

SIMULATION STUDY ON WATERFLOOD FRONT: BLOCK HADE OF TARIM OILFIELD IN NORTHWEST CHINA

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Abstract

Block Hade consist of a deep thin sandstone reservoir of two sub-layer reservoirs. The thickness is about 1.5 m for each layer. The two-layer "staircase" horizontal well is used for recovery. In order to determine water displacement front and edge water movement, tracer test is conducted in the reservoir. But the cycle of field tracer monitoring is about 150-360 days. This prevented the efficient monitoring of waterflood swept area and waterflood advance direction and velocity, after the cycle of tracer monitoring. Conservation of mass with respect to tracer flow and history performance matching of tracer enabled the study of water-flood front and edge-water advance. The simulation result is basically consistent with the monitored field tracer results. Therefore, numerical model can be used to conduct a longer monitoring period. It can make up for the disadvantage of the complexity of the tracer monitoring setup, its implementation, and time-consuming monitoring cycle. The water-flood front, water-flood swept area, advancing velocity and the predominant water injection direction can be obtained. Furthermore, it is possible to evaluate and predict the injection-production well interaction and can also provide a reliable basis to deploy reasonable flood patterns to enhance oil recovery.

Keyword: waterflood front; tracer monitoring; simulation; Hade reservoir.

1. Introduction

Based on the existing active edge water support and water injection into the reservoir, the waterflood front is studied alongside the flow direction/orientation and change, and the displaced region to enable the restructuring of the production-injection well flood pattern for improved oil recovery. Inter-well tracer test has not been widely used for many years because only average parameters from injector to producer can be determined from inter-well tracer test data. In order to get more useful information, a three-dimensional two-phase (oil, water) and four-component (oil, water, partitioning tracer and non-partitioning tracer) mathematical model was used and a tracer numerical interpretation model was developed. Based on this model, the pressure, saturation and tracer concentration can be obtained. In recent years, some scholars have used micro-seismic monitoring technology to monitor the water displacement front ^[1,2], while the use of tracer technology for simulation studies and research, and its application to water displacement front determination is low. Currently, qualitative means of assessing the connectivity between injection and production wells and the zones/regions of high permeability is relatively mature ^[3-7]. Some researchers describe tracer diffusion by the conservation of mass, fluid density, capillary pressure and the arbitrary ratio of oil flow mathematical model, based on the model, a semi-analytical tracer test interpretation software was developed, and achieved good results ^[8-12]. Based on our knowledge, there are no reports on the use of tracer data to calculate the breakthrough time of injected water to the production well and to determine the edge water advance velocity. In this paper, the environmental tracer model of a commercial oil reservoir simulator, "Eclipse", is applied to monitor water displacement front, and the streamline model is applied to study edge water advance.

2. Geological setting

Block Hade is located in Shaya county in XinJiang province, West China. Structural location of the field is Hadexun structural belt in the north of Manjiaer depression in the Tarim Basin (see Fig 1). The oil bearing zones is thin sand layers of the Carboniferous Kalashayi group. The mudstone is a grayish brown mudstone, belongs to tidal flat deposits. The general trend of sand thickness is thinning from the South to North, it reflects the sediment thickness thinning from sea to shore. Overall tectonic setting of sandstone show the South is higher than in the North.

