Water Flooding Timing Research and Field Practice in Light Oil Reservoir

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Abstract. Water flooding timing is the research focus in the process of reservoir development, especially for offshore reservoir, reasonable water flooding timing can ensure better development effect, at the same time, it can save the investment cost in the process of reservoir development, so as to achieve sustainable and efficient development of offshore oilfield. At present, there are many researches on the flooding timing of conventional heavy oil reservoir, but few on the flooding timing of light oil reservoir. In order to clarify the development effect of light oil reservoir under different water flooding timing, taking offshore oilfield A as an example, combining with numerical simulation technology and reservoir engineering analysis method, the development effect under different water flooding timing is analyzed. The results show that when the reservoir pressure drops to half of the saturation pressure, the development effect of water flooding for light oil reservoir is the best. Therefore, the water flooding time can be postponed for the light oil reservoir with high porosity and permeability. The research results are applied to the actual development case of oilfield A. The practice shows that water flooding in the late development stage of light oil reservoir can effectively prolong the water-free oil production period, improve the initial oil recovery rate, reduce the initial development investment, thus effectively shorten the investment recovery period and improve the development effect of the reservoir in the whole life production cycle.

Keywords. Light oil reservoir, water flooding timing, numerical simulation technology, reservoir pressure, field practice.

1. Introduction

As the main method of secondary oil recovery, water flooding has been widely used in both onshore and offshore oilfields, for it can effectively supplement formation pressure and flooding reservoir crude oil in the formation, so as to improve oil recovery rate and ultimate oil recovery. At present, it is generally believed that in the early stage of oilfield development, which is, before the reservoir pressure drops to 85% of saturation pressure, water flooding can prevent the degassing of crude oil, so as to reduce the interference of multiphase seepage in the reservoir and the oilfield could obtain higher oil recovery. This viewpoint has been confirmed by a large number of field practice and laboratory experiments [1-6]. However, most of the existing researches on water flooding timing are focused on conventional heavy oil reservoir, while few on light oil reservoir. The existing water flooding timing of light oil reservoir is mainly based on the experience of conventional heavy oil reservoir [7-10]. The water to oil mobility ratio of the light oil reservoir is relatively low, and it generally has a high oil recovery rate. Therefore, it is necessary to conduct a more objective study on the water flooding timing.
timings of the light oil reservoir, so as to obtain a more reliable water flooding strategy for the offshore light oil reservoir.

Compared with the early water flooding of conventional reservoirs, some oilfields are limited by development conditions and other factors. They choose to start water flooding after the formation pressure is far lower than the saturation pressure, or after dissolved gas drive, which can be called the late stage water flooding oilfields, such as Changchun oilfield, Qikou oilfield, Yowlumne oilfield [11-13]. The oilfield A studied in this research has the characteristics of low viscosity of crude oil and better physical properties of reservoir, which is similar to the water flooding oilfield in the late stage of development mentioned above. In order to determine whether water flooding in the late stage of development is feasible for oilfield A, numerical simulation and reservoir engineering analysis are carried out. Different water flooding timing is designed in different development schemes, and the best water flooding timing is determined according to the development effect under each scheme, and the actual water flooding development strategy of oilfield A is guided. After the application of the research results to the practice water flooding work at oilfield A, the specific reasons for the different development characteristics of different reservoirs are analyzed. The study is of great significance to the optimization of water flooding timing in similar oilfields.

2. General Situation of Oilfield A

Oilfield A is located at the high point of faulted anticline structure on the west slope of Sumatra Basin in Southeast Indonesia, The target layer is the Talang Akar formation of Oligocene early Miocene, the sedimentary facies of the reservoir is fluvial facies, and the rock type is fine-grained quartz sandstone. The physical properties of the reservoir are generally good, with an average porosity of 26.8% and an average permeability of 1100 mD. Oilfield A is a structural lithologic reservoir with weak edge water, including A4, A6, A1W and A1E reservoirs. The surface crude oil density is 0.87 g/cm³, viscosity is 22 mPa·s, wax content is 13.5%, sulfur content is 0.14% ~ 0.15%. The surface crude oil has the characteristics of medium density, medium viscosity, high freezing point, high wax content, medium gum and asphaltene, and low sulfur content. The formation crude oil is a low viscosity crude oil with viscosity of 4 mPa·s, This is expressed as light oil reservoir characteristics, dissolved gas oil ratio of 110, saturation pressure of 6.23 MPa-6.87 MPa and volume coefficient of 1.1. The total salinity of formation water is 13500 mg/L-17620 mg/L, and the water type is NaHCO₃ type. The reservoir belongs to normal pressure and temperature system.

