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Well placement optimization for offshore oilfield based on Theil index and differential evolution algorithm

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Abstract Proper well placement should match the heterogeneity of reservoir and development schedule, in which case the displacement is balanced. A balanced displacement process can achieve a good development performance of reservoir. Present parameters to evaluate the displacement balanced degree are not fit for high water-cut oilfields and need a specific reservoir simulator. In this work, a well placement optimization method for offshore oilfield is established. A displacement balanced degree evaluation method is proposed based on Theil index. By using minimum Theil index as the objective function, well placement optimization model for offshore oilfield is built. In this model, constraints about the available infilling scope and minimum inter-well distance are considered to find the realizable optimal location. This optimization model is solved by a derivative-free optimization algorithm, differential evolution algorithm. This method is applied and validated in a semisynthetic offshore oilfield to find optimal well locations. Results demonstrate that this proposed method can find the optimal well placement for offshore oilfield to achieve a more balanced displacement and a higher oil recovery.

Keywords Well placement · Optimization model · Offshore oilfield · Theil index · Differential evolution algorithm

List of symbols

c_{r}	Rock compressibility
CR	Crossover probability
D	Problem dimension
Dis	Inter-well distance
f	Objective function in DE algorithm
F	Mutation factor
g_k	Total number of injector–producer lines in the *k*th injection–production group
H	Vertical distance between the wellhead tower and the top surface of reservoir
i	*i*th injector–producer line
j	*j*th optimized well
k	*k*th injection–production group
K	Total number of injection–production groups
L_i	Length of *i*th injector–producer line
max	Maximum
min	Minimum
N	Total number of injector–producer lines
N_k	Number of injector–producer lines in the *k*th injection–production group
NP	Population size in DE algorithm
p	*p*th vector $\mathbf{x}$ in DE algorithm
q	Component number
q_{rand}	A random integer
t	Iteration step
T	Theil index
T_{b}	Displacement balanced degree between injection–production groups
T_{w}	Displacement inequality degree within injection–production groups
U	Uniformly distributed random number sample
$\mathbf{v}$	Mutation vector
$\mathbf{x}$	Target vector
x_i	Oil saturation at *i*th injector–producer line

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x_{h}	Coordinates of heel position
x_t	Coordinates of toe position
$\mathbf{x}_{r1}^{t}$	Chosen vector at iteration t
$\mathbf{x}_{r2}^{t}$	Chosen vector at iteration t
$\mathbf{x}_{r3}^{t}$	Chosen vector at iteration t
X_i	The equivalent oil saturation of ith injector–producer line
X_k	Total oil saturation of the kth injection–production group
$\overline{X}$	Average equivalent oil saturation of all injector–producer lines
y_{h}	Coordinates of heel position
y_{t}	Coordinates of toe position
$\mathbf{y}$	Trial vector
Y_k	Total oil saturation in the reservoir
z_{h}	Coordinates of heel position
z_t	Coordinates of toe position
μ_{o}	Oil viscosity
μ_w	Water viscosity
ρ_{o}	Oil density
ρ_{w}	Water density
ϕ	Porosity

