Select the Optimal Development Strategy for Layered Sandstone Reservoir by Creating System Economic Model and the Accumulated Oil Production Prediction Method

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Select the optimal development strategy for layered sandstone reservoir by creating system economic model and the accumulated oil production prediction method

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Abstract

To determine the development mode of different oil field in layered sandstone reservoir, a system economic model was established, including the primary production layer section and the upper layer. The cumulative oil production limits of the primary layer were described under different oil prices, using the existing well method (UEWM) and drilling new well method (DNWM). The first layer's oil production limit for DNWM and UEWM was determined. The established economic ultimate water cut (EUWC) model, the solution prediction model of water cut arctangent, and the water drive curve were combined, to calculate the accumulative oil production from planning time of the upper layer production to the economic limited water cut of block. When the oil price is 40$/BBL, the SME block should be developed by UEWM method. While for 70$/BBL, DNWM should be adopted. This work provides theoretical support for the optimization of up (down) layer return development mode. It is of great significance to guide the development of layered sandstone reservoir.

Key words: System Economic model; Up (down) layer return development; Development mode; Water cut arctangent curve; Economic ultimate water cut; Layered sandstone reservoir

1 Introduction

Most of the oil reservoirs in China belong to continental deposits, which have multi layers, strong heterogeneity, low water displacement efficiency and low natural energy (Mu *et al.*, 2016; Li *et al.*, 2016). One of the typical reservoirs in Daqing Oilfield is the terrestrial multi-layered sandstone reservoir (Zhu *et al.*, 2019). Three reservoir groups were exploited vertically, including more than a dozen of oil layers. These oil reservoirs were divided into 3 types for development. The 1st typical reservoir was PI formation，whose sedimentary unit was fluvial facies. Its effective permeability was more than $0.8\times10^{-3}\mu m^2$ and effective thickness was more than 4m. The 2nd type reservoir was SII formation, whose sedimentary unit with fluvial sand area was more than 30%. Its effective permeability was more than $0.1\times10^{-3}\mu m^2$. Its sand deposition channel width differed from 200 to 1000 m (Li *et al.*, 2012; Shi *et al.*, 2009; Pu *et al.*, 2015). The 3rd type GI-III layer was thin and poor oil situation. In the 1990s, the oil layer PI was determined to be developed first, which could ensure the Daqing Oilfield maintain a steady oil production of 5000×10^3t. Till now, all PI oil layers had been put into tertiary recovery development. The first layer development stage of type II reservoirs was performed in 2002, which gradually entered the follow-up water flooding stage. Now the next development of the second upward (downward) layer had been planned, which raises some inevitable questions. For example, whether the second upper (lower) layers should be developed? If so, how to arrange the sequence? Should the production be upward or downward of the first layer? How to choose the drilling well network, the original one or a new developed one? To answer these questions, many researchers worked in different ways (Fang *et al.*, 2016; Qiao *et al.*, 2007; Zhou *et al.*, 2011; Gao *et al.*, 2015; Zhang *et al.*, 2016; Wu *et al.*, 2015). However, the problems haven't been totally solved.

The objective of this study is to determine the upper (downer) layer return development method and establish the system economic model. The disused water cut of first layer stage will be calculated. The joint solution prediction model will be built, based on the inverse tangent water cut prediction method and the water drive law prediction model.

2 Method

2.1 The system economic evaluation model establishment

The existing well method (UEWM) is used to plug the first layer and fill hole of upward reservoir for development. The upward reservoir development is taken as an example. The drilling new well method (DNWM) is conducted to retain the first layer development wells production and drill new wellss to develop upper layer.

To better develop oil field with UEWM or DNWM method, the first layer stage and the upper return layer were treated as a system. Benefits contrast of the two modes were considered overall. Then the return layer develop model would be used (Fig. 1).

According to the model, benefit of UEWM for development is expressed as:

$$B_1=B_{sf}-B_{bl}-B_{fd}-B_{bk} \tag{1}$$

Among them:

$B_{sf}= N{\cdot}dth{\cdot}hl{\cdot}a{\cdot}P$. The benefit of the upper return section will produce oil, M$;

$B_{bl}=N_{bl}{\cdot}dth{\cdot}hl{\cdot}a{\cdot}P$. Retention benefits of cumulative oil that produced by first reservoir, M$;

$B_{fd}=n_{do}{\cdot}P_{do}+ n_{dw}{\cdot}P_{dw}$. The first reservoir section block charge, M$;

$B_{bk}=n_{bo}{\cdot}h_{bo}{\cdot}P_{bo} +n_{bw}{\cdot}h_{bw}{\cdot}P_{bw}$. The cost of old well perforate upper layer, M$.

The benefit of DNWM is expressed as follows:

$$B_2=B_{bl}+B_{sf1}-B_z-B_j-B_s \tag{2}$$

where,

$B_z=(n_{zo}+n_{zw}){\cdot}H_z{\cdot}P_z$. Drilling new well costs, M$;

$B_j=(n_{jo}+n_{jw}){\cdot}P_j$. New well construction cost, M$;

$B_s=(n_{so}+n_{sw}){\cdot}P_s$. Perforation cost, M$;

$B_{sf1}=N_1 \cdot dth \cdot hl \cdot a \cdot P$. Cumulative oil production benefit of return to upper reservoir interval, M$;

$B_{bl}=N_{bl} \cdot dth \cdot hl \cdot a \cdot P$. Benefit of retaining yield of the first stage, M$.

The development mode was determined by comparing the benefits of UEWM and DNWM. If $B_1<B_2$, that is the benefit of UEWM was less than DNWM. Then the DNWM was adopted.

Therefore,

$$B_{sf}-B_{bl}-B_{fd}-B_{bk}<B_{bl}+B_{sf1}-B_z-B_j-B_s \tag{3}$$

Assume that the new well was drilled at the exiting well location, so conditions of new wells would be with the same as the exist wells to develop the upper strata. Put $B_{sf1}=B_{sf}$ in formula (3), then it was simplified to

$$B_{bl}+B_{fd}+B_{bk}>B_z+B_j+B_s-B_{bl} \tag{4}$$

The benefit comparison of the two methods was then transformed into the investment comparison. The DNWM would be adopted, if its investment was less than UEWM.

In practice, the new well could not be drilled in the existing well location, the new well would be drilled in the best well location. Therefore, the enhanced oil recovery factor "A_B" was calculated to indicate how the DNWM could improve oil recovery than UEWM.

Then, the formula (4) was changed to:

$$B_{bl}+B_{fd}+B_{bk}>B_z+B_j+Bs-B_{bl}-A_B \tag{5}$$

Here $A_B=N_o \cdot \sigma \cdot d_{th} \cdot h_l \cdot a \cdot P$ is the benefit of DNWM through well infill and adjustment to enhance oil recovery. It could be seen from the formula (5), the expenses for plugging (B_{fd}), supplementary perforation cost (B_{bk}) of UEWM, the expenses for drilling (B_Z), construction cost on ground (B_j) and perforation cost (B_S) of DNWM were determined in the oilfield development designing. All the five constants could be known from the reservoir development planning. The profit of recoverable reserves in the first reservoir stage (B_{bL}) was the only variable, so the key factor in the formula (5) was the remaining oil could be product of the first layer stage.

If $B_1=B_2$, both UEWM and DNWM could be used, then it should be chosen according to the completeness of the injection-production system on ground surface. While $B_1>B_2$, old well pattern utilization methods should be used, and the formula derivation was the same as the above steps.

This method could quickly determine DNWM or UEWM should be adopted in the oil block. It could also provide reