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Optimization method for three-dimensional intelligent equilibrium flooding in thin interbed reservoirs: A case study in P Oilfield, China

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ABSTRACT

Quick water breakthrough, rapid water cut rise, poor water flooding efficiency in single layer is common problem in most of thin interbed reservoirs. Finer injection-production strategy should be developed to avoid serious water channeling and ineffective water cycle. To narrow this gap, this work presents a three-dimensional intelligent equilibrium displacement model (3D-IEDM) to optimize water flooding in thin interbed reservoirs. The implementation in pilot B36 well group test of PL oilfield indicate that the optimization velocity of 3D-IEDM can optimize the vertical water injection profile of thin interbed reservoirs, and improve the sweep efficiency, and the length of time is approximately 14 times less than conventional simulator-based methods. Compared with the conventional injection-production scheme, the initial productivity of pilot well group using 3D-IEDM increases by 6.45 %, and the utilization factor of water injection improves by 15%.

Keywords: intelligent energy, equilibrium flooding, interbed reservoir, particle swarm optimization

NONMENCLATURE

Abbreviations	
PSO	Particle Swarm Optimization
Symbols	
Q_w	Water injection volume of water injection wells, m^3/d
Q_l	Production of production wells, m^3/d
Layer	Number of layers of the multi-layer reservoir
$s_{w,k}^n$	The water saturation of the kth injection-production well pair at the nth iteration step, %
k	k=1,2...N, is the number of independent variables

1. INTRODUCTION

Non-equilibrium flooding is common[1] in water flooding oil filed, especially for the reservoir with thin interbeded layers.

P Oilfield is the largest offshore oilfield in China, which consist of over 20 thin and thick interbeded layers in vertical. After over 20 years development with long well section combined injection and production, the water cut rise rapidly and leads to a large volume of oil left underground.

Although complete equilibrium displacement cannot be achieved in real reservoirs, extensive researches were conducted in recent years. Generally, two main methods are used in Former researches. One is adjusting a development plan during a high water cut with numerical simulations to achieve equilibrium displacement[2][3][4][5][6]. Because of large workload and work cycle in numerical simulation, some intelligence methods were developed to maintain oil production stabilized and reduce the water cut in recent years[5][7][8][9]. However, the adaptability of intelligence methods in thin interbedded reservoirs remains to be determined, and there are limited investigations on the

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influence of the three-dimensional flooding and the permeability damaged after long-time water flooding.

The purpose of this paper is to establish an intelligent equilibrium displacement optimization model based on the minimum variance of saturation between plane and vertical direction. Furthermore, one well pattern section of P oilfield is selected for verifying the feasibility and universality.

2. MATERIAL AND METHODS

In terms of optimization methods, the maximization of oil production was generally taken as theoptimization goal, but the final optimization results of this method was achieved by strong injection and strong production, which promoted the production of high-yield liquid wells and aggravated the ineffective water cycle. Therefore, this paper proposes the use of three-dimensional equilibrium as the optimization index, which is mathematically represented as shown in:

$$\mathrm{Min}[\sigma(\mathrm{S_w})] \tag{1}$$

The physical meaning of Eq. (1) refers to the minimum variance of saturation between injection-production well pairs. That is, attention is paid to the location of production potential in the process of equilibrium replacement to improve the efficiency of water injection utilization. For single-layer reservoirs to achieve plane equilibrium displacement, adjusting the development dynamics of production wells can minimize the saturation variance. Compared with plane equalization, the goal of stereoscopic equalization optimization for multi-layer reservoirs with separate injection and commingled production is to minimize the variance of saturation for all injection-production wells. The variables to be optimized are the single layer splitting component of water injection wells and the development performance of production wells. The distribution of injection-production well pairs is shown in Fig. 1.

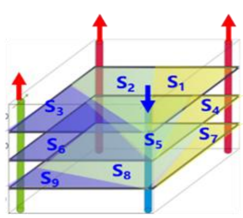


Fig. 1. Injection and recovery well pair distribution model of multi-layer reservoir

In multi-layer reservoirs, the water injection and liquid production of single well are the sum of layered injection and production, respectively. The water injection and the liquid production of a single well are expressed in equation (2) and equation (3). respectively. The saturation update equation of different flow units is shown in equation (4). In actual calculation, the number of injection-production well pairs are adjusted according to the plugging situation of layers.