Introduction

Determining the optimal well placement plays an important role in the oilfield development (Humphries and Haynes 2015; Arinkoola et al. 2015; Dossary and Nasrabadi 2016; Chen et al. 2017a; Ogbeiwi et al. 2017). A proper well placement can yield a balanced displacement and large financial return (Siavashi et al. 2016; Awotunde and Naranjo 2014; Ogbeiwi et al. 2017). And a balanced displacement process can achieve a good development performance of reservoir (Zhou et al. 2017). However, due to the heterogeneity of reservoir and fluid property, the displacement is often unbalanced. Many parameters are used to measure the displacement balanced degree. Li et al. (2006) determined the well placement according to the water breakthrough time in each injection–production line. They adjusted the well placement to make well placement match with the geological vector. Zhou et al. (2017) proposed a well placement optimization method to realize maximum equilibrium displacement. In their method, displacement balanced degree was measured by the variance of the water breakthrough time. Siavashi et al. (2016) established a well placement optimization method to achieve the distribution of streamline be more uniform. The objective function was constructed by the coefficient of variance of streamline number and time of flight to measure the displacement balanced degree. This method made sure that most regions of the reservoir could be swept. Jesmani et al. (2016) analyzed the optimal well placement according to the time of flight. The optimal well locations in their research could obtain an even time of flight in each injection–production line. However, most waterflooding oilfields have entered into high water-cut stage and many producers have seen the water. The water breakthrough time is not fit for high water-cut oilfields. Besides, time of flight can be obtained by the specific reservoir simulator which would limit its application to a certain degree. The average oil saturation of injection–production group can reflect the displacement degree (Feng et al. 2016; Chen et al. 2017a). It can be used in any development stage of oilfield. And most reservoir simulator can obtain the oil saturation during simulating process. Therefore, in this work oil saturation is used to reflect the displacement degree of each injection–production region. The distribution of remaining oil in the reservoir can reflect the displacement balanced degree. For the whole reservoir, the displacement balanced degree depends on the displacement balanced degree between injection–production groups and within injection–production groups. However, the evaluation methods in current researches cannot provide the comprehensive evaluation. Theil index is widely used to describe the inequality characteristic (Alcantara and Duro 2004; Padilla and Serrano 2006; Clarke-Sather et al. 2011). It describes the total amount of inequality in a distribution by the extent of inequality within groups and between them (Padilla and Serrano 2006). Given the same evaluation range, Theil index can effectively evaluate the displacement balanced degree of the oilfield. To the best of our knowledge, Theil index has not been applied in the evaluation of displacement balanced degree.

Well placement optimization problem is usually complex, nonconvex and multimodal (Awotunde and Naranjo 2014; Wang et al. 2016). In order to solve well placement optimization problem, both gradient-based and derivative-free optimization algorithms are applied (Yeten et al. 2002; Bangerth et al. 2006; Taware et al. 2012; Bouzarkouna et al. 2012; Nwankwor et al. 2013; Awotunde 2014; Isebor et al. 2014; Humphries and Haynes 2015; Carosio et al. 2015; Khademi and Karimaghaee 2016; Bagheri and Masihi 2016), such as finite difference gradient (FDC), simultaneous perturbation stochastic approximation (SPSA), genetic algorithm (GA), particle swarm optimization (PSO) algorithm, covariance matrix adaptation evolution strategy (CMA-ES) algorithm and differential evolution (DE) algorithm. Due to the simple metaheuristic mechanism, DE algorithm has shown good performance in solving the real parameter optimization problem and global optimization problem (Carosio et al. 2015). It has been used to deal with well placement optimization problem in many researches (Awotunde 2014; Carosio et al. 2015). In this paper, we apply DE algorithm to solve the well placement optimization problem in offshore oilfield.

This paper establishes a well placement optimization method for offshore oilfield based on Theil index and differential evolution algorithm. Firstly, the evaluation method of displacement balanced degree is proposed based on Theil index, which can provide a detailed evaluation of displacement balanced degree in the whole reservoir, within injector–producer well groups and between them. Then, well placement optimization model for offshore oilfield is established to realize the maximum equilibrium displacement, which uses minimum Theil index as the objective function and is solved by DE algorithm. Finally, we apply this well placement optimization method to find optimal locations of infilling wells in a semisynthetic offshore oilfield. This paper can provide an well placement optimization method for offshore oilfield to realize the balanced displacement.

Methodology

In order to find the optimal well placement for offshore oilfield to realize the balanced displacement, three basic elements are needed: (1) displacement balanced degree evaluation method; (2) well placement optimization model; and (3) optimization algorithm. In this section, we apply Theil index to evaluate the displacement balanced degree. Then, given the characteristics of offshore oilfield, we establish the well placement optimization model. To deal with this discontinuous and multilocal optimums optimization problem, a derivative-free optimization, differential evolution (DE) algorithm, is used to solve the problem.

Displacement balanced degree evaluation based on Theil index

Theil index is an efficient inequality evaluation index. It can provide a detailed description of inequality within groups and between them (Alcantara and Duro 2004; Padilla and Serrano 2006; Clarke-Sather et al. 2011). The displacement unbalanced degree of the whole reservoir can be decomposed into two synthetic components, i.e., within injection–production groups component and between injection–production groups component. Based on Theil index, the displacement balanced degree evaluation method is built.

