

# Study on the influence of injection/production type and well pattern and spacing on producing degree of thin and poor layers

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**Abstract** Daqing Oilfield has already entered the period of high water-cut oil production, and currently the target within the oilfield is thin and poor reservoir layers, whose thickness is less than 0.5 m, and it has very low permeability. These layers also have complicated pore structure and poor developmental benefits because of the low permeability, yet several million tons of remaining reserves exist in these low-permeability, poor and thin layers. This paper analyzed the influence of several factors on the degree of production from these thin and poor layers, specifically focusing on the injection/production type and well pattern and spacing, in order to provide guidance for development of thin and poor reservoir. Two producing models were used to analyze the influence of injection and

production type on the production degree of these thin and poor layers: water injection into thick layers, and producing from the thin layers, and vice versa. Also, the effects of well spacing and pattern under different pressures were analyzed by calculating the effective producing coefficient and areal sweep efficiency based on the flow tube model and oilfield examples. The results show that the best way to develop a thin and poor reservoir is thin injection and thick production type and that a reasonable well spacing range should be within 200 m. Beyond this 200 m spacing, it is difficult to increase production, even if the reservoir pressure is significantly increased.

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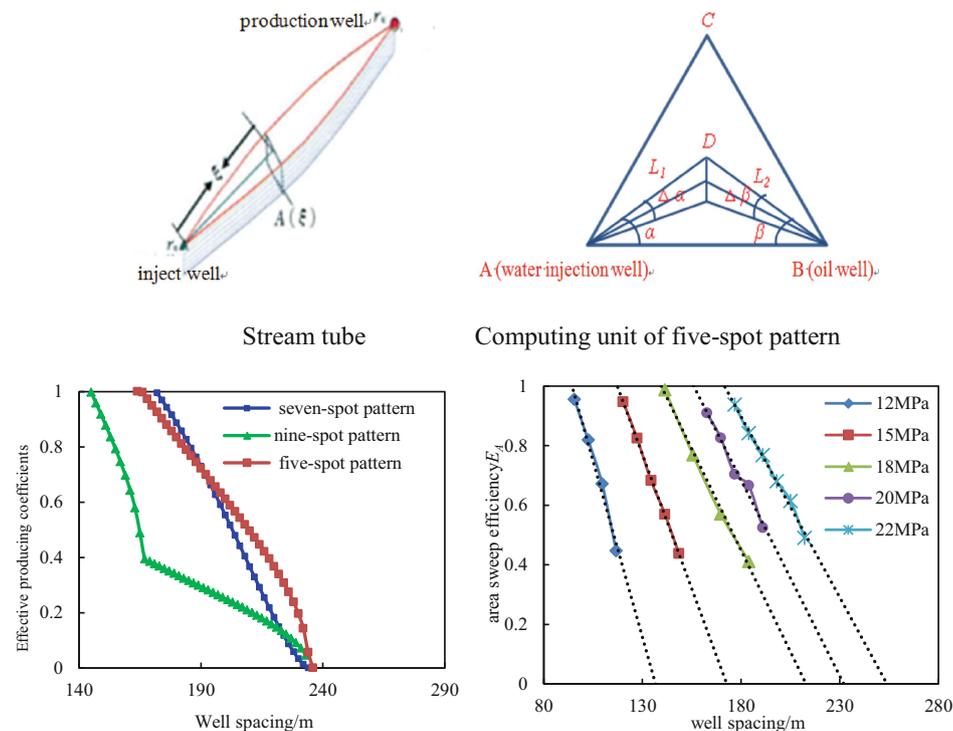
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## Graphical Abstract

### Stream tube model



Effective producing coefficient and areal sweep efficiency of different well pattern, well spacing

**Keywords** The thin and poor layers · Injection/production types · Well pattern and spacing

## Introduction

The Daqing Oilfield is one of the China's largest oilfields since the 1950s and has reached a steady state of production since the 1970s, with recent subtle decline in production. The Daqing Oilfield contains relatively thin and poor reservoir layers along with its major producing layers. These thin and poor layers have recently become a target with the advancement of technology now that the oilfield has reached a late stage of development (Zhuo et al. 2011). The thin and poor layers refer to reservoirs with low permeability and thicknesses that are between one and four meters, particularly untabulated reservoirs, whose effective thickness is zero ( $<0.2$  m). They have complicated connectivity, frequent facies changes in horizontal direction and high diversity between layers in vertical direction, particularly compared to the conventional reservoirs within

the Daqing Oilfield (Cheng et al. 2007). These reservoirs have been ignored because of these inadequate characteristics, yet they contain an estimated 40% of the remaining hydrocarbons within the Daqing Oilfield.