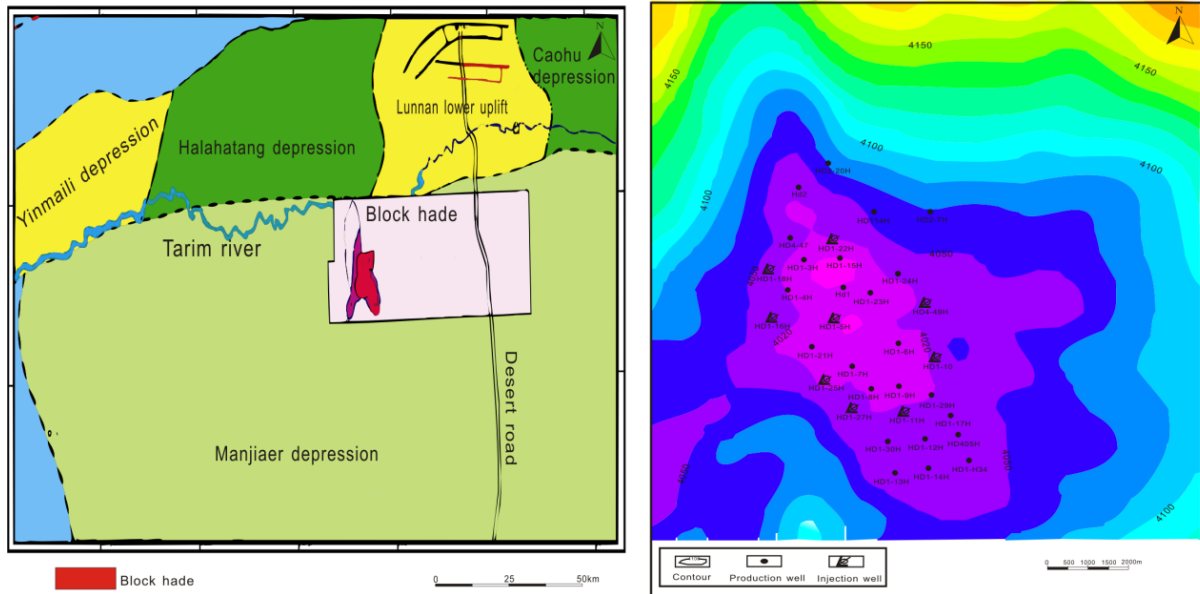


Figure 1 Block Hade shows (a) regional structural position (b) well location and structure

The analysis and statistics of physical property for 228 core samples of 10 cored wells show: research block physical property is mainly mid-porosity and mid-permeability. The maximum value of porosity is 20.40% and minimum value is 3.94%. the mean value is 12.24%. The value of permeability is mainly between $10\sim 100\times 10^{-3}\mu\text{m}^2$ ($10\sim 100\text{md}$), the mean value is $62.5\times 10^{-3}\mu\text{m}^2$ (62.5md).

At present, Block Hade is developed by the two-step (staircase) horizontal well system. However, there are certain different properties between the two sand layers, the situation varies laterally along the sand body penetrated by the horizontal well, hence, injection and production performance are difficult to predict. The edge water pressure support (water influx) is active, so carrying out the studies of water displacement front and tracer monitoring is difficult. Due to the fact that monitoring the production and injection profile for horizontal wells is difficult, the fundamental laws/equations governing fluid flow in the reservoir for each layer of thin sand is still not clear, so it needs to be systematically analysed for existing data from tracer monitoring, combined with dynamic and static data on the thin oil sand.

3. Principles of tracer test and transport in porous media

3.1. Principles of stable isotope tracer test

First, based on a set of related analysis of reservoir fluid data of the monitoring wells, a suitable tracer is selected, and then tracer solution placed into injection wells by the squeezing method. According to the sampling system, samples from the production wells around the injection wells (injection wells with tracer squeezed into) are obtained. By the analysis of samples, the production curve of tracer from the production well is obtained. Based on the location of the wells having tracer breakthrough and the characteristics of production-well tracer production curve (tracer breakthrough time, the peak number and magnitude appears on the curve), this specifically explains the advance direction, velocity, swept volume, the effectiveness of injection, the recovery rate of tracer and mean residence time.

The following steps are carried out in applying the stable isotope tracer technique in field experiments: (1) tracer preparation before injection (2) determination of tracer concentration prior to injection (3) calculation of the amount of tracer injected (4) development of sampling time (5) sample analysis and (6) analysis and assessment.

3.2. Tracer transport in porous media

Dispersion in porous media refers to the spreading of contaminants over a greater region than would be predicted solely from the average water velocity vectors [13-15]. Dispersion is caused by mechanical dispersion, a result of deviations of actual velocity on a micro-scale from the average water velocity, and by molecular diffusion driven by concentration gradients. Molecular diffusion is generally secondary and negligible, compared with the effects of mechanical dispersion, and only becomes important when water velocity is very low. The sum of mechanical dispersion and molecular diffusion is termed hydrodynamic dispersion, or simply dispersion.

