A Novel Method to Evaluate the Well Pattern Infilling Potential for Water-Flooding Reservoirs

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Abstract. Well pattern infilling is a form of productivity construction in old oil fields. The economy of new drillings determines the infilling feasibility and the increased quantity of recoverable reserves. Therefore, a new potential evaluation method for well pattern infilling is proposed, which considers the well pattern infilling as productivity construction project while taking the economic standard as feasible criterion for infilling. Firstly, the rules and main factors for increasing the recoverable reserves of new drilling wells are analyzed. Secondly, infilling wells with different scales are considered as a series of productivity construction projects, for which the oil production curves and the parameters of economic evaluation are determined. Thirdly, the economy of these projects is evaluated under different oil prices, and the scale of drilling and increasing recoverable reservoir is optimized according to the evaluation results under the given economic standard. On that basis, a relationship is established. The new method has been shown to be more practical, accurate, and suitable for strategic planning research and oil reservoir management work.

Keywords: Water-flooding reservoir · Well pattern infilling · Economic evaluation · Development potential

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Nomenclatures

E_R	recovery factor, %
E_D	displacement efficiency, %
f	well density, wells/km^2
b	well pattern coefficient
E_{Rf}	recovery factor of the well pattern with the well density of f, %
E_{Rcw}	recovery factor in the case of the current well density, %
f_{cw}	current well density, wells/km^2
$\boldsymbol{N}$	oil initially in place, 100,000,000 tons
$\boldsymbol{S}$	oil-bearing area, km^2
$q(f_i)$	the initial daily production per well in the case of the production capacity building project sequence i, *t/d*
r_n	injector/producer ratio, dimensionless
n	total quantity of wells
C_r	production capacity contribution ratio, %
A_r	production realization rate, %
D_j	decline rate, %
NPV	net present value, RMB yuan
IRR	internal rate of return, %
i_c	benchmark yield, %
i	sequence number of the production capacity building project
j	production lifecycle of the project, year

1 Introduction

Infilling drilling is a frequently used potential tapping method to increase the recoverable hydrocarbon initially in place and enhance the recovery factor of old oil fields. By infilling the well pattern, the oil initially in place (OIIP) controlled and recovered by water flooding is promoted, and so is the recovery factor [1]. However, as the well pattern is seen with narrowing spacing (growing well density), the well interference and inter-layer interference are strengthened, which leads to decline in the production of an individual well and meanwhile great increase in the investment. This can heavily impact the production and revenue of the oil field. Moreover, no notable variation in the recovery factor occurs, with the well density exceeding a certain value. Given the aforementioned, the economic limit of the well density has attracted tremendous attention. The well density economic limit and appropriate well density are often calculated in a way combining the Sherkachov formula and input–output balance principle [2–6]. It is well known that well patter infilling is a method used in the production stimulation of mature blocks. Strict technical and economic evaluation is preferred, given the current development situation of the oil field. To this end, a technical and economic evaluation approach was proposed. The approach in question targets the well pattern filling used for production stimulation and uses the economic index as the feasibility determination index for the infilling drilling project. This approach can provide strategic research-level accuracy, take oil prices and economic feasibility-relevant factors into consideration, and produce rapid assessment.

2 Method to Evaluate Technically Recoverable Reserve Gains Triggered by Well Pattern Infilling

The main concept of this method can be concluded as using the typical classified oil reservoir unit to represent the specific block and calculating the production variation of the newly gain production capacity contributed by the well pattern infilling and the growth in the recoverable OIIP, on the basis of effects of well interference on the production capacity of new wells and the treatment of injection wells.