Oilfield A was put into production in December 1990, with 4 sets of strata reservoir, which were exploited separately. The initial development mode of the reservoir is rely on natural energy development, and water flooding development was gradually implemented in July 1999. Water flooding is carried out in two stages, the first stage include reservoirs of A4, A6 and A1W, and the implementation time is from July 1999 to August 2000; the second stage include reservoirs of A1E, and the implementation time is begin in May 2005. The reservoir pressure drops rapidly before water flooding. From 1990 to 2000, the formation pressure decreased from 9.66 MPa to 2.76 MPa, at this stage, the oilfield is in low water cut stage. In the stage of rely on natural energy development, water cut is at a low level (10%-40%). After water flooding, the water cut of oil field rises rapidly, but the effect of water control techniques is obvious. In the early stage of water flooding development, the oil production of each oil reservoir is obviously improved. The daily oil production of reservoir A4 increased from 954 m³ before water flooding to 1828 m³. The daily oil production of reservoir A6 increased from 127 m³ before water flooding to 366 m³. The daily oil production of reservoir A1W increased from 16 m³ before water flooding to 207 m³. The daily oil production of reservoir A1E increased from 65 m³ before water flooding to 159 m³. As of August 2012, the cumulative production of water flooding reservoir has reached 906 × 10⁴ m³, accounting for 16.5% of the total production of the oilfield. According to the existing production performance prediction, water flooding development can increase the recovery rate of Oilfield A by 11%.
3. Water Flooding Timing Analysis

3.1. Water Flooding Timing Optimization

In order to optimize the timing of water flooding, numerical simulation is carried out according to the structural characteristics, fluid properties and physical parameters of Oilfield A. The whole development process depends on natural energy development as the basic scheme, and four sets of contrast schemes with different water flooding timing are designed:

- Scheme 1: Rely on natural energy development;
- Scheme 2: Water flooding carried out when reservoir pressure is original reservoir pressure;
- Scheme 3: Water flooding carried out when reservoir pressure drops to saturation pressure;
- Scheme 4: Water flooding carried out when reservoir pressure drops to 1/2 of the saturation pressure;
- Scheme 5: Water flooding carried out when reservoir pressure drops to 1/4 of the saturation pressure.

It is observed from the cumulative oil production curves of different schemes that with different water flooding timing, when the reservoir pressure drops to 1/2 of the saturation pressure for water flooding, the cumulative oil production of the reservoir is the highest (figure 1), and the predicted oil recovery is greater (table 1).

![Cumulative oil production](image_url)

**Figure 1.** Comparison of cumulative oil production in different water flooding timing schemes.

**Table 1.** Comparison of oil recovery in different water flooding timing schemes.

| Scheme No. | Water flooding year | Injection production ratio to Water timing | Cumulative production ($10^4$ m$^3$) | Oil recovery (%) |
|------------|---------------------|------------------------------------------|-----------------------------------|-----------------|
| 1          | -                   | -                                        | -                                 | 27              | 16.7           |
| 2          | 1999                | 1.0                                      | original reservoir pressure       | 32              | 19.9           |
| 3          | 1999                | 1.0                                      | saturation pressure               | 42              | 26.2           |
| 4          | 2003                | 1.0                                      | 1/2 of the saturation pressure    | 46              | 28.6           |
| 5          | 2011                | 1.0                                      | 1/4 of the saturation pressure    | 45              | 28.0           |
3.2. Analysis of Actual Water Flooding Timing

In the process of relying on natural energy for development, Oilfield A has the following situations. First of all, the reservoir pressure drops rapidly. As of 1994, the formation pressure drops to the saturation pressure of 6.5 MPa. By the end of 1999, the pressure drops to 2.5 ~ 3.0 MPa, which is less than half of the saturation pressure (6.5 MPa). At this time, the reservoir has been seriously degassed. Secondly, the oil recovery rate is declining rapidly, which can't slow down the decline of oil production by increasing the number of production wells. Thirdly, with the increase of the number of production wells and the progress of liquid extraction measures, the increase of recovery degree, the increase of water cut rise rate and the increase of comprehensive decline rate of oil production, it is urgent to supplement the reservoir energy through secondary oil recovery. Therefore, in July 1999, water flooding was carried out for Oilfield A. Compared with conventional offshore oilfield; the water flooding timing of this oilfield is relatively late.