Although the dispersion mechanism is generally understood, the representation of dispersion phenomena in a transport model is the subject of intense continuing research. The treatment of mechanical dispersion as a Fickian process (in effect, additive to diffusion) represents a pragmatic approach through which realistic transport calculations can be made without fully describing the heterogeneous velocity field, which, of course, is impossible to do in practice. Many different approaches and theories have been developed to represent the dispersion process. The equations below are still the basis for most field-scale simulations.

4. Mathematical and numerical model

4. 1. Mathematical model of tracer transport in the reservoir

The governing equation of tracer transport in the reservoir can be derived based on Darcy's Law, Fick's Law and mass conservation principle. The mathematical model for black oil flow is:

$$\begin{aligned} \nabla \cdot \left[\frac{\bar{k}k_{rw}}{B_w\mu_w} \nabla(p_w - \rho_w gD) \right] + q_{vw} &= \frac{\partial}{\partial t} \left(\frac{\phi S_w}{B_w} \right) \\ \nabla \cdot \left[\frac{\bar{k}k_{ro}}{B_o\mu_o} \nabla(p_o - \rho_o gD) \right] + q_{vo} &= \frac{\partial}{\partial t} \left(\frac{\phi S_o}{B_o} \right) \end{aligned}$$

and,

$$\begin{cases} S_o + S_w = 1 \\ P_{cow} = P_o - P_w \end{cases}$$

where: k —permeability, $10^{-3}\mu\text{m}^2$; k_{rw} , k_{ro} —relative permeability; μ_w , μ_o —the dynamic viscosity of water and oil, resp., mPa.s, p_w , p_o —pressure of water and oil, resp., MPa; ρ_w , ρ_o —density of water and oil, resp., g/cm^3 ; B_w , B_o — formation volume factor of water and oil, resp.; S_w , S_o —water saturation and oil saturation, resp., ϕ —porosity, p_{cow} —capillary pressure, MPa.

Usually in the porous medium, the migration of tracer fluid is controlled by two factors (hydrodynamic dispersion and convection). This effectively put forward the large influence of diffusion on tracer flow and diffusion coefficient will affect the history match [9-11]. Combining well pattern and production, the convection effect is very small, its impact can be ignored, but the dispersion factors must be considered.

The governing equation of tracer transport in Eclipse simulator is:

$$\frac{\partial C}{\partial t} = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) \cdot \begin{pmatrix} D_1(|v_x|, c)D_2(|v_y|, c)D_3(|v_z|, c) \\ D_4(|v_x|, c)D_5(|v_y|, c)D_6(|v_z|, c) \\ D_7(|v_x|, c)D_8(|v_y|, c)D_9(|v_z|, c) \end{pmatrix} \cdot \begin{pmatrix} \partial / \partial x \\ \partial / \partial y \\ \partial / \partial z \end{pmatrix} \cdot S_p C$$

where: C —tracer concentration (mg/L); $D_1 - D_9$ —dispersion coefficient; S_p —phase saturation.

In the model, the different tracers are set at different diffusion coefficients, and the diffusion coefficient and other parameters are adjusted within the permissible range, the diffusion coefficients (D_1 - D_9) are adjusted until a satisfactory match result is obtained. The fitted model can be used to further predict the concentration distribution of tracer, at the end of operation, the contour maps of tracer concentration reflect intuitively water displacement front of the water injection wells.

4.2 Numerical model of tracer transport in Hade Oilfield

According to the reservoir rock and fluid properties (Table 1), combined with precision and computer simulation capabilities, detailed model of the reservoir is optimized. The reservoir is discretized into 200m×195m×5m grid system. The porosity, NTG and permeability were interpolated based on well log interpretation data.