$$Q_w = \sum_{l=1}^{Layer} I_w \tag{2}$$

$$Q_l = \sum_{l=1}^{Layer} q_l \tag{3}$$

$$s_{w,k}^{n+1} = s_{w,k}^{n} - \frac{F(s_w)}{F'(s_w)} \tag{4}$$

3. RESULT AND DISCUSSION

3.1 Numerical model

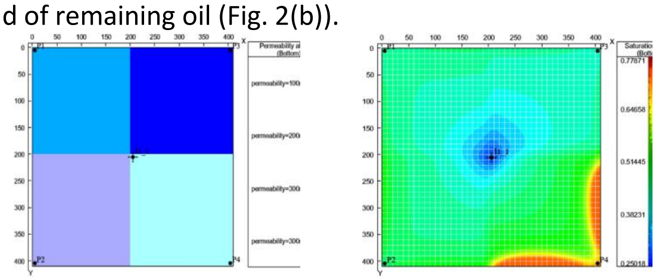
In order to verify the rationality of the three-dimensional equilibrium displacement design software, the numerical simulation method was adopted to test and analyze the software results.

The numerical model was established by commercial numerical simulation software, and the injection-production system adopted the mode of one injector and four producers. The basic parameter information is shown in Table 1.

Table 1 Basic parameter information of numerical model

Number of grids	41×41×1	Porosity (%)	25
Grid size (m^3)	10×10×2	Bottom hole flow pressure of water injection wells (MPa)	15
Viscosity(mPa·s)	10	Bottom hole flow pressure of production well (MPa)	10
Reservoir thickness (m)	10	Number of perforated well sections	25

According to the permeability distribution field (Fig. 2(a)), the permeability of oil producing wells P1, P2, P3 and P4 are 100mD, 200mD, 300mD and 300mD respectively. As the permeability was distributed in blocks, there was still remaining oil in the area with low permeability in this model according to the distribution field of remaining oil (Fig. 2(b)).



(a) (b)

Fig. 2. Basic information of numerical model. (a) Permeability distribution field; (b) Remaining oil distribution field in high water cut period

3.2 Optimization results of plane equilibrium displacement

For injection-production well pairs I-P1, I-P2, I-P3 and I-P4, the optimization model and numerical model were used to calculate the plane splitting ratio of injection wells and the saturation between wells pairs respectively. Additionally, the plane equilibrium displacement optimization was carried out on the established splitting model. The numerical model was established according to different schemes and had been operated for 1 year. The calculation results of the splitting model and numerical simulation are shown in Table 2.

Table 2 Calculation results between the optimization model and numerical model

Well pairs / Model comparison		I-P1	I-P2	I-P3	I-P4
Split proportion	Optimization model	33.13 %	18.43 %	43.35 %	5.09 %
	Numerical model	33.84 %	19.67 %	41.54 %	4.95 %
Saturation	Optimization model	0.54	0.53	0.56	0.47
	Numerical model	0.55	0.53	0.57	0.46

As can be seen from Table 2, the splitting proportion and saturation calculated by the optimization model are basically consistent with the numerical simulation results. Compared with the numerical simulation method, the calculation results were selected from the iterative process of the optimization model to further verify the accuracy of the model. The results are shown in Fig. 5.

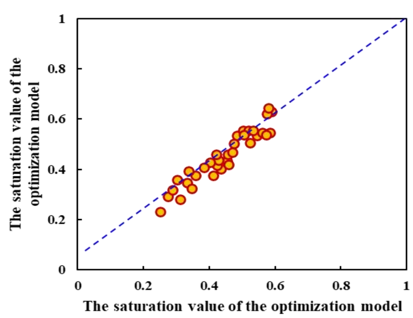


Fig. 3. Comparison of optimization model and numerical simulation results

In Fig.3.the abscissa represents the saturation value of the well pair calculated by the software, and the ordinate represents the numerical simulation result. It can be seen that the calculation results of the optimization model and the numerical model are basically close in different saturation ranges, with values mainly in the range of 0.2-0.6. The numerical model results further validate the accuracy of the splitting model in the software.

The improved particle swarm optimization algorithm was used to iterate 50 times, with 50 schemes in each iteration. As can be observed from the Fig. 4, the change range of the optimized value gradually becomes smaller and gradually approaches the optimal value with the increase of the iteration.