The displacement balanced degree of the whole reservoir can be defined as follows:

$$T = \frac{1}{N}\sum_{i=1}^{N}\frac{X_i}{\overline{X}}\ln\frac{X_i}{\overline{X}} \tag{1}$$

where T is the Theil index denoting the displacement balanced degree of the whole reservoir; N is the total number of injector–producer lines; X_i is the equivalent oil saturation of ith injector–producer line; and $\overline{X}$ denotes average equivalent oil saturation of all injector–producer lines. Because water flooding performance is mainly influenced by the parameters on mainstream line (Zhou et al. 2017; Chen et al. 2017b), we use oil saturation in injector–producer line to reflect the displacement process. Because oil saturation is not a constant along the injector–producer line, the equivalent oil saturation of each injector–producer line X_i is calculated by:

$$X_i = \frac{1}{L_i}\int_{l} x_i(x,y)\mathrm{d}x_i \tag{2}$$

where L_i is the length of ith injector–producer line; $x_i(x,y)$ is the oil saturation at (x,y) of ith injector–producer line.

The displacement balanced degree of the whole water flooding reservoir can be decomposed into between injection–production groups and within injection–production groups as follows:

$$T = T_\mathrm{b} + T_\mathrm{w} \tag{3}$$

where T_b represents the displacement balanced degree between injection–production groups; T_w denotes the displacement inequality degree within injection–production groups.

T_b is calculated as:

$$T_\mathrm{b} = \sum_{k=1}^{K}\frac{X_k}{Y_k}\ln\frac{X_k/Y_k}{N_k/N} \tag{4}$$

where K is the total number of injection–production group; X_k is the total oil saturation of the kth injection–production group; Y_k is the total oil saturation in the reservoir; and N_k is the number of injector–producer lines in the kth injection–production group.

T_w is calculated as:

$$T_\mathrm{w} = \sum_{k=1}^{K}\frac{X_k}{Y_k}\left(\sum_{i\in g_k}^{N_k}\frac{X_i}{X_k}\ln\frac{X_i/X_k}{1/N_k}\right) \tag{5}$$

where g_k is the total number of injector–producer lines in the kth injection–production group.

Therefore, parameters T, T_b and T_w can provide a detailed description of displacement balanced degree in the whole reservoir, within injector–producer well groups and between them.

Optimization model based on Theil index

The range of Theil index is from zero to one. When the displacement of the reservoir is absolutely balanced, in which case all injector–producer line's oil saturations are equal, Theil index attains its minimum (zero). One represents that the displacement is extremely unbalanced. The objective of well placement optimization is to realize maximum equilibrium displacement (Zhou et al. 2017). Therefore, the objective function of well placement optimization model is the minimum difference of injector–producer lines' oil saturations which can be formulated as:

$$\min T = \frac{1}{N}\sum_{i=1}^{N}\frac{X_i}{\overline{\overline{X}}}\ln\frac{X_i}{\overline{\overline{X}}} \tag{6}$$

The optimization variables are the well placement. Wells are drilled from wellhead tower in offshore oilfield (Marir et al. 2015), and they are usually in a cluster type (Cao et al. 2016). For this kind of well, the available infilling scope is determined by the wellhead tower. If we do not take this constraint into account, the optimized well may be unrealized in offshore oilfield development. Besides, many wells are drilled from a same wellhead tower in offshore oilfield for cluster well group. The inter-well distance should not be too small in which case wellbore anti-collision could occur. Therefore, constraints about available infilling scope and minimum inter-well distance should be considered in well placement optimization for offshore oilfield.

Six parameters (x_h, y_h, z_h, x_t, y_t and z_t) are usually used to describe the well location in three-dimensional reservoir. x_h, y_h and z_h are the coordinates of heel position, and x_t, y_t and z_t are the coordinates of toe position. The constraint of available infilling scope can be given as:

$$\begin{cases} x_{\min} \le x_\mathrm{h} \le x_{\max} \\ y_{\min} \le y_\mathrm{h} \le y_{\max} \\ z_{\min} \le z_\mathrm{h} \le z_{\max} \\ x_{\min} \le x_\mathrm{t} \le x_{\max} \\ y_{\min} \le y_\mathrm{t} \le y_{\max} \\ z_{\min} \le z_\mathrm{t} \le z_{\max} \end{cases} \tag{7}$$

where $x_{\min}$, $y_{\min}$, $z_{\min}$ and $x_{\max}$, $y_{\max}$, $z_{\max}$ are the minimum and maximum boundary of available infilling scope.