2.1 Method to Determine the Appraisal Unit

The potential appraisal for all oil field blocks of the company or even the whole country is the essence of the strategic planning research, which is challenged by the excessive quantity of the oil field block, the overwhelming evaluation workload, and the incomplete data of some block. Conventional methods are found incompetent in such works, and in general, the task is accomplished by summarizing the appraisal result submitted by each local company. Taking an oil company in China as an example, it has 14 oil districts (local companies), including over 300 oil fields. There are totally over 1000 units, of which over 900 are exploited using water flooding. It is clear that extreme difficulties will be encountered if these blocks are evaluated one after another. Under such circumstances, this paper proposed an appropriate appraisal unit classification method, with respect to the data accuracy required by the strategic research. According to the principle that the reservoir geological characteristic should comply with the development characteristic, the water-flooding oil blocks in each oil district are classified in terms of their permeability, namely medium-high-permeability ($K \geq 50$), low-permeability ($10 \leq k < 50$), extra-low-permeability ($1 \leq k < 10$), ultra-low-permeability ($k < 1$), and tight oil reservoirs. Then, the average recovery factor of each block type is used as the standard, according to which the oil reservoir is further divided into the above-average and equal-to-or-below-average sub-types. Through the above classification, the aforementioned over 900 appraisal units are represented by only 140 analogous units, which tremendously decreases the appraisal workload and meanwhile maintains the data accuracy desirable for strategic planning.

2.2 Method to Determine the Early-Stage Daily Per-Well Production

The initial daily production per well of new wells is determined by the average per-well daily production of this type of blocks. Then, the daily production of an individual new well declines, with the increasing quantity of the infill well, which arouses the need to clarify the regularity behind the effect of the well interference induced by new wells on the per-well production. By taking the natural logarithms on both sides of the Shelkashov equation [1] (Eq. 1), Eq. (2) can be obtained:

$$E_{\mathrm{R}} = E_{\mathrm{D}} e^{-b/f} \tag{1}$$

$$\ln E_{\mathrm{R}} = \ln E_{\mathrm{D}} - b \cdot \frac{1}{f} \tag{2}$$

In Eq. (2), the recovery factor of the current well pattern ER, the displacement efficiency ED, and the well density f for each type of oil reservoir units are all known. By fitting in accordance with Eq. (2), the slope of the straight line, namely the well pattern coefficient b for this specific type of reservoir units, can be calculated. It can also be calculated using the following equation:

$$b = f \ln \frac{E_{\mathrm{D}}}{E_{\mathrm{R}}} \tag{3}$$

After substituting b back into Eq. (1), then the gain of the recoverable OIIP for an individual new well can be estimated using Eq. (4):

$$\Delta N_{well}(f) = \frac{(E_{Rf} - E_{Rcw}) \cdot N}{(f - f_{cw}) \cdot S} \tag{4}$$

The per-well recoverable OIIP increment for new wells is the summation of the per-well production. The growth of the quantity of wells stimulates the well interference, decreases the per-well production, and consequently impacts the per-well recoverable OIIP gain. Therefore, the variation of the per-well production can be calculated according to the change in the recoverable OIIP increment of an individual well, as is shown in Eq. (5):

$$q(f_i) = q(f_{i-1}) \cdot \left[1 - \frac{\Delta N_{\mathrm{well}}(f_i)}{\Delta N_{\mathrm{well}i}(f_{i-1})}\right] \quad (i \geq 1) \tag{5}$$

2.3 Method to Calculate the Technically Recoverable OIIP Gain from New Wells

Well pattern infilling does not only involve drilling new oil production wells, but also water injection wells. These water injection wells are believed to make a certain contribution to oil production, although they do not directly produce any crude oil. The injection well can be regarded as a virtual production well, of which the oil production is quantified according to the injector/producer ratio.

Given that the well pattern infilling is implemented in a large-scale way involving the whole oil field, the layout of the injection and production wells are determined according to the well pattern. It is the general pattern that a production capacity building project contributes only part of the production in the year of the building process, reaches its maximum production rate in the next year, and starts to see production declines since the third year. Hence, the production rate can be calculated using Eq. (6):

$$Q = \begin{cases} 300 \times \left(\frac{r_n^2 \cdot n + n}{r_n + 1}\right) \cdot q(f_i) \cdot C_r & j = 0 \\ 300 \times \left(\frac{r_n^2 \cdot n + n}{r_n + 1}\right) \cdot q(f_i) \cdot A_r & j = 1 \\ 300 \times \left(\frac{r_n^2 \cdot n + n}{r_n + 1}\right) \cdot q(f_i) \cdot A_r \cdot D_j & j \geq 2 \end{cases} \quad (6)$$

In the case of the production lifecycle of 30 years, the produced oil can be expressed as:

$$N_r = 300 \times \left(\frac{r_n^2 \cdot n + n}{r_n + 1}\right) \cdot q(f_i) \cdot (C_r + A_r) + \sum_{i=2}^{i=30} \left(300 \times \left(\frac{r_n^2 \cdot n + n}{r_n + 1}\right) \cdot q(f_i) \cdot A_r \cdot D_j\right) \quad (7)$$

In this way, the correlation between the gain in the technically recoverable OIIP and the quantity of infill wells is established.