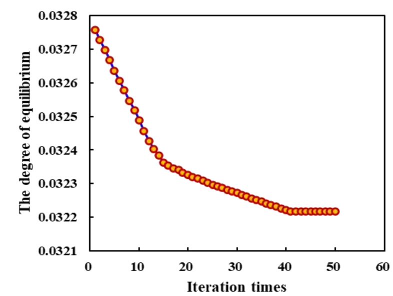
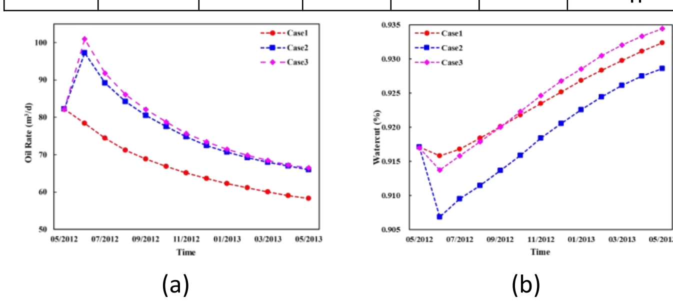


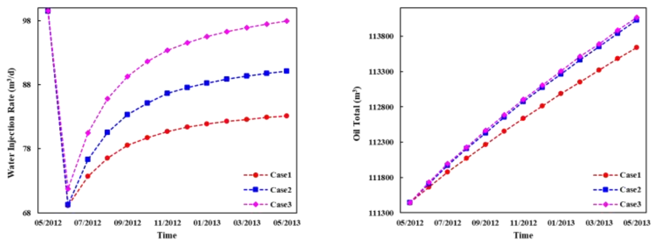
Fig. 4. The degree of equilibrium changes with the number of iterations

Three schemes were designed to demonstrate the rationality of optimization results using numerical model (Table 3).

Table 3. Working system of injection production wells in different schemes

Schemename	Water injection well pressure	Bottom hole flow pressure of production well				Scheme
		P1	P2	P3	P4	
Case1	15MPa	10MPa	10MPa	10MPa	10MPa	Original scheme
Case2	15MPa	9.31MPa	9MPa	9.91 MPa	9MPa	equilibrium displacement
Case3	15MPa	9MPa	9MPa	9MPa	9MPa	Maximum liquid production





(c) (d)

Fig. 5. Comparison of production dynamics of different schemes within one year. (a) Oil Rate; (b) Watercut; (c) Water Injection Rate; (d) Oil Total.

The numerical model was adopted to obtain the production dynamic curve of each scheme within one year (Fig. 5). Compared with the original scheme, the productivity of the equilibrium displacement scheme increased by 24.92 % in the first three months, the water cut decreased by 1.37 %, the water injection efficiency increased by 2.88 %, and the cumulative production increased by a total of 19.48% in one year. Compared with the maximum liquid production scheme, the two scenarios have similar production rates after six months of production, but the equilibrium drive scenario has a slow increase in water content and a 0.18% increase in water injection efficiency. After one year of development, the water content rate decreased by 0.95%, and the final production rate of both scenarios was only 1.19%. The numerical simulation results show that the equilibrium displacement scheme can maximize the use of injected water and improve economic efficiency. Grid saturation and variance were calculated for the three numerical models after one year. The comparison results are shown in Fig. 6.

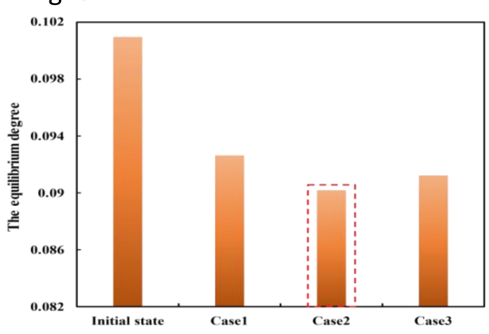
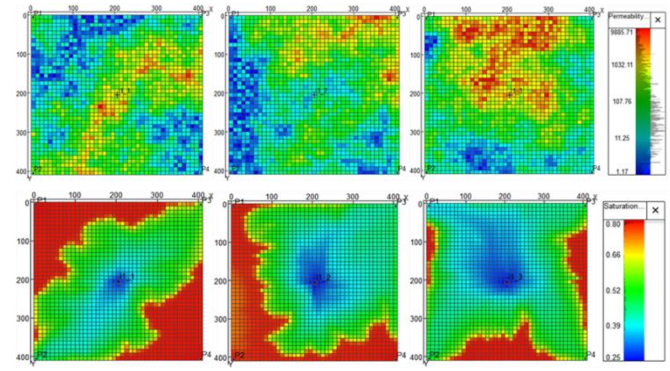


Fig. 6. Comparison of equilibrium degree of different schemes

3.3 Optimization results of stereoscopic equilibrium displacement

On the basis of single-layer model optimization, two layers were added to establish a multi-layer model to test the equilibrium displacement software. Different from the single-layer model, the variables to be adjusted in the multi-layer model include production rate of production wells and injection allocation of water injection wells. The basics of the multilayer model are shown in Fig. 7.