Minimum inter-well distance constraint has been studied in many researches (Awotunde and Naranjo 2014; Jesmani et al. 2016; Zhang et al. 2017). According to the minimum distance between two line segments, the minimum inter-well distance $\mathrm{Dis}_\mathrm{well}$ can be obtained. Therefore, the constraint of minimum inter-well distance can be formulated as:

$$\mathrm{Dis}_\mathrm{well} \ge \mathrm{Dis}_{\min} \tag{8}$$

where $\mathrm{Dis}_{\min}$ is the minimum inter-well distance.

Therefore, the well placement optimization problem for offshore oilfield can be stated as: determining the optimal well placement to realize the maximum equilibrium displacement, i.e., minimize the difference of injector–producer lines' oil saturations denoted by Theil index objective function, subjected to available infilling scope and minimum inter-well distance. It can be formulated as:

$$\min T = \frac{1}{N}\sum_{i=1}^{N}\frac{X_i}{\overline{\overline{X}}}\ln\frac{X_i}{\overline{\overline{X}}} \tag{9a}$$

subject to

$$\begin{cases} x_{\min} \le x_\mathrm{h} \le x_{\max} \\ y_{\min} \le y_\mathrm{h} \le y_{\max} \\ z_{\min} \le z_\mathrm{h} \le z_{\max} \\ x_{\min} \le x_\mathrm{t} \le x_{\max} \\ y_{\min} \le y_\mathrm{t} \le y_{\max} \\ z_{\min} \le z_\mathrm{t} \le z_{\max} \\ \mathrm{Dis}_{\mathrm{well}j} \ge \mathrm{Dis}_{\min} \end{cases} \tag{9b}$$

For the offshore oilfield which the infilling well pattern is known, the well placement optimization can be simplified to only having the constraint of infilling well scope.

Optimization algorithm

In this research, DE algorithm is applied to solve the well placement optimization problem. DE algorithm outperforms many other optimization algorithms because of its excellent performance in convergence speed and robustness (Huang et al. 2006). Several papers have applied DE to solve optimization problems including well placement optimization and well control optimization (Carosio et al. 2015). Therefore, we use DE algorithm to optimize the well placement.

DE algorithm is an evolutionary algorithm with the iterative process of mutation, crossover and selection operators (Carosio et al. 2015). A population of *D*-dimensional vectors inside the problem bounds is generated as the initial population firstly. The objection functions for all the vectors are evaluated, and some candidate solutions are maintained at each generation. Besides, some candidates are chosen to create new candidates. The optimization process stops until a stopping condition is satisfied.

In DE evaluation strategy, the each vector $\mathbf{x}_p$ in a population *NP* is used to generate mutation vector $\mathbf{v}_p$ by mutation operator. Three vectors are randomly selected for the population to generate the mutation vector $\mathbf{v}_p$ at iteration t which is calculated by (Nwankwor et al. 2013).

$$\mathbf{v}_p^{t+1} = \mathbf{x}_{r1}^t + F\left(\mathbf{x}_{r1}^t - \mathbf{x}_{r3}^t\right) \tag{10}$$

where $\mathbf{x}_{r1}^t$, $\mathbf{x}_{r2}^t$ and $\mathbf{x}_{r3}^t$ are three chosen vectors at iteration t; F is the mutation factor with the range of 0–2. This process is called mutation.

Then, the trial vector $\mathbf{y}_{p,q}^{t+1}$ is calculated according to the target vector $\mathbf{x}_{p,q}^t$ and the mutation vector $\mathbf{x}_{p.q}^{t+1}$ by crossover operator (Carosio et al. 2015):

$$\mathbf{y}_{p,q}^{t+1} = \begin{cases} \mathbf{v}_{p,q}^{t+1}, & \text{if } U(0,1) \le CR \text{ or } q = q_{\text{rand}} \\ \mathbf{x}_{p,q}^{t}, & \text{if } U(0,1) > CR \text{ or } q \ne q_{\text{rand}} \end{cases} \tag{11}$$

where $q \in \{1, 2, \ldots, \mathrm{NP}\}$; $U(0,1)$ is a uniformly distributed random number sample between 0 and 1; CR is the crossover probability between 0 and 1; q_{rand} is a random integer from 0 to NP.