Currently, most of the research is aimed at low permeability of poor reservoirs, rather than a combination of low-permeability and thin layers. The Klinkenberg-corrected permeability has been successfully estimated from a single-point and steady-state measurements on samples from low-permeability sands (Florence et al. 2011). Also, several problems concerning refracturing in low-permeability reservoirs have been studied, including the effectiveness of initial fractures, effects of water cut, reservoir pressure on post-refract performance and selection of candidate wells, optimization of fracture length, treatment design, implementation and evaluation. Both technological and economic achievements have been obtained on these fronts (Wang et al. 1998). New solutions also have been presented for infinite-conductivity vertically fractured wells with wellbore storage (including the fracture storage, which may be important even if the flow rate is measured at

the wellbore) and skin effects. Two examples demonstrated the use of the new interpretation methods for both draw-down and buildup tests by Kuchuk (1987). Blasingame (2008) focused on the issue of low permeability in conjunction with reservoir heterogeneity. Results show that low-permeability reservoirs require programs of data acquisition which evolve as the reservoir is developed; petrophysical data are derived from core, well logs and imaging tools and are necessary for optimal development of a low-permeability reservoir system. The development of an integrated reservoir description is particularly important for low-permeability gas reservoirs systems, and characterization of the well/reservoir performance is the critical link for understanding the flow behavior of low-permeability reservoirs systems.

These thin and poor reservoirs are different from low-permeability reservoir. Much of the research stems from China as the Daqing Oilfield is an interesting and extensive location for this type of reservoir. The discussions typically focus on the remaining oil potential and tapping method, such as subdivisional water injection, wells acidification, profile modification for injection wells and reservoir fracturing, reperforating and water plugging for producing wells (Ji 2014; Yuan 2014; Zhao 2014). Relevant research based on reservoir numerical simulation focuses on layer recombination and injection/production system adjustment (Zhou 2014; Shen 2013; Mu 2014). Furthermore, the polymer injection technology has also been applied to thin and poor reservoirs (Zhang et al. 2016a, b), while the water-out oil reservoir discrimination is a vital technology for thin and poor reservoirs (Zhang et al. 2016a, b; Miao et al. 2015; Jiang 2012). It is difficult to develop thin and poor reservoir; therefore, the research on production technology and their limitations are far more important (Liang et al. 2016; Meng 2016; Zhao 2015; Wan 2013).

As far as we know, there is currently a limited discussion on various factors influencing the production on these thin and poor reservoirs within the literature, particularly on the injection/production type and well pattern and spacing. Reservoir research shows that near 40% of the thin and poor reservoir thickness is not water washing in Daqing Oilfield (Dai 2012; Zhang and Hu 2013). It is particularly important to develop the thin and poor reservoir effectively. In this paper, we analyze the influence of several development factors on producing thin and poor reservoirs, including the injection/production type, well pattern and spacing. This is accomplished by using geological modeling and IMPES simulation of the middle of Block Xing6, Xingshugang Oilfield, China. This Block mostly consists of argillaceous sandstones in the thin and poor reservoir with poor physical properties and permeability, oil immersion, oil patch and oil trace, combined complex spatial distribution. The remaining oil distribution

is highly scattered, and the producing thickness is still not ideal.

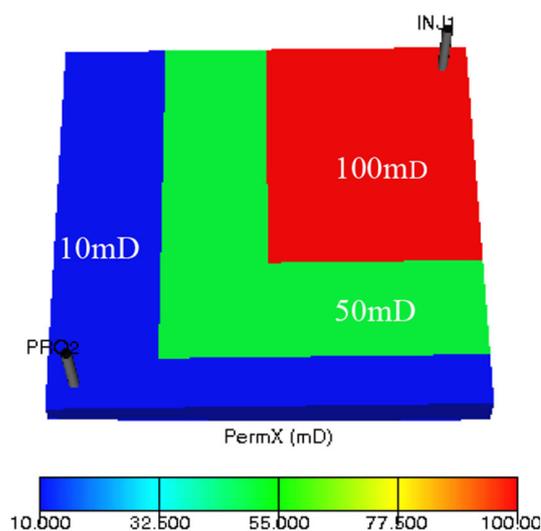
## The influence of injection/production type

### Model parameters

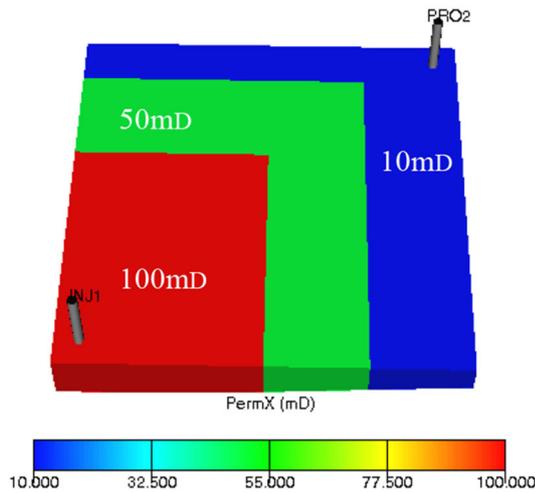
Using the physical parameters of Block Xing6, Xingshugang Oilfield, a geologic model of a thin and poor reservoir was created. It included the plane heterogeneity of typical thin and poor reservoir. Using IMPES simulation method, there were two scenarios used to test the influence of injection/production type on production. The geological model with one injection well and one producing well had a well spacing of 250 m and gridding number of  $25 \times 17$ . The thickness varied from 1 to 4 m for each plane. Porosity and permeability changed with thickness, with the porosity varying from 0.21 to 0.24 and permeability varying from 10 to 100 mD (Figs. 1, 2, 3, 4). The viscosity of crude was set to 6.4 mPa s, and the permeability saturation curve is shown in Fig. 5. The INJ1 is injection well and the PRO2 is producing well. There were two types of injection that were simulated in these scenarios: injection into a thick layer and production from a thin, and vice versa. The degrees of recovery were calculated to show which type of production would be better suited for these very low-permeability and thin reservoirs within this oilfield.