4. Development Effect Analysis of Field Practice

4.1. Overall Development Effect Analysis

Oilfield A has achieved good production effect since the implementation of water injection development in July 1999. By August 2012, the cumulative oil production of water flooding reservoir has reached $914 \times 10^4\text{m}^3$, accounting for 16.5% of the total oil production of the oilfield. The formation pressure has been recovered well, for example, the pressure of reservoir A4 and A6 has recovered from 3.0MPa before water flooding to 6.9 MPa at present, and with the increase of water cut, the recovery degree increases higher (figure 2). The water flooding reservoir (A4, A6, A1W) implemented in first stage has a relatively complete injection-production system, and its oil recovery degree is 9% ~ 12% higher than that before water flooding, The second stage water flooding reservoir (A1E) implemented in 2005 has a recovery degree of 2.4% higher than that before water flooding due to short water flooding development time (table 2). After the two-stage water flooding project and other measures to increase oil production and potential-tapping, the crude oil production increased significantly, and the decline trend of oilfield production slowed down. The recoverable reserves increased from 5280 $\times 10^4\text{m}^3$ to 5630 $\times 10^4\text{m}^3$, and the ultimate oil recovery increased from 41.7% to 52.5%.

According to the evaluation of four categories and ten indexes, such as oil recovery, comprehensive decline rate and formation pressure level, the overall evaluation result is category first (table 3), so it is considered that the water flooding development effect of oilfield A is generally good.

**Table 2.** Comparison of development indexes before and after water flooding.

| Reservoir flooding year | Water Production well | Injection well | Cumulative oil production ($10^4\text{m}^3$) | Cumulative Water cut (%) | Oil recovery (%) | Water Oil cut (%) | Recovery Ratio | Cumulative Injection to production Ratio | Added value of oil recovery (%) |
|------------------------|----------------------|---------------|------------------------------------------|-------------------------|----------------|------------------|---------------|----------------------------------------|-----------------------------|
| A4 2000                | 33                   | 21            | 176                                      | 11.9                    | 7.7            | 440              | 94.4          | 19.1                                   | 1.2                        | 11.4                        |
| A6 2000                | 12                   | 4             | 110                                      | 86.6                    | 16.4           | 174              | 93.0          | 25.9                                   | 0.7                        | 9.5                         |
| A1W 2000               | 6                    | 3             | 53                                       | 74.0                    | 13.3           | 101              | 94.6          | 25.4                                   | 1.1                        | 12.1                        |
| A1E 2005               | 8                    | 2             | 177                                      | 89.2                    | 36.3           | 198              | 96.4          | 38.7                                   | 0.1                        | 2.4                         |
| Total                  | 59                   | 30            | 516                                      | -                       | -              | 914              | -             | -                                      | -                          | -                           |
Table 3. Summary of development index.

| Evaluation content | Evaluation category | Oilfield A Evaluation result |
|--------------------|----------------------|-----------------------------|
|                    | Category first | Category second | Category third |                        |
| First level index  | Target oil recovery of water flooding |                               |                        |
|                    | ≥30%           | 30%~20%               | ≤20%            | 30.8%              | Category first |
|                    | Injection production correspondence |                               |                        |
|                    | ≥65%           | 65%~45%               | ≤45%            | 90.30%             | Category first |
|                    | Control degree of water flooding reserves |                               |                        |
|                    | ≥80%           | 80%~70%               | ≤70%            | 80.04%             | Category first |
|                    | Production degree of water flooding reserves |                               |                        |
|                    | ≥75%           | 75%~65%               | ≤65%            | 76.29%             | Category first |
| Second level index | Water cut rise | ≤1%                   | 1%~2%            | ≥2%                | 2.02 | Category third |
|                    | Water cut | Lower than theoretically | Close to theoretically | Higher than theoretically | Lower than theoretically | Category first |
|                    | Decline rate | ≤7%                   | 7%~9%            | ≥9%                | 8.28% | Category second |
|                    | Water storage rate | Higher than theoretically | Close to theoretically | Lower than theoretically | Higher than theoretically | Category first |
|                    | Water flooding index | Higher than theoretically | Close to theoretically | Lower than theoretically | Higher than theoretically | Category first |
|                    | Energy retention level | ≥0.85 | No degassing | Degassing | ≥0.85 | Category first |

Overall evaluation results Category first

4.2. Reservoir Unit Development Effect Comparison
In the four water flooding development reservoirs of Oilfield A, the formation pressure has been reduced to less than half of the saturation pressure when water flooding, the timing of water flooding is relatively late, and the water flooding development effect is obvious. After the implementation of water flooding, the total recoverable reserves increased by 350 × 10^4 m³, oil recovery increased by 11%. The daily oil production of reservoirs A4 and A6 increased from 359 m³ to 1707 m³ after water flooding, the decline rate decreased from 30% to 21%, and the recoverable reserves increased by 281
The daily oil production of reservoirs A1W increased from 71 m$^3$ to 569 m$^3$ after water flooding, the decline rate decreased from 22% to 19%, and the recoverable reserves increased by 41 $\times$ 10$^4$ m$^3$. The daily oil production of reservoirs A1E increased from 77 m$^3$ to 165 m$^3$ after water flooding, the decline rate decreased from 33% to 23%, and the recoverable reserves increased by 28 $\times$ 10$^4$ m$^3$.