The vectors for the next iteration $t + 1$ are generated by comparing the target vector $\mathbf{x}_{p,q}^t$ with the trial vector $\mathbf{y}_{p.q}^{t+1}$. If the objective value of trial vector $\mathbf{y}_{p.q}^{t+1}$ is bigger than objective value of trial vector $\mathbf{x}_{p,q}^t$, trial vector $\mathbf{y}_{p.q}^{t+1}$ will replace the trial vector $\mathbf{x}_{p,q}^t$. Otherwise, the $\mathbf{x}_{p,q}^t$ will be maintained in the next iteration. This process is conducted by selection operator:

$$\mathbf{x}_{p,q}^{t+1} = \begin{cases} \mathbf{y}_{p,q}^{t+1}, & \text{if } f\left(\mathbf{y}_{p,q}^{t+1}\right) \le f\left(\mathbf{x}_{p,q}^{t}\right) \\ \mathbf{x}_{p,q}^{t}, & \text{if } f\left(\mathbf{y}_{p,q}^{t+1}\right) > f\left(\mathbf{x}_{p,q}^{t}\right) \end{cases} \tag{12}$$

where f is the objective function; $\mathbf{x}_{p.q}^{t+1}$ is the vector for iteration $t + 1$.

During the well placement optimization process, a reservoir numerical simulator ECLIPSE 100 (GeoQuest 2010) is used to calculate the remaining oil distribution under different well placements. ECLIPSE 100 is a full-implicit black oil simulator. It can calculate the remaining oil and development indexes by inputting the reservoir parameters and well placements. We use MATLAB software (MATLAB 2013) to perform the DE algorithm optimization process and apply ECLIPSE software to calculate the objective function. The flow diagram for well placement optimization based on Theil index and DE algorithm in offshore oilfield can be seen in Fig. 1.

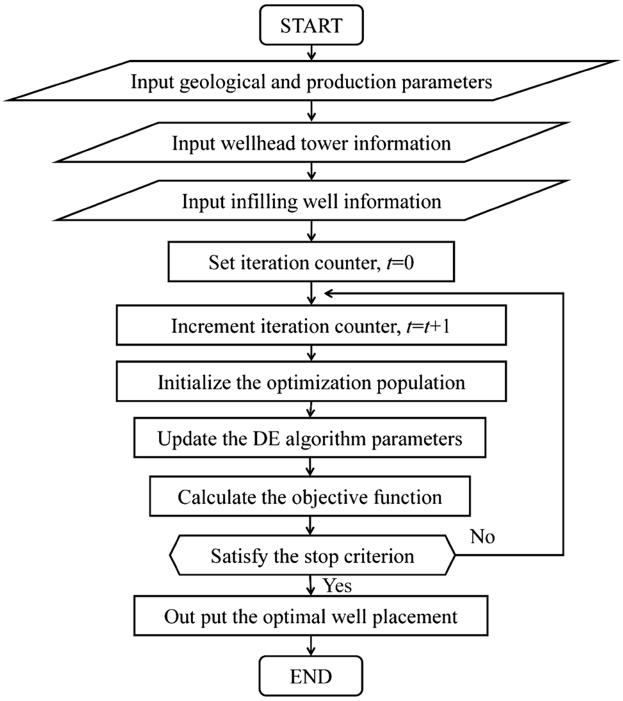


Fig. 1 Flowchart of well placement optimization based on Theil index and DE algorithm

Results and discussion

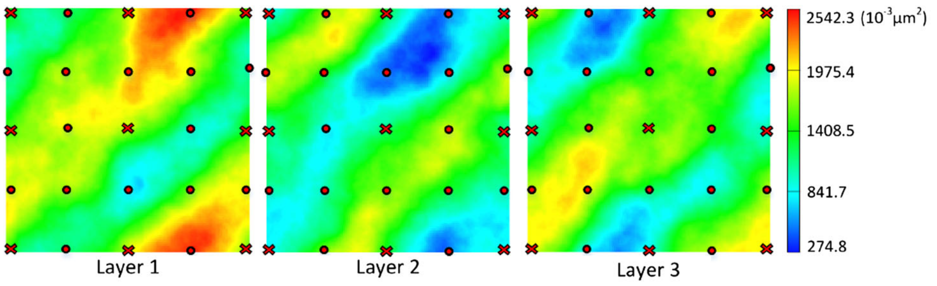
In this work, the well placement for offshore oilfield is optimized based on Theil index and DE algorithm to realize maximum equilibrium displacement. A semisynthetic offshore oilfield model is applied in this section.