3 Method to Evaluate to the Economically Recoverable OIIP Gain from New Wells

The well pattern infilling is regarded as a production capacity building project and put through economic evaluation, in which a net present value (NPV) or the internal rate of return (IRR) is used as the evaluation indicators. A NPV above zero or IRR over the benchmark yield indicates that the well pattern infilling is economically feasible, and the recoverable OIIP is considered as the economically recoverable OIIP.

$$\mathrm{NPV} = \sum_{t=0}^{m} \mathrm{CI}_t (P/F, i_0, t) - \sum_{t=0}^{m} \mathrm{CO}_t (P/F, i_0, t) \quad (8)$$

$$\mathrm{NPV} > 0 \quad (9)$$

$$\mathrm{NPV}(\mathrm{IRR}) = \sum_{t=0}^{m} (\mathrm{CI} - \mathrm{CO})_t (1 + \mathrm{IRR})^{-t} = 0 \quad (10)$$

$$\mathrm{IRR} > i_c \quad (11)$$

The main workflow is as follows:

First, a production capacity building project sequence with varied infilling engineering scales is built, with increasing quantities of newly drilled wells, and the correlation between the well density and the technically recoverable OIIP gain is identified. The well density versus technically recoverable OIIP is shown in Fig. 1.

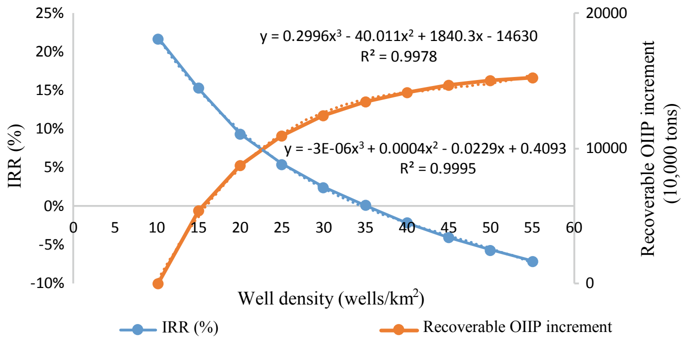

Fig. 1. Well density versus technically recoverable OIIP and IRR

Then, under scenarios of different oil prices, the economic feasibility of each infilling project is evaluated, and the correlation between the well density and the economic evaluation indicator under varied oil price circumstances is concluded (the well density vs. IRR is presented in Fig. 1). The economic evaluation cutoff is subsequently substituted into the found correlation, which determines the critical well density that makes the project just comply with the economic criterion in the case of a specific oil price.

Finally, the maximum economically applicable well density under different oil price scenarios is substituted into the correlation between the well density and the technically recoverable OIIP gain. The resultant economically recoverable OIIP under difference oil price scenarios is shown in Fig. 2.

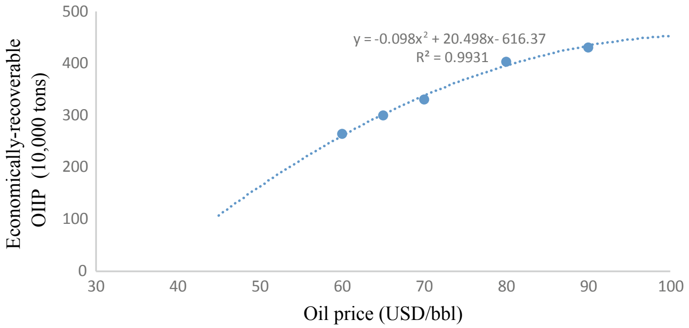

Fig. 2. Oil price versus economically recoverable OIIP increment

4 Case Study

An oil field in China totally has 244 blocks for appraisal. The OIIP reaches 3.55 billion tons, the current recovered degree is 7.6%, and the current recovery factor is 19.7%. Evaluating 244 blocks one by one requires a huge appraisal workload, and many economic and technical data are hard to access. Using the method described in Sect. 2.1, the 244 blocks are divided into 5 reservoir units (Table 1).