Layer1 Layer2 Layer3

Fig. 7. Basic information of the multi-layer model

Fig.7. shows the distribution of permeability and saturation in three different layers. It is worth noting that the third layer where P1 is located and the second layer where P3 is located have been flooded, and has less development potential. The development effects of different layers vary greatly during the combined injection development because of the serious heterogeneity of the reservoir. The comparison of development status of different layers is shown in Fig. 8.

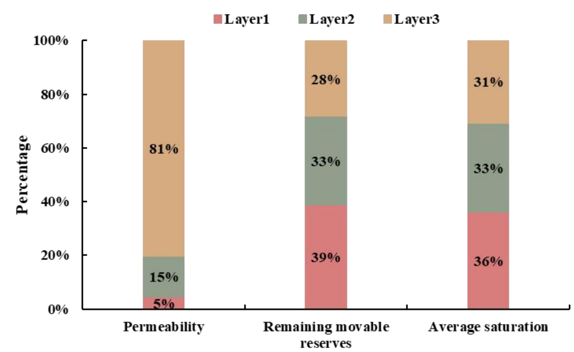
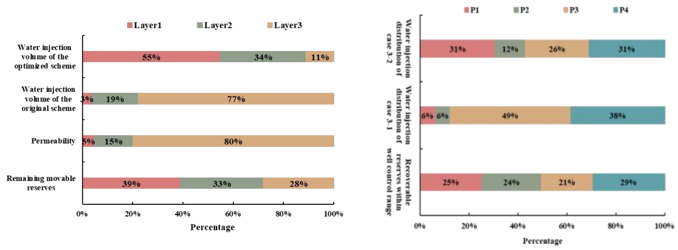


Fig. 8. Comparison of development status of different layers

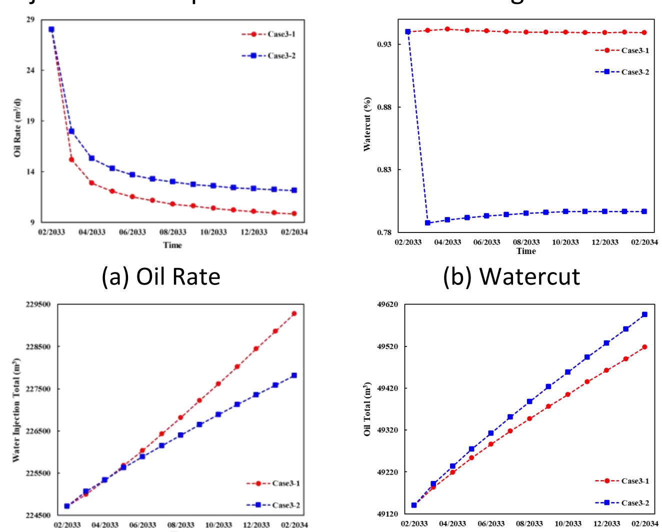
The proportion distribution of permeability, remaining movable reserves and average saturation of different layers are shown in Fig. 8. It can be seen from the figure that the three layers have strong interlayer heterogeneity. The current remaining reserves are mainly concentrated in the upper two layers. Combined with the distribution of remaining oil in the numerical model, the equilibrium displacement adjustment was mainly carried out for 10 injection-production well pairs. The adjustment results of injection wells are shown in Fig. 9.



(a) (b)

Fig. 9. Water injection distribution of different layers and different water injection wells. (a) Water injection splitting of different layers; (b) Water injection distribution of production wells in different schemes.

The comparison graph of the water injection distribution coefficients of each injection well in each layer of the equilibrium replacement scheme (Case 3-2) and the original scheme (Case 3-1) show that the original scheme distributes water injection according to the relative permeability values, while the equilibrium replacement scheme distributes water injection mainly by increasing the water injection in layers 1 and 2 (Fig. 9(a)). According to the distribution ratio of water injection of different production wells (Fig. 9.(b)), compared to the original scheme, the equilibrium displacement scheme improves the split ratio of water injection wells of the P1 and P2 wells, reduces the split ratio of water injection wells of the P3 well, and basically maintains the split ratio of the P4 well. The adjusted development effect is shown in Fig. 10.