In the simulator, one (dimensionless) concentration tracer with different tracer codes are injected into the injection wells separately, based on the constant injection method. Two different tracer injection time sets, A and B (Table 2) are used. Set-A; in accordance with the report of the field tracer release time, this time is set in the simulator, with the aim to match the results (breakthrough time, advance velocity, etc.) of field tracer. Set-B; consistent with oil/water production and water injection time (history performance) from/to wells in the simulator, the working system of tracer production and injection maintains the same system, that is, as injection wells are shut in a moment, tracer injection is suspended (shut), wells are re-opened, then tracer production/injection is resumed, the purpose is tracking water injection.

Table 1 Reservoir parameters

Parameters	Units	Value
Reservoir datum depth	m	4070
Datum reference pressure	Mpa	54.3
Oil density	g/cm ³	0.8668
Water density	g/cm ³	1.095
Oil compressibility	Mpa ⁻¹	10.47×10 ⁻⁶
Dead oil viscosity	mPa.s	82.3
Reservoir temperature	°C	70
Rock compressibility	Mpa ⁻¹	5.78×10 ⁻⁴
Formation water	Mpa ⁻¹	4.35×10 ⁻⁴
Formation water viscosity	mPa.s	0.5
Standard temperature	°C	20

Table 2 Tracer time design (Design A and B)

Well name	Time Set	
	A	B
HD1-16H	2007.05.18	2003.10.09
HD1-18H	2007.05.18	2003.10.02
HD1-5H	2005.12.14	2003.10.06
HD1-10H	2005.12.14	2001.11.24
HD1-11H	2004.12.21	2003.10.04
HD1-22H	2007.09.29	2003.10.13

The same approach is applied to edge-water, assuming the whole edge-water is replaced by a tracer, the initial concentration of edge-water is set to one (dimensionless) in the simulator, and its code named EDGEWATER tracer. The six water injection wells take the B set. The purpose is to judge whether production wells are invaded by the edge-water and the specific time of breakthrough. In order to accurately reflect the invasion situation of the edge-water directly, streamline simulation is employed.

5. Results and discussion

5.1 History match results (model and field tracer)

In the history match process, tracer release time for Set-A in the simulation model is done by repeatedly adjusting the input parameters (including the diffusion coefficient). This is done until the match results are in accordance with the monitored field results. Based on well spacing and the breakthrough time, the average advance velocity of the fluid can be calculated. The match of monitored field tracer results and simulation results are carried out in seven production groups of Block Hade. Take three production groups for example (Table 3).

Table 3 Match result of field tracer and simulation tracer (three well groups)

Well Group	Well name	Well spacing	Breakthrough time	Average advancing velocity
			day	m.day ⁻¹
			Results of field monitoring/simulation	
16H	HD1-1H	992.96	—/—	—/—
	HD1-4H	1333.8	315/313	4.23/4.24
5H	HD1-1H	1379.5	—/—	—/—
	HD1-4H	2058.0	—/—	—/—
	HD1	967.0	—/—	—/—
	HD1-6H	2453.9	—/—	—/—
	HD1-7H	2074.4	—/912	—/2.27
	HD1-21H	1843.09	—/—	—/—
	HD1-23H	1356.5	—/—	—/—
22H	HD-3H	1363.6	—/—	—/—
	HD1-15H	630.1	248/265	2.54/2.54
	HD4-47H	1228.1	—/—	—/—

Note: "—" no tracer

On comparing results from the match analysis, the match results of seven well groups are good. Breakthrough time and the average advance velocity error are within the permissible range. Take the 16H and 5H well groups for example, monitored field tracer completed tracer release in the injection well of 16H well group on May 18, 2007, two wells (HD1-1H and HD1-4H) were monitored throughout the 363 days. On March 29, 2008 (315 days), the sampled produced fluid from well HD1-4H showed the presence of tracer for the first time, for well HD1-1H no tracer was detected in the produced fluid. Seven oil wells of 5H well group were monitored for 150 days from December 21, 2004 to May 20, 2005; the seven wells do not have a tracer production curve.