It is a three-dimensional two-phase reservoir model. There are a total of 140 × 140 × 3 uniform grid blocks, and the reservoir is 1400 × 1400 × 30 m^3. The permeability distribution of each layer is shown in Fig. 2a. There are 4 regular inverted nine-spot patterns with 16 producers and 9 injectors. The position of each well can be seen in Fig. 2. They are controlled by constant liquid production rate and constant injection rate, respectively. We assume this reservoir has been developed for a certain time, and the present oil saturation distribution is shown in Fig. 2b. Other data of the reservoir model are listed in Table 1. The oil and water relative permeability curves are plotted in Fig. 3. And the capacity pressure is ignored.

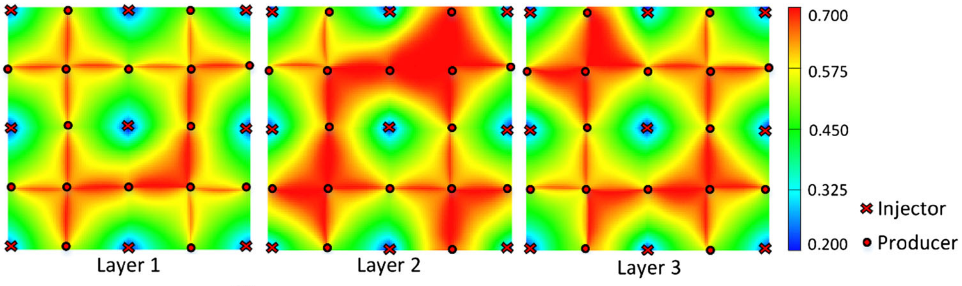
As shown in Fig. 3b, remaining oil is mainly distributed between the producers. In order to extract more oil and improve the development performance, infilling wells are needed to be drilled. For the offshore oilfield with inverted nine-spot pattern, the successful infilling pattern is to convert the producer which locates between injectors to injector and the infilling producers are drilled between producers. This sketch of infilling pattern can be seen in Fig. 4. Therefore, 8 infilling producers are drilled in this case. We suppose all wells in this case are vertical wells. These infilling producers are controlled by a constant liquid production rate of 160 m^3/day. The reservoir produces 7200 days from now on.

The locations of infilling wells are determined by two methods. One is the regular infilling method. For this

Fig. 2 Permeability and present oil saturation distribution



(a) Permeability distribution



(b) Present oil saturation distribution

Table 1 Reservoir conditions and rock and fluid properties

Parameter	Symbol	Value
Porosity	ϕ	0.3
Oil viscosity	μ_o	0.005 Pa·s
Water viscosity	μ_w	0.001 Pa·s
Oil density	ρ_o	0.947 g/m^3
Water density	ρ_w	0.998 g/m^3
Rock compressibility	c_r	5×10^{-4} MPa^{-1}

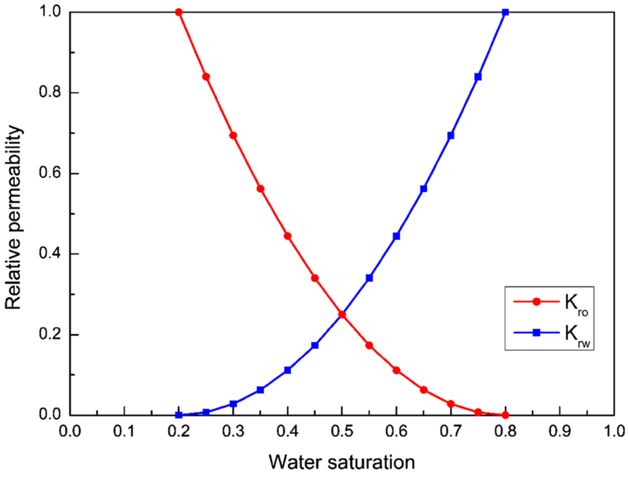


Fig. 3 Oil and water relative permeability curve

method, infilling wells locate in the middle of the producers. The other method is the optimization method. Locations of these infilling wells are optimized by the

