as shown in Figure 3. So the conclusion obtained by the conceptual reservoir model can be validated by the large-scale field applications.

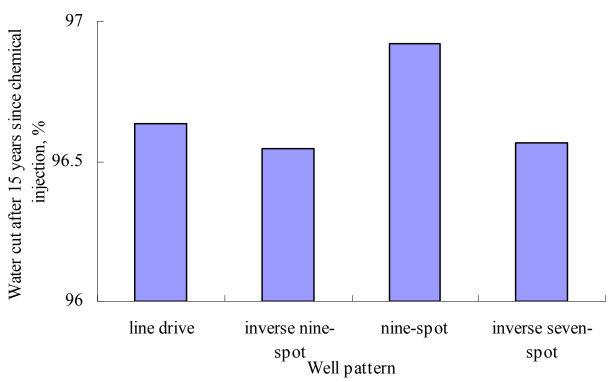


Figure 11. *The water cut after 15 years since chemical injection.*

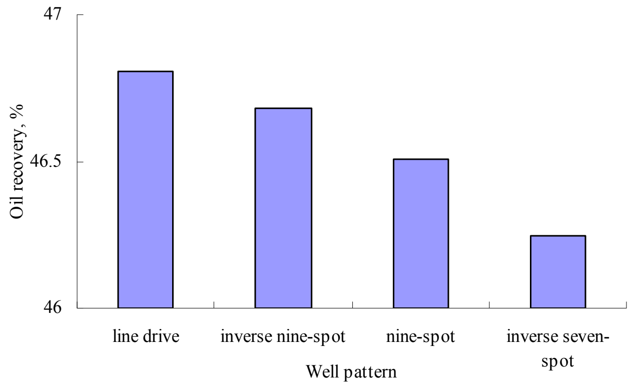


Figure 12. *The oil recovery at the water cut of 98%.*

5. Conclusions

Based on reservoir numerical simulation method, the effect of well patterns on surfactant/polymer flooding has been studied. Results show that the line drive and five-spot well patterns can obtain much higher oil recovery than the nine-spot, inverse nine-spot and inverse seven-spot well patterns. Mechanism analysis indicates that the dominate factor behind this result is displacement efficiency. So when determining which well pattern should be used, the displacement efficiency have to be increased as much as possible. Moreover, the well pattern should be reasonably selected in order to ensure that the flow direction of injection well and production well can be perpendicular with the high permeability channels. Several well patterns may be used together if the heterogeneity of an actual large-scale oilfield is strong and complex.

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