After the numerical model run (Figure 2), 16H and 5H well groups of single well tracer production curve is shown in Figure 2. From the production curves view, Well HD1-1H of 16H well group do not have a production curve, and also showed no tracer until March 2009; Well HD1-4H has tracer production curve on March 27, 2008 (313 days), the results are in accordance with that of field data. For the 5H well group, Wells HD1-1H, HD1-4H, HD1, HD1-6H, HD1-21H, and HD1-23H showed no tracer, that is, no production curves, these are consistent with results of field data. Well HD1-7H showed tracer on September 2007 (breakthrough time of 912 days), a production curve shows the difference with the field data survey. However, the latest oil field water chemistry test results showed that Well HD1-7H is affected by injection well HD1-5H indeed, combined with oil field production data, Well HD1-7H produce a substantial increase in water significantly from the previous month on September 2007, indicating that the simulation results are correct. The main reason is caused by differences in monitoring days, simulation results show that tracer breakthrough time was 912 days, beyond the field tracer monitoring cycle (150 days), it also reflects the field monitoring was restricted by the monitoring cycle.

5.2 Water displacement front

Based on the analysis of match results of reservoir history performance and tracer, the model can accurately reflect the reservoir heterogeneity and subsurface flow scenario, thus, this model can be used to study the water displacement front. The Set-B data is used for this; the other basic parameters remain unchanged.

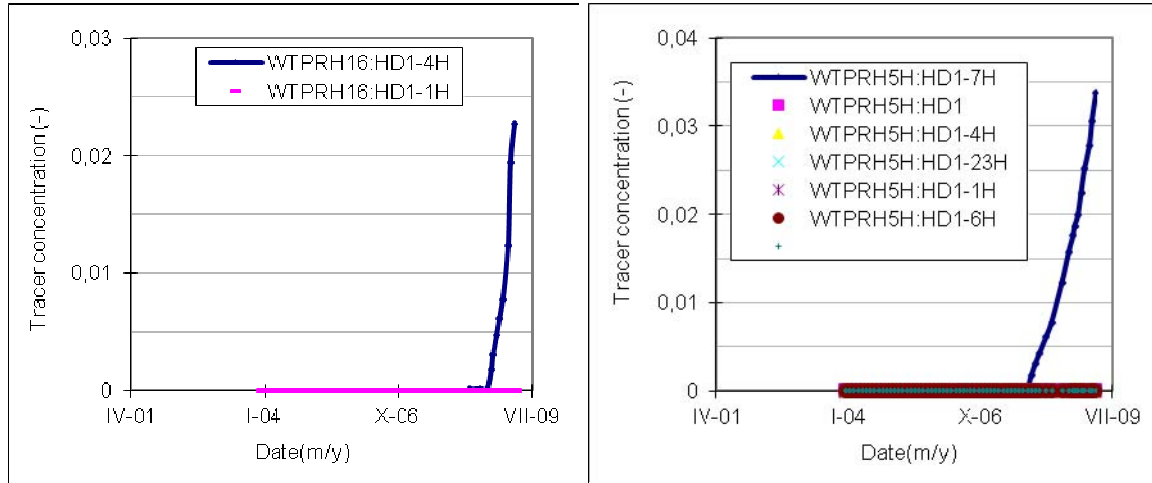


Figure 2 Single-well tracer production curve in two-well group (left: 16H well group; right: 5H well group)

At the end of May, 2007, two contour diagrams of tracer concentration are obtained (Figure 3). We can deduce from the basic principles above, tracer concentration contour map is a direct reflection of water displacement front of water injection, the shape of the contour reflect the forward direction and trend of injected water. Figure3 shows that 16H, 5H, 25H, 10H and 11H well groups are relatively affected by water injection.