It is found by comparing four water flooding development reservoirs of Oilfield A (figure 2). Reservoir A4 is the first to implement water flooding, in 1999, the water cut before water flooding was only 11.9%, the recovery degree was 7.7%, in 2012, the water cut was 94.4%, and the recovery degree was only 19.1%. Reservoir A1E was last to implement water flooding, in 2005, the water cut before water flooding was 89.4%, the recovery degree was 36.3%, in 2012, the water cut was 96.4%, and the recovery degree was 38.7%. It is the slowest curve between water cut and recovery degree. The other two reservoirs are between the two, the recovery degree in 2012 is about 25.6%, in which the water cut of reservoir A6 in 2000 is 86.6%, the recovery degree is 16.4%. The water cut in 2012 is 93%, and the recovery degree is 25.9%. The water cut of reservoir A1W in 2000 is 74.0%, the recovery degree is 13.3%. The water cut in 2012 is 94.6%, and the recovery degree is 25.4%.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The relationship between water cut and recovery degree.}
\end{figure}

4.3. Causal Analysis

For the reservoir with weak edge water energy, a large drop in formation pressure will cause certain damage to the reservoir and fluid, make the fluid degasify and form the three-phase seepage of oil, gas and water, and greatly reduce the relative permeability of crude oil, thus reducing crude oil production. In Oilfield A, even when the formation pressure drops below half of the saturation pressure and the formation is seriously degassed, water flooding can still achieve good development results. The reason is that the reservoir has better physical properties and oil quality. The overall physical properties of each reservoir in Oilfield A are good, with an average porosity of 25% ~ 30% and an average permeability of 500 mD ~ 5000 mD. Compared with four water flooding reservoirs, the physical properties of reservoir A1E with water flooding in late development stage are better than that of reservoir A4 with water flooding in early development stage. Due to the good physical properties, with the development, even if the formation is seriously degassed, oil, gas and water three-phase seepage and gas lock phenomenon are formed near the well zone, the large pore throat radius of the reservoir, the capillary force is weak, the interface tension is small, and the gas lock ability is weak. The oil phase permeability will not be greatly reduced, and crude oil can still flow into the wellbore through the seepage channel. At the same time, the four water flooding reservoirs are all light oil reservoirs. The viscosity of the formation crude oil is 4 mPa·s. The water flooding area is large and the recovery degree is high. In general, after degassing, the viscosity of crude oil increases, which also changes the
thermal dynamic balance of the reservoir and makes wax evolution. However, oilfield A is a light oil reservoir, even if the crude oil is degassed, the viscosity of the crude oil does not change much compared with that before degassing, and the interference of multiphase flow is not obvious, which is conducive to water flooding development after degassing. Therefore, water flooding in the late development stage of oilfield A will still achieve good results.

5. Conclusions
The optimization of water injection timing in Oilfield A shows that water flooding in the late stage of development can achieve good results. The results show that when the reservoir pressure drops to half of the saturation pressure, the cumulative oil production index is the highest, the recovery degree is the highest, and the reservoir development effect is the best.

The field case of oilfield A shows that water flooding in the late stage of development can also achieve good results. The formation pressure has decreased to less than half of the saturation pressure, and the water flooding timing is relatively late. Based on the evaluation of four categories and 10 indexes of water flooding development, the conclusion that the overall development effect of water flooding in the late development stage is good of light oil reservoir is drawn.

Water flooding timing can be postponed in high porosity and high permeability reservoirs with low crude oil viscosity. Oil reservoir A has good physical properties, large pore throat radius, weak capillary force, small interfacial tension and weak gas lock capacity. Even if degassed, crude oil can still enter the wellbore through the seepage channel. The crude oil is good in quality and low in viscosity. The viscosity of crude oil changes little before and after degassing, and the interference of multiphase flow is not obvious, which is conducive to water flooding development after degassing.

For different types of reservoirs, the timing of water flooding needs specific analysis. The specific conditions of each oilfield and the physical properties of crude oil are different, it is impossible to meet the requirements of unified standards for all oilfields.

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