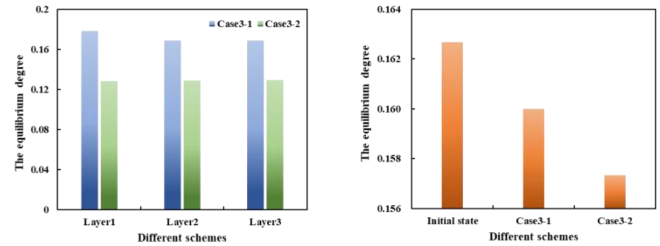


(a) Oil Rate (b) Watercut

(c) Water Injection Total (d) Oil Total

Fig. 10. Comparison of production dynamics in the next year for different schemes. (a) Oil Rate; (b) Watercut; (c) Water Injection Total; (d) Oil Total.

By the adjustment of the equilibrium scheme, the numerical model was used to predict the development effects of the two schemes within one year. From Fig. 10, the capacity of the equilibrium displacement scheme increased by 9.34 % in the first three months. Due to the closure of the high aquifer section, the water cut decreased by 15.31 %, the water injection utilization rate increased by 6.52 %, and the cumulative production within one year increased by 20.59 %. The equilibrium degree of the two schemes was calculated, and the results are shown in Fig. 11.



(a) (b)

Fig. 11. Comparison of grid saturation equilibrium degree for different schemes. (a) Comparison of equilibrium degree ofdifferent layers; (b) Comparison of overall equilibrium ofdifferent schemes.

It can be concluded that the equilibrium displacement optimization scheme has the same equilibrium degree in the three layers, and is superior to the original scheme(Fig. 11(a)). From the overall comparison diagram of the model (Fig. 11(b)), the equilibrium degree of the original scheme and the equilibrium displacement optimization scheme is better than that before the adjustment, and the equilibrium displacement optimization scheme is better than the original scheme.

3.4 Field application

After all, the software above was used to optimize the design of B36 well group in P oilfield, and the adjustment scheme of component layer injection allocation was designed to verified the effectiveness.

The well B36 was put into production in December 2010, and water was injected into 7 oil wells according to 7 sand layers. The well location distribution is depicted in Fig. 12.

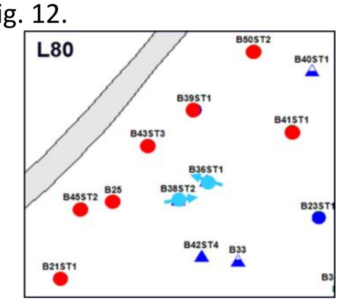


Fig. 12. B36 well group L80 layer well location distribution

According to the development dynamic analysis, a layered injection allocation adjustment scheme was formulated. The implementation plan is shown in Table 4.

Table 4. Adjustment scheme for layered injection allocation

Water injection layer	L54-L56	L60-L76	L82	L86-L90	L92-L96	L102	L104-L108
Water injection thickness (m)	11.2	21.1	7.6	11.8	7.5	9.7	9.9
Connected thickness (m)	10.7	18.6	9.6	7.6	4.8	7.0	2.5
Overpressure / under-pressure (MPa)	0.5	-1.0	1.0	-1.5	-2.5	1.5	-1.0
Water injection volume (m^3/d)	234.5	139.0	121.5	61.5	94.0	373.0	79.0
Injection allocation rate (m^3/d)	234.5	158.5	121.5	86.0	126.0	283.5	58.5
Water injection status	Maintain	Strengthen	Maintain	Strengthen	Strengthen	Limit	Limit

The layered injection allocation scheme increased the injection volumes of layers L60-L76, L86-L90, and L92-L96, and the adjusted daily oil production of 25 m^3/d of B41ST1, B39ST1, and B43ST3 arose. According to the reservoir physical properties and remaining oil distribution of each layer of the B36 well group, the software of stereo equilibrium displacement was used to optimize the design. Compared with the original injection allocation scheme, the injection allocation rates of different layers are shown in Fig. 13.

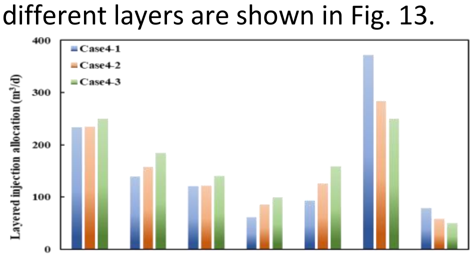


Fig. 13. Layered injection allocation of different schemes in the B36 well group

As described in Fig. 13, different schemes have different injection allocation in different layers, with less injection allocation in L86-L90 and more in L102. The equilibrium displacement scheme limits the water injection of the L102 layer with water channeling channel, and enhances the water injection of L86-L90 and L92-L96 layers with abundant remaining oil. The numerical model was constructed to simulate the original water injection scheme (Case4-1), the layered deployment scheme (Case4-2) and the equilibrium displacement scheme (Case4-3) for one year. The development effect of different schemes is displayed in Fig. 14.

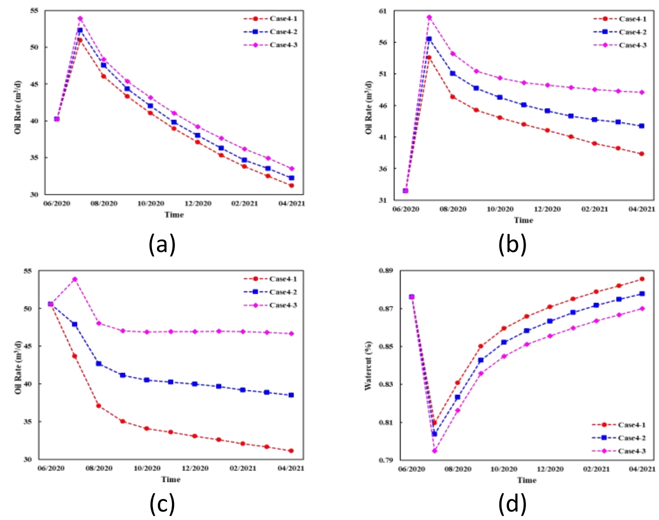


Fig. 14. Production performance of adjustment schemes for the B36 well group. (a) Oil Rate of Oil Well B41ST1; (b) Oil Rate of Oil Well B39ST1; (c) Oil Rate of Oil Well B43ST3; (d) Watercut of different schemes.

Both the equilibrium displacement scheme and the layered injection allocation scheme effectively increase the oil production of adjacent wells, and the daily oil increase of the equilibrium displacement scheme is 6.45 % higher than that of the layered allocation scheme (Fig. 14). The water cut of the scheme was greatly reduced compared with the original scheme. In general, the equilibrium displacement scheme works best. The grid saturation variance of different schemes was calculated to obtain different equilibrium degrees. The calculation results are shown in Fig. 15.

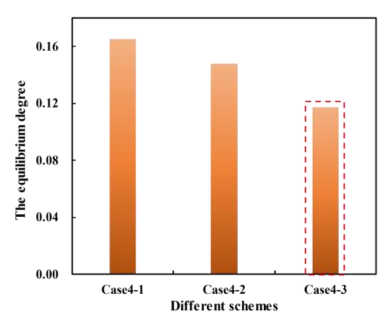


Fig. 15. Equilibrium degree of adjustment schemes of the B36 well group

As can be seen in Fig. 15., the overall equilibrium degree of the equilibrium displacement scheme was better than that of the layered injection allocation scheme and the original scheme, and the overall equilibrium degree of this scheme was increased by 15%. The application of three-dimensional equilibrium displacement software in the B36S well group of PL oilfield further reflected the accuracy and effectiveness of the optimization model. This facilitates the popularization and application of the software.

4. CONCLUSIONS

In this study, a three-dimensional equilibrium displacement optimization method was proposed for thin interbed reservoirs. The conclusions of this study are as follows:

(1) Considering the time-varying parameters in the development of thin interbed reservoirs and based on the change of saturation in the injection-production unit, the saturation variance of multi-layers between producers and injectors was used as a quantitative objective to be optimized with improved PSO algorithm.

(2)Both numerical model and actual field application proved that it can improve the degree of equilibrium of water flooding and recovery of remaining oil more effectively than conventional simulator-based method with maximum liquid production constraint.

(3)The current limitation of this method is that the injectors and producers are vertical wells. Further work needs to be done on the consideration of horizontal wells in somewhere thicker layers.Acknowledgement

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