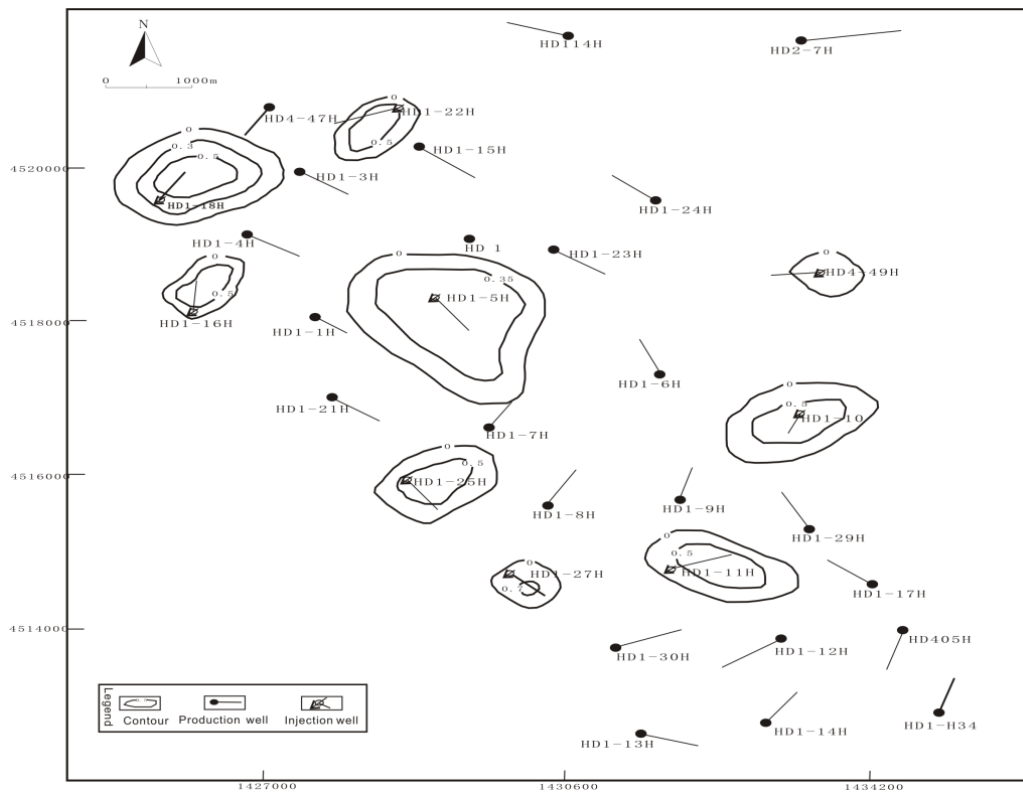


Figure 3 Plane contour diagram of tracer concentration superposition for two sets of oil layers (CI, CII) (May 2007)

At the end of September, 2009, some important conclusion can be drawn from the tracer concentration contour maps of the CI and CII layers of 5H well group (see Figure 4), the main direction of water displacement front advances from the north to south, by calculating the superposed mesh, the length of the water-flood sweep of 5H well group is 1082 m, the width is 783 m, the coverage of waterflood is $40.5 \times 10^4 \text{ m}^2$, the waterflood front is relatively smooth. Wells HD1-1H, HD1, HD1-23H and HD1-7H are located in the main direction of the waterflood front, indicating, relatively controlled high degree of waterflood. While wells HD1-6H and HD1-21H are located in the lateral direction of waterflood front with poor waterflood advance, this is mainly due to reservoir areal heterogeneity.

Due to the differences of physical properties and heterogeneity of the two sets of oil reservoir (2 layers), waterflood swept area and response time will be different. By way of calculating tracer breakthrough time and the velocity of advance of the two sets of oil reservoir respectively (Table 4), the waterflood response can be studied. In view of the results, the response time to production wells in CII layer is earlier than that of CI, and the advancing velocity is faster.