### Results

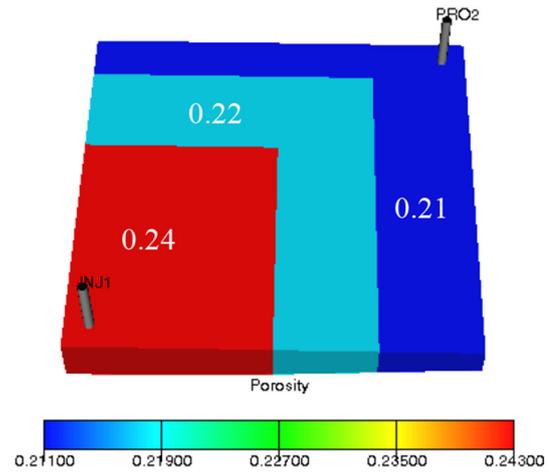
The reservoir plane is heterogeneous, and with the combined effect of varying thickness and permeability–porosity, the recovery degree of the thin injection and thick



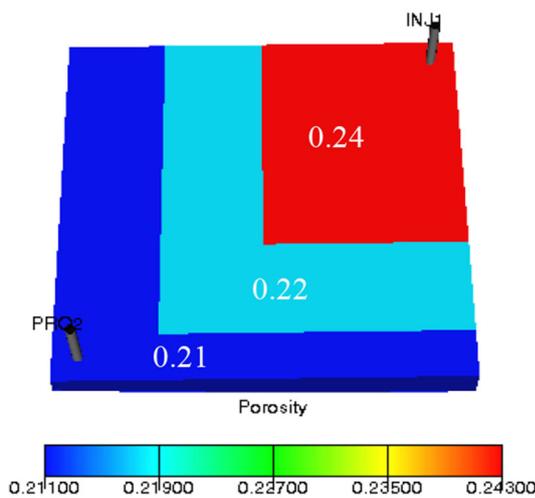
**Fig. 1** Permeability model for injecting into thin layers and producing from thick ones



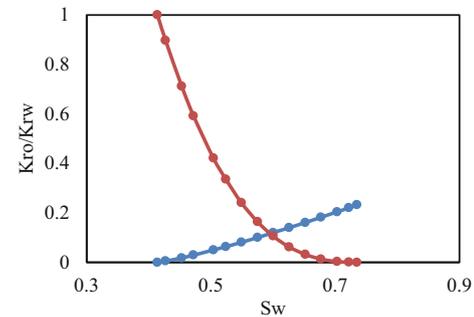
**Fig. 2** Permeability model for injecting into thick layers and producing from thin ones



**Fig. 4** Porosity model for injecting into thick layers and producing from thin ones



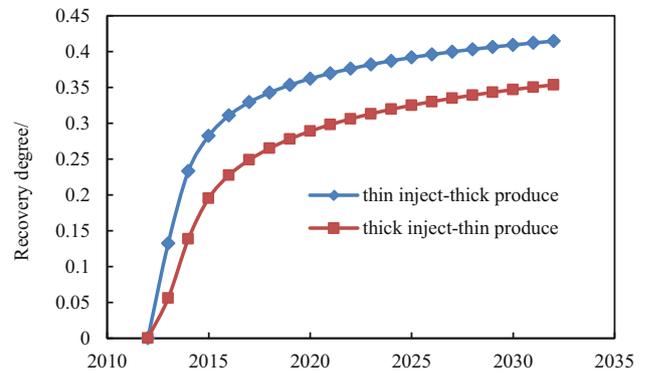
**Fig. 3** Porosity model for injecting into thin layers and producing from thick ones



**Fig. 5** Permeability saturation curve

production reservoirs should be higher than that of the thick injection and thin production reservoir (Figs. 6, 7, 8). When water is injected from a high-permeability zone with a greater thickness, the displacement effect is much less than from a poor-permeability zone with a smaller thickness. Due to the pressure consumption mainly near injection wells, the thin injection and thick production type can provide an effective production of thin and poor reservoir. Concurrently, it slows down injected water breakthrough in the high-permeability thick oil layer and expands the swept volume.

It can be seen that plane heterogeneity has a great influence on recovery of different types of reservoir. And based on the above research results, the thin injection and thick production type is the best way to produce a thin and poor reservoir.