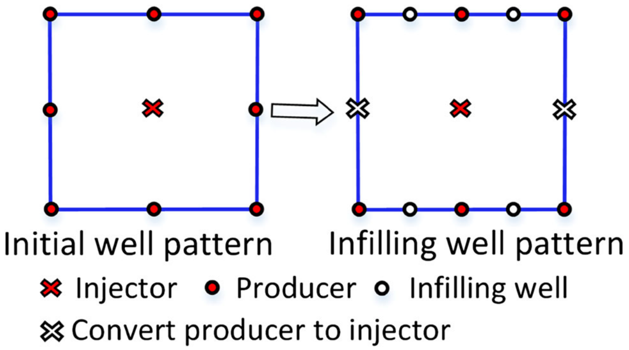


Fig. 4 Sketch of infilling pattern in inverted nine-spot pattern

proposed optimization method in this work. The coordinates of wellhead tower in *x*–*y* plane are (70, 70), and the vertical distance between the wellhead tower and the top surface of reservoir is 1000 m. The maximum angle of the line between the wellhead tower and the maximum infilling scope making with the vertical plane is $\pi/4$. And the minimum inter-well distance is 80 m. According to the infilling pattern of this case, locations of infilling wells can be optimized only considering the infilling scope constraint. For this method, the parameters of DE algorithm are listed in Table 2. The problem dimension (*D*) is 16. The number of population (NP) we set is 50. The mutation factor (*F*) is equal to 0.5, and the crossover probability (CR) is 0.9. The total number of iterations is 30. In order to overcome the stochastic property of DE algorithm, 10 runs are performed. Figure 5 shows the convergence progress of the proposed optimization method over 10 runs.

Figures 6 and 7, respectively, show the locations of infilling wells and oil saturation distribution after

Table 2 DE algorithm parameters

D	NP	*F*	CR	Iterations
16	50	0.5	0.9	30

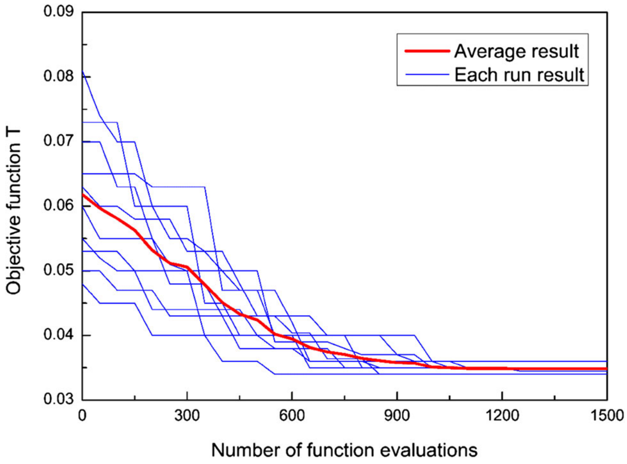


Fig. 5 Convergence curve for all ten runs versus number of simulations

7200 days for two infilling methods. The displacement balanced degrees under the regular infilling method and the proposed optimization method are listed in Table 3. From Table 3, it can be observed that the displacement balanced degree of the whole reservoir and between injection–production groups is decreased by 14.29 and 20.00% after optimization, respectively. In comparison with the regular infilling method, the oil saturation distribution under the proposed optimization method is more balanced as shown in Figs. 6 and 7.

The well production performance comparison of the regular infilling method and the proposed optimization method is shown in Fig. 8. It illustrates that the cumulative oil production under the proposed optimization method can increase 4.3% cumulative oil production than the cumulative oil production under the regular infilling method. It validates that the proposed optimization method can effectively improve the offshore oilfield development performance.

Therefore, well placement optimization established in this work can find the optimal well placement to increase oil production. It can realize the displacement in water flooding reservoir be more balanced which improves the production performance.

Conclusions

1. A well placement optimization method for offshore oilfield has been established based on Theil index and

Fig. 6 Oil saturation distribution under regular infilling method

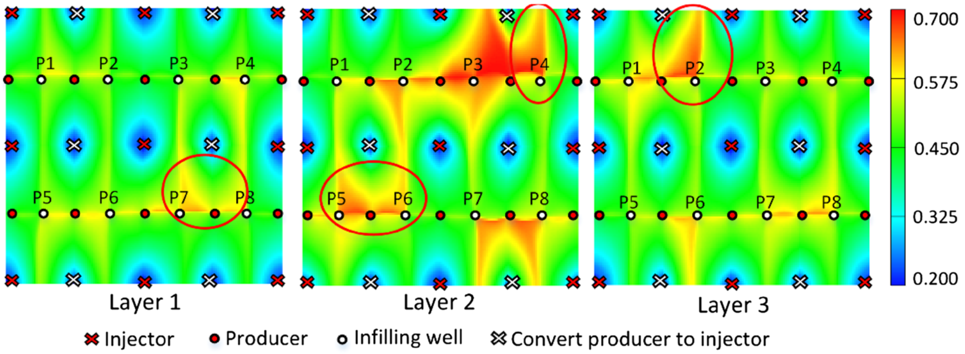


Fig. 7 Oil saturation distribution under proposed optimization method

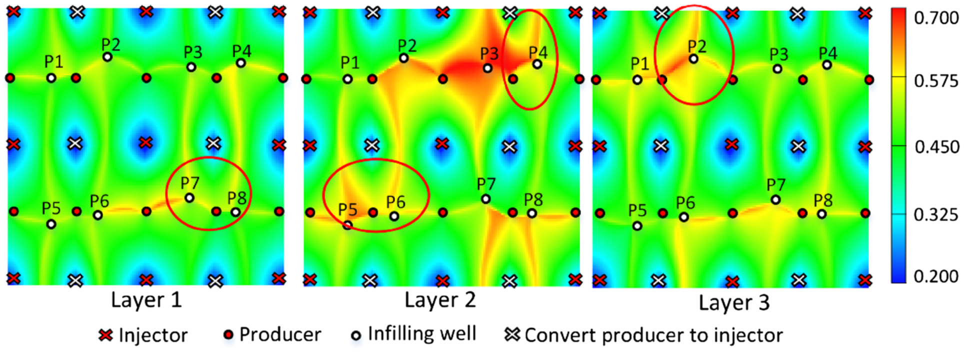


Table 3 Displacement balanced degree of different infilling method after 7200 days

Infilling method	T	T_b	T_w
Regular infilling method	0.0040	0.0030	0.0010
Proposed optimization method	0.0035	0.0024	0.0012

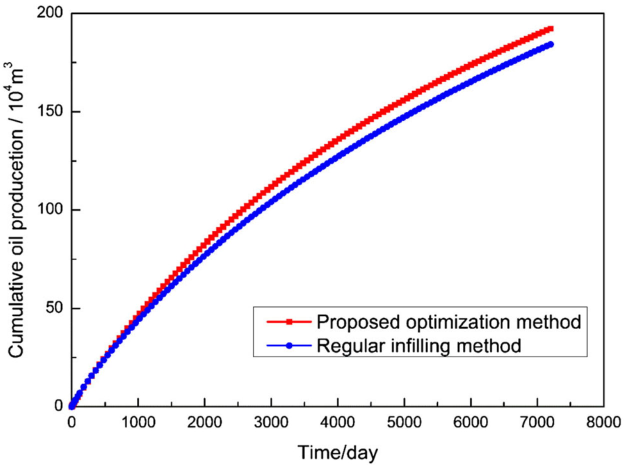


Fig. 8 Cumulative oil production comparison curve of different infilling method

differential evolution algorithm. The target of this method is to realize the maximum equilibrium displacement of the offshore oilfield.

2. A well placement optimization model for offshore oilfield is built. Minimum Theil index is used as the objective function to reflect the displacement balanced degree. Considering the characteristics of offshore oilfield, available infilling scope and minimum interwell distance have been taken into account during well placement optimization procedure. A derivative-free optimization algorithm, DE algorithm, is applied to solve this well placement optimization problem by being combined with a reservoir numerical simulator.
3. The locations of infilling wells in a semisynthetic offshore oilfield model are optimized by the established method. Results demonstrate that this method can find the optimal well placements to increase oil production. The displacement under the optimal well placements can be more balanced which can improve the production performance.

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