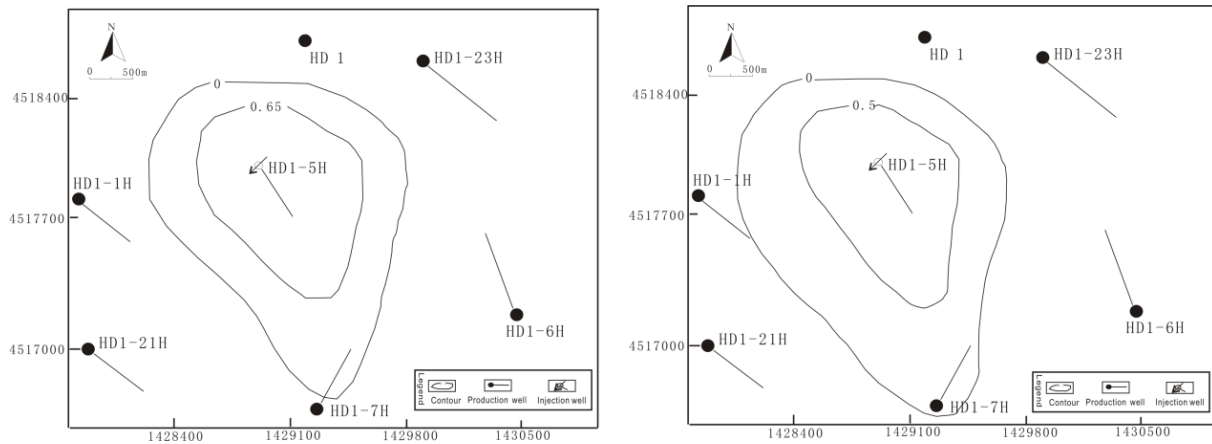


Figure 4 Plane contour diagram of oil layers tracer concentration for the 5H well group (September 2009) (left: CI oil layer; right: CII oil layer)

Table 4 Water breakthrough time and the oil wells affected by the injection wells

Well name	Commissioning date	CI layer			CII layer		
		Breakthrough time Year-month	Injection well	Advancing velocity M.day^{-1}	Breakthrough time year-month	Injection well	Advancing velocity m.day^{-1}
HD1-3H	2002-04	2005-12	HD1-18H	1.04	2005-07	HD1-18H	1.23
HD1-4H	2002-03	2005-08	HD1-22H	0.92	2005-04	HD1-22H	1.01
		2005-05	HD1-16H	1.23	2003-02	HD1-16H	4.18
HD1-15H	2002-05	2003-07	HD1-22H	1.92	2003-03	HD1-22H	2.51
HD1-13H	2002-03	—	—	—	—	—	—
HD1-7H	2001-07	2004-04	HD1-25H	1.32	2004-02	HD1-25H	1.37
HD1-29H	2006-09	2005-07	HD1-5H	0.95	2005-05	HD1-5H	0.99
		2006-12	HD1-10	1.42	2006-11	HD1-11H	1.02
		2006-12	HD1-11H	21.20	2006-11	HD1-11H	21.40

Note: "—" no tracer

In view of the analysis of waterflood front and production wells response, the work of water flood has reached an advanced stage, and flow lines, inter-well communication, response among the wells are formed. In order to avoid the phenomenon of excessive water advance to the production wells from injection wells, that is water channeling, some appropriate measures have to be taken such as plugging.

5.3 Edge water advance

Because of edge water invasion/recharge and edge water advance is not uniform, in actual production, failing to determine the production wells affected by water injection wells or edge-water and the specific water breakthrough time qualitatively or quantitatively, the reasonable development of waterflood development programs and the intensity of edge-water support will be affected. Thus it is necessary to understand edge water breakthrough to production wells.

In accordance with the edge water tracer parameters, streamline model is applied to this study. Combined with pressure distribution of Block Hade, the dynamic streamline map show (Figure 5): edge water mainly invades the central location from the eastern and western sides of the block, the wells in the southern parts of the block (down-dip structure location) are affected by edge-water. Since water injection wells in the central part of the reservoir hinders the advancing edge-water, the wells affected by edge-water are concentrated at the border of the reservoir, most of the wells in the central are not currently affected by edge-water, indicating that edge-water failed to advance to the whole block.