**Fig. 6** Recovery degree of different injection/production types in heterogeneous 2D formation

### The influence of well pattern and spacing

#### Methods

##### Effective producing coefficient

These thin and poor reservoirs within the Block Xing6 consist of low permeability, and in order to have fluid flow

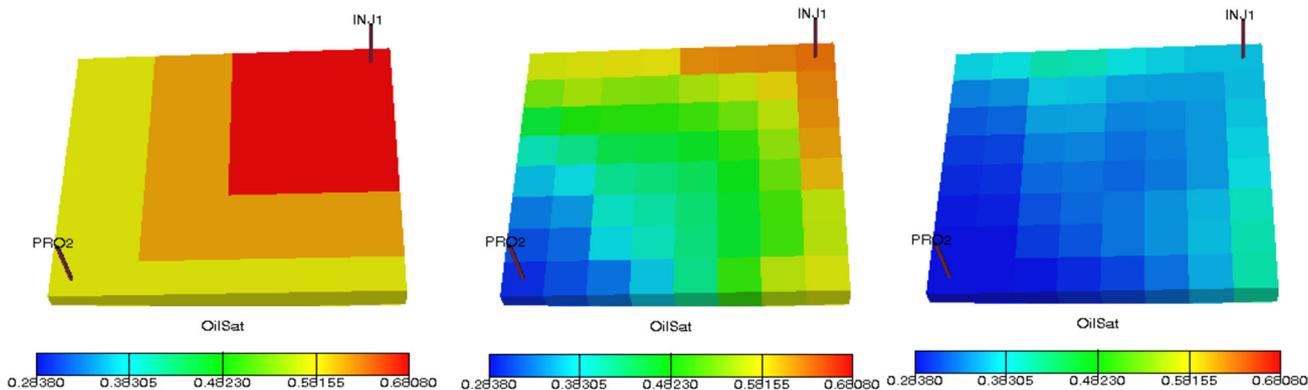


Fig. 7 Oil saturation charts for injecting into thin layers and producing from thick ones

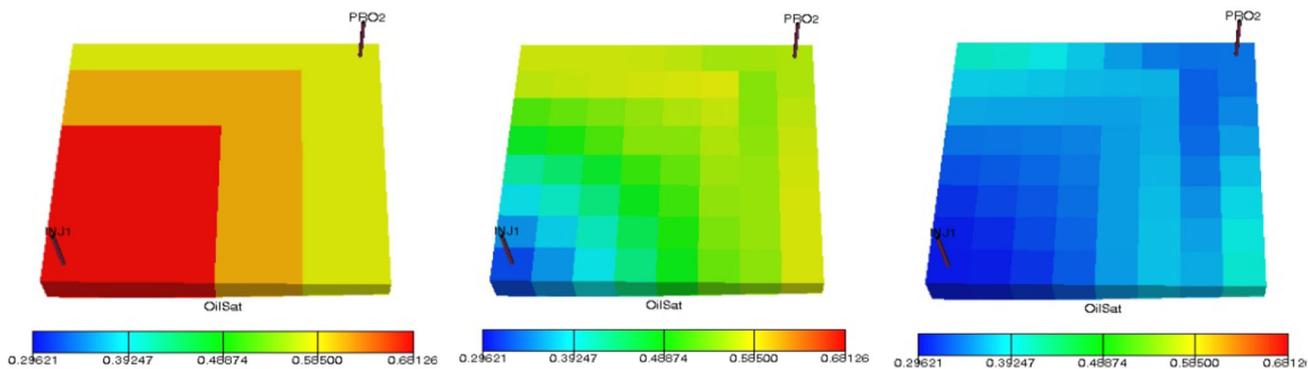


Fig. 8 Oil saturation charts for injecting into thick layers and producing from thin ones

within the formation, it requires a start-up pressure gradient, and percolation appears to be non-Darcy flow. Because of this low permeability, previous calculations have been based on Darcy filtration theory and conditions do not meet the engineering calculation of a target reservoir. It is necessary to use formulas with start-up pressure gradient to describe the fluid flow curves. The relationship between the threshold pressure gradient and permeability is shown in Fig. 9. We use flow tube integral method to compute the effective producing coefficient.

We define the effective producing coefficient as the ratio of the start-up area to the entire unit area (Liang et al. 2014). It is assumed there are a series of flow pipes between oil wells and water injection wells, which is shown in Fig. 10. The stream model is used to deduce the effective producing coefficient calculation formula of the five-spot square pattern, seven-spot, nine-spot and rhombus five-spot pattern.

$$\text{five-spot pattern } A_5 = \frac{2 \sin \alpha_0 \sin \beta_0}{\sin(\alpha_0 + \beta_0)} \tag{1}$$

$$\text{seven-spot square pattern } A_7 = \frac{4 \sin \alpha_0 \sin \beta_0}{\sqrt{3} \sin(\alpha_0 + \beta_0)} \tag{2}$$