Table 1 Basic data for the oil field of China in question

Oil reservoir unit	Quantity of blocks	Producing area (km^2)	Producing OIIP (one billion tons)	Current well density (wells/km^2)	Current recovered Degree (%)	Current recovery Factor (%)
Medium-high-permeability	29	295.4	0.18	6.4	21.6	28.3
Low-permeability	56	1053	0.59	11.7	10.4	20.9
Extra-low-permeability	71	3533	1.82	10.2	7.7	19.6
Ultra-low-permeability	33	1685	0.86	7.9	3.0	18.6
Tight oil	55	230.8	0.10	4.0	2.1	11.5
Total	244	6797	3.55	9.5	7.6	19.7

Table 2 Economically recoverable OIIP with varied oil prices for the oil field of China in question

Appraisal unit	Oil price (USD/bbl)	60	65	70	80	90
Medium-high-permeability	Economically recoverable OIIP (10,000 tons)	264	300	331	404	432
	Quantity of new wells	351	692	1001	1846	2220
Low-permeability	Economically recoverable OIIP (10,000 tons)		72	516	2215	2758
	Quantity of new wells		218	1666	3636	7111
Extra-low-permeability	Economically recoverable OIIP (10,000 tons)		883	2093	3807	4711
	Quantity of new wells		993	6822	16,149	21,784
Ultra-low-permeability	Economically recoverable OIIP (10,000 tons)			290	722	1126
	Quantity of new wells			13	2979	6038
Tight oil	Economically recoverable OIIP (10,000 tons)				110	559
	Quantity of new wells				109	553
Total	Economically recoverable OIIP (10,000 tons)	264	1255	3250	7259	9587
	Quantity of new wells	351	1903	9523	24,718	37,706

The evaluation results of the quantity of newly drilled wells and corresponding potential recoverable OIIP growth of each type of oil reservoirs are shown in Table 2. One can also correlate the oil price with the economically recoverable OIIP increment by fitting the data presented in the table, and then, economically recoverable OIIP corresponding to oil prices not included in the table can be obtained.

5 Conclusions

A well pattern infilling potential evaluation method of developed oil fields applicable to strategic planning is proposed on the basis of the interaction between the production variation and the recoverable OIIP increment of the production capacity building project. By appropriately identifying the appraisal unit, this method significantly reduces the evaluation workload and eases the access to the evaluation data. The proposed method is more applicable to the practical situation of the well pattern infilling and also capable of providing data accuracy desirable for strategic planning. More importantly, this method sheds light upon the correlation between the economic feasibility of the well pattern infilling project and the oil price and economically recoverable OIIP and thus overcomes the difficulty for oil field operators to assess the infilling potential of water-flooding well pattern as well as the project economy.

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References

1. Yu Q. A method for calculating the reasonable and extreme well pattern density in water flooding sandstone reservoirs. Petrol Explor Dev. 1986;(04):49–54.
2. Zhang F, et al. How to identify rational and ultimate well spacing density for low permeability reservoir. Petrol Geol Oilfield Dev Daqing 2008;(02):88–90.
3. Liang S, et al. Well pattern calculation method based on economic limit in old oilfields using well spacing and well-controlled reserves. PGRE. 2014;21(4):104–6.
4. Wu Q. A new method for determining the rational well net density of water drive oil field. Petrol Geol Eng. 2012;26(06):71–3, 147.
5. Zhu W. Determination of economic limit for well pattern density of oilfield. Fault-Block Oil Gas Field. 2008;(04):66–67, 75.
6. Huang J. A new method of economic limit well pattern density calculation in oilfields. Petrol Geol Recovery Effi. 2013;20(03):53–5, 59, 114–5.