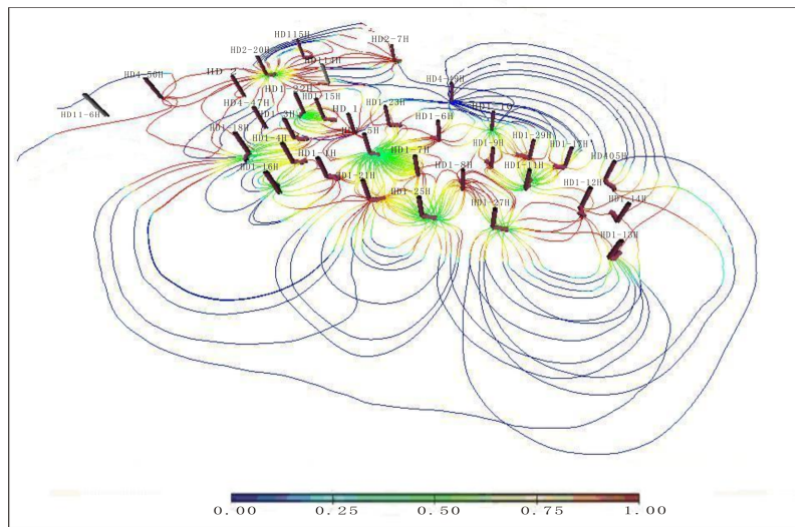


Figure 5 The streamline of tracer concentration of edge-water and injection wells in research block (blue: tracer concentration is 0; green: tracer concentration is 0.5; brown: tracer concentration is 1) (September 2009)

In view of the different tracer code names that are set for each injection well and edge-water, by analyzing production curves of concentration of the tracer recovery, it is ease to distinguish production wells that are affected by edge-water or various injection wells, and the water breakthrough time, and then the waterflood front advance velocity of edge-water and injected water are obtained respectively. The summary of water breakthrough time and waterflood advance velocity for each well based on edge-water advance is presented in Table 5.

As earlier stated, the different code name of the tracer from each well and the edge-water makes for ease identification of which injection well or edge-water that impacts a given production well. This enables the appropriate study of water breakthrough time and its advancing velocity for waterflood performance projection and response. In view of the tracer concentration production curve, twelve production wells are affected by edge-water, wells HD10, HD114 and HD1-13H are affected by the edge-water as soon as production commenced since water advance velocity is very fast compared to the other 9 production wells. Water breakthrough into the 9 wells took 2-3 years with an average advance velocity of 1.5-3m/d with water breakthrough time been earlier for the CII layer than the CI layer.

For the benefit of infill well locations, determination of reasonable oil production rates is plausible. Likewise, for adequate reservoir pressure maintenance scheme and the prevention of premature water breakthrough, the knowledge of the waterflood front and edge-water advance velocity is necessary.

Table 5 Water breakthrough time and advancing velocity of the wells affected by edge-water

Well name	Well startup time	CI layer		CII layer	
		Breakthrough time year-month	Advancing velocity m.day ⁻¹	Breakthrough time year-month	Advancing velocity m.day ⁻¹
HD1-3H	2002-04	2005-07	2.11	2005-05	2.21
HD1-4H	2002-03	2005-01	2.53	2005-01	2.53
HD1-15H	2002-05	2004-08	1.35	2004-05	1.46
HD1-13H	2002-03	2002-05	11.32	2002-07	10.61
HD1-17H	2002-08	2004-02	2.57	2004-01	2.57
HD1-21H	2002-06	2007-07	0.89	2007-07	0.93
HD1-7H	2001-07	2005-08	1.71	2005-07	1.72
HD2	1998-09	2000-02	1.56	2000-02	1.56
HD4-47	2005-05	2007-03	3.62	2007-03	3.61
HD10H	2004-03	2004-04	312.21	2004-04	312.22
HD1-6H	2001-06	2006-04	0.91	2006-04	0.91
HD114H	2004-10	2004-11	256.72	2004-11	256.72

6. Conclusion

Based on the study carried out, the following salient conclusions can be drawn:

- By using the verified numerical simulation model result with the field monitoring/survey of tracer concentration at the production wells, the shortcoming of short monitoring period of tracer concentration can be scaled-through with high reliability.
- Intuitively, or by deduction, the simulation results of tracer concentration reflects the area swept by the injected water, waterflood direction in the two layers, and when combined with dynamic and static data can further model subsurface flow.
- The impact of edge-water intrusion can be accurately evaluated by means of tracer simulation, as is practiced, the results obtained by this technique is reliable, and it can be applied to oil production

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