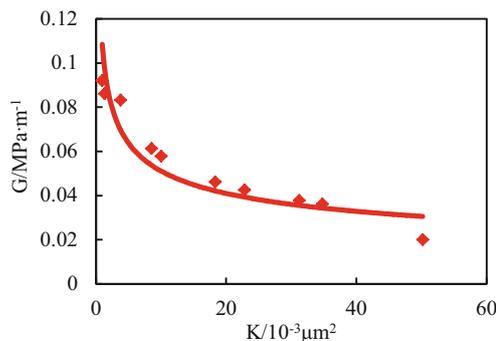


Fig. 9 Relationship between threshold pressure gradient and permeability

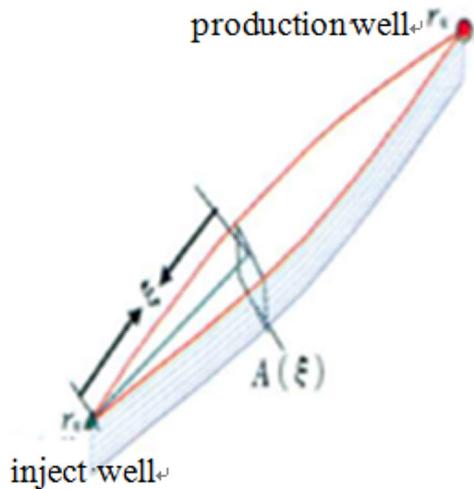
nine-spot square pattern

$$A_9 = \frac{\sin \alpha_1 \sin \beta_1}{\sin(\alpha_1 + \beta_1)} + \frac{2 \sin \alpha_2 \sin \beta_2}{\sin(\alpha_2 + \beta_2)} \tag{3}$$

rhombus five-spot pattern

$$A_{5'} = \frac{L_1^2 \sin \alpha_1 \sin \beta_1 + L_2^2 \sin \alpha_2 \sin \beta_2}{L_1 L_2 \sin(\alpha_1 + \beta_1) \sin(\alpha_2 + \beta_2)} \tag{4}$$

In the equation,  $A$ —effective producing coefficient;  $L_1$ —well spacing, m;  $L_2$ —row spacing, m;  $\alpha_0$ —maximum injection well angle, (°);  $\beta_0$ —maximum production well



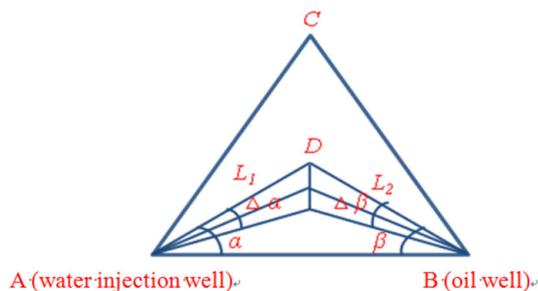
**Fig. 10** Diagram of stream tube

angle, (°);  $\alpha_1, \alpha_2, \beta_1$  and  $\beta_2$ —start angle of the injection/production unit, (°).

*Areal sweep efficiency*

The areal sweep efficiency is the ratio of the reservoir volume spread due to the flooding agent to the total volume of reservoir. It includes the vertical conformance factor and plane conformance factor. Based on the stream model in Fig. 8, it uses a flow tube infinitesimal between water well and oil well as shown in Fig. 11.

The formula for the area sweep efficiency is complicated, particularly when calculating the maximum areal sweep efficiency under different injection pressures. In order to calculate the area sweep efficiency more intuitively, simply and quickly, the three factors, namely pressure difference, well spacing and area sweep efficiency, were analyzed by multiple regression. A simple and convenient mathematical model of area sweep efficiency  $E_A$  can then be obtained, as shown in Formula (7).  $E_A$  is a dimensionless value, the unit of  $\Delta p$  is MPa, and the well spacing  $L$  is m. Therefore, dimensionless analysis of  $\Delta p$  and  $L$  is carried out. The obtained dimensionless injection/



**Fig. 11** Computing unit of the five-spot pattern

production pressure difference and dimensionless injection/production well spacing are as follows:

$$\Delta p_D = \frac{Kh}{1.842 \times 10^{-3} q \mu B} \Delta p \tag{5}$$

$$L_D = \frac{L}{r_w} \tag{6}$$

The obtained injection/production pressure difference, well spacing and area sweep efficiency data are analyzed by multiple regression, and a binary function with the form  $E_A = f(\Delta p, L)$  was determined as follows. The fitting precision is 0.9825.

$$E_A = -7.38211\Delta p_D^2 + 2.85363 \times 10^{-7}L_D^2 + 12.02459\Delta p_D - 0.00236L_D + 0.66537 \tag{7}$$

In the formula,  $\Delta p_D$ —dimensionless injection/production pressure difference and  $L_D$ —dimensionless injection/production well spacing.

**Results**

*The influence of well pattern*

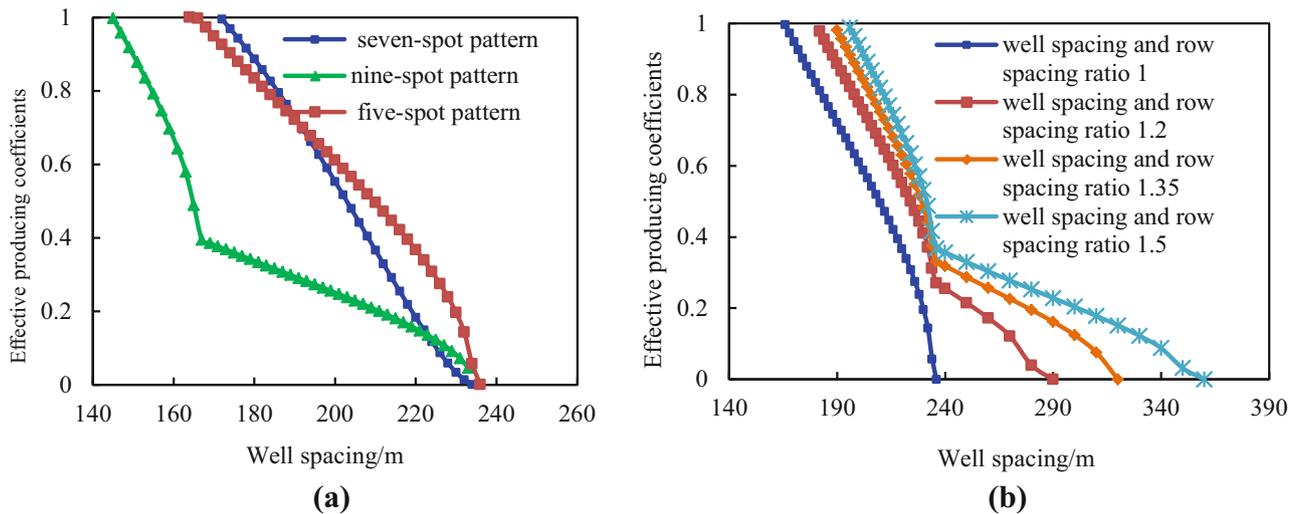
According to Fig. 9, the relationship between the threshold pressure gradient and permeability curves and the relationship between starting pressure gradient and permeability can be obtained by:

$$\lambda = 0.1064K^{-0.318} \tag{8}$$

In the equation,  $\lambda$ —threshold pressure gradient and  $k$ —permeability.

Taking the effective permeability of these thin and poor layers as  $5 \times 10^{-3} \mu m^2$ , a starting pressure gradient can be calculated using Formula (8). The value was calculated to be 0.064 MPa/m, and the injection/production pressure difference was 15 MPa. The effective producing coefficients compared to the well spacing for the three different configurations (five-spot, seven-spot and nine-spot patterns) are shown in Fig. 12.

Different well patterns and well spacing correspond to different producing coefficients, which illustrates that different pattern configurations have great influence on the development. The producing coefficient increases with a decrease in well spacing, indicating that reducing the well spacing may improve the reservoir development effect (Fig. 12a). The maximum producing well spacing of five-spot, seven-spot and nine-spot pattern is similar. Namely when the well spacing is greater than 236 m, the effective producing coefficient reaches 0, and the reservoir cannot be produced. When the well spacing is greater than 190 m but less than 236 m, and under the same well spacing, the five-



**Fig. 12** Well spacing compared to the calculated effective producing coefficients for three different well-spot patterns (a) and for various well spacing and row spacing ratios (b)

spot pattern is the best and effective producing coefficient reaches 0.7. The second best placement pattern is the seven-spot pattern, while the nine-point method is relatively poor.

When the well spacing is between 170 and 190 m, the seven-spot pattern is the best, followed by the five-spot pattern, while nine-spot pattern is relatively poor. When the ratio of space between wells and rows is 1, effective producing coefficient result of rhombus five-spot pattern is the same as that of five-spot square pattern. This also shows the derived producing coefficient calculation formula of the rhombus five-spot pattern is correct, which considers the effects of injection/production well spacing and row spacing.

It can be obtained from the curve of different well pattern, well spacing and effective producing coefficient of the rhombus five-spot pattern. The rhombus five-spot pattern is divided into two computational units to calculate the effective producing coefficient, the well spacing calculation unit and row spacing calculation unit. It shows two stages in Fig. 12b. The initial steep slope of the well spacing 168–236 m has an excessive influence on the effective producing coefficient. With these relatively small well spacing (<236m), the main factor that the influence displacement effect is the injection/production well spacing. When the injection/production well spacing is larger, the effective producing coefficient is smaller, and the displacement effect is much less. The curve of different well patterns, well spacing and effective producing coefficient appears at the inflection point when injection/production well spacing is 236 m. It can be seen that the shape of the curve has obviously changed; the small slope shows that the row spacing has greater influence on the effective

producing coefficient. The calculating unit in this stage is only the row spacing calculation unit, and the influencing factor is only the row spacing. When the row spacing is large (>236 m), the well/row spacing ratio is smaller, the effective producing coefficient is smaller, and the displacement effect is worse. With increasing the well/row spacing ratio, the range of ultimate injection/production well spacing of the effective producing expanded. Overall, the thin and poor reservoir must choose a reasonable well pattern to develop efficient and reasonable. The best well pattern of thin and poor reservoir is the five-spot pattern.

*The influence of well spacing*

Tertiary infill wells in Block Xing6 are for Saertu and Putaohua (poor) layers and mainly exploit the untabulated reservoir (when the effective thickness is less than 0.2 m). Average value of the effective permeability is typically taken as  $5 \times 10^{-3} \mu\text{m}^2$ , and the corresponding starting pressure gradient is 0.064 MPa/m. The relationship between the effective producing coefficient and the well spacing was calculated, and the relationship curve between effective producing coefficient and the well spacing under different injection/production pressure differences was obtained from formula (1) (Fig. 13).

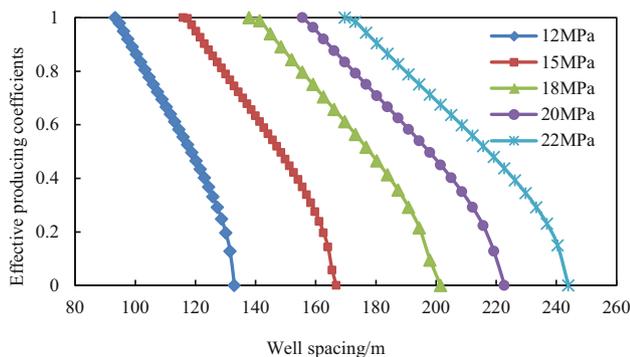
With the same permeability, the reservoir starting pressure gradient is the same, with the injection/production pressure difference gradually increasing and the sensitivity of well spacing to effective producing coefficient gradually decreasing (Fig. 13). This illustrates that when the injection/production pressure difference is small, through the adjustment of wells spacing, the effective producing coefficient can be improved significantly. That is, when the

injection/production pressure difference is small, reducing the well spacing is an effective way to improve the effective producing coefficient. Under the same pressure difference, the well spacing inversely relates to the effective producing coefficient. When effective producing coefficient is 0, the well spacing is the limit spacing. The limit spacing under different pressure differences in the Block Xing6 was also obtained (Table 1). When the effective producing coefficient is 1, the well spacing is the minimal well spacing.

According to above simplified model (Eq. 7), the relationship between the injection/production well spacing and area sweep efficiency under different injection/production pressure differences was calculated and is plotted in Fig. 14.

Through the above calculation, the injection/production well spacing range of different injection/production pressure differences under different permeabilities was determined and compared to the calculation result of effective producing coefficient method, as given in Table 1.

In view of the above analysis, combined with the current injection/production pressure difference 20.32 MPa, a reasonable spacing should be between 156 and 228 m.



**Fig. 13** Effective producing coefficient of different injection/production pressure

**Table 1** Well spacing calculated by two methods

Injection/production pressure difference/MPa	Effective producing coefficient method		Area sweep efficiency method		Average value	
	Minimal well spacing/m	Maximum well spacing/m	Minimal well spacing/m	Maximum well spacing/m	Minimal well spacing/m	Maximum well spacing/m
12	93	133	95	137	94	135
15	116	167	118	173	117	170
18	138	202	140	214	139	208
20	156	223	156	232	156	228
22	170	244	171	254	171	249

### Oilfield Example Validation

An oil layer with an effective thickness greater than 0.5 m is called a thick oil layer. According to the geological conditions, the developmental characteristics of the whole Block and injection/production type will be divided into thick injection and thin production type, and thin injection and thick production type. Within the Block, seven ideal injection and production groups were selected, with injection wells as the center wells, to obtain the influence of injection/production types on development through analyzing the relationship between the injection/production type and reservoir producing degree (Fig. 15).

With the ratio of thin injection and thick production increasing, the water absorption thickness ratio also shows a rising trend, indicating a corresponding relationship. Under the condition of equivalent injection rate for every well group, the end of injection of the thin injection and thick production well group needed relatively higher injection pressure compared to thick injection and thin production. Because the pores and pore throats of these thin and poor oil layers are narrow and the fluid needs a certain start pressure to flow, the external pressure needs to be greater than the threshold pressure. This higher pressure is beneficial for reservoir development. Therefore, increasing the pressure of the injection end for thin injection and thick production type wells group is equal to enlarging the production pressure difference between the oil and water wells. This is beneficial for development of the thin and poor oil layers. The injection end of the thick injection and thin production type well group easily forms a high-permeability zone, which makes it difficult to improve the injection pressure of the reservoir; therefore, the low-permeability reservoirs are difficult to produce.

Table 2 shows that the producing degree of thin and poor layers in Block Xing 6 dong is relatively higher, mainly because the well spacing and row spacing are smaller and the producing degree is only 21.5% which is not particularly ideal. The pressure difference of the Block Nanzhongxi is higher, but the well spacing and row spacing

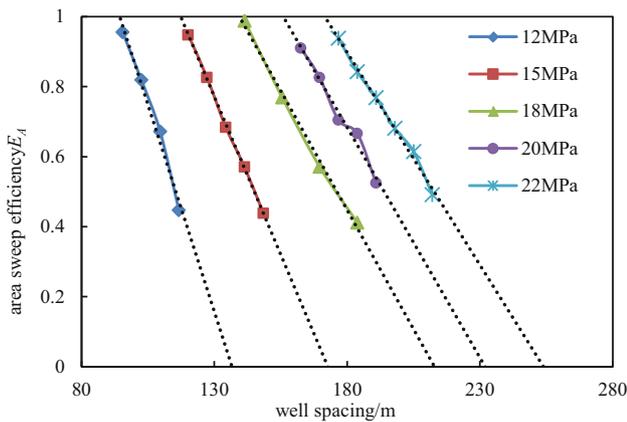


Fig. 14 Curves of well spacing and areal sweep efficiency in thin and poor layer

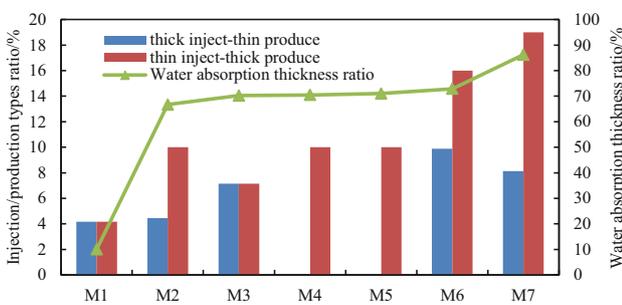


Fig. 15 Relationship between injection/production types “thick inject–thin produce, thin inject–thick produce” ratio and water absorption thickness ratio

are also larger. Therefore, the effective producing coefficient is 0.65, area sweep efficiency is 0.79, and the producing degree is only 13%. The Block Nan4xi, due to higher permeability, and smaller well spacing than Block Bei2xi, has a higher degree of producing than the Block Bei2xi.

In summary, for the thin and poor layers (permeability  $<50 \times 10^{-3} \mu\text{m}^2$ ), reasonable well spacing should be within 200 m. If outside of this range, even with amplification in the pressure difference, the effective producing coefficient and area sweep efficiency are still relatively low. Meanwhile, there is a good correlation between the effective producing coefficient, the area sweep efficiency

and producing degree. Also, it was proved that effective producing coefficient formula and area sweep efficiency formula are deduced.

### Conclusion

This paper has designed two numerical models according to the geological conditions and physical parameters, discussed the influence of injection/production type on development effect for thin and poor reservoirs and put forward two methods to evaluate producing degree. The two methods are effective producing coefficient and areal sweep efficiency, then use the methods to analyze the influence of well pattern and spacing on producing degree of thin and poor layers. The following suggestions and conclusions can be made:

1. The intersection angle of the main stream line (the ligature between the injection well and producing well) and physical property distribution is about  $45^\circ$ . If injection well is in the high-permeability zone, the preferential seepage channel maybe formed easily. The percolating resistance cannot form and the injected water cannot enter the low-permeability zone, resulting in a small water flooding area and low recovery. The oilfield example also verified the most effective injection/production pattern is injecting into a thin layer and production from the thick layer.
2. Effective producing coefficient formula is obtained according to stream tube model by reservoir engineering method, and the relationship curve between different wells spacing and effective producing coefficient is also obtained. Results show that the well spacing is greater than 190 m but less than 236 m, and under the same well spacing, the five-spot pattern is the best and effective producing coefficient reaches 0.7. The second best placement pattern is the seven-spot pattern, while the nine-point method is relatively poor. When the well spacing is between 170 and 190 m, under the same well spacing, the seven-spot pattern is the best, followed by the five-spot pattern, while nine-spot pattern is relatively poor. Rhombus

Table 2 Effective producing coefficient and area sweep efficiency for several thin and poor Blocks

Block	Series of strata	Permeability/ $10^{-3} \mu\text{m}^2$	Pressure difference/MPa	Well spacing/m	Rows spacing/m	Effective producing coefficient	Area sweep efficiency	Producing degree/%
Bei2xi	PII, GI	37	20	300	250	0.63	0.72	10
Nan4xi	SIII, PII, GI	45	20	250	250	0.70	0.82	15
Nanzhongxi	SI, GI, GII	30	25	300	300	0.65	0.79	13
Xing6dong	S + P (poor layers)	20	20	141	141	0.72	0.88	21.5

five-spot pattern is divided into two computational units to calculate the effective producing coefficient, the well spacing calculation unit and row spacing calculation unit. With increasing the well/row spacing ratio, the range of ultimate injection/production well spacing of the effective producing expanded. The different pattern configuration has significant influence on development effect, and the thin and poor reservoir must choose suitable well pattern and well spacing to reach reasonable and efficient development.

- Effective producing coefficient and areal sweep efficiency of several thin and poor Blocks in Daqing Oilfield are calculated by the above methods. Effective producing coefficient and areal sweep efficiency is 0 and the well spacing is limit spacing, and the effective producing coefficient and areal sweep efficiency is 1 and the well spacing is minimal well spacing. Compared with the reservoir parameters and producing degree, it was found that from the actual oilfield parameters for the thin and poor layers (permeability  $<50 \times 10^{-3} \mu\text{m}^2$ ), reasonable well spacing should be within 200 m, and more than this range, even with the pressure difference amplification, the effective producing coefficient and area sweep efficiency are still relatively low.

## Description

Thick injection and thin production refers to inject into thick oil layer and product from thin oil layer.

Thin injection and thick production refers to inject into thin oil layer and product from thick oil layer.

Untabulated reservoir refers to reserves which physical properties are relatively poor and not included in proven reserves calculation table several years ago in Daqing Oilfield, whose effective thickness is zero ( $<0.2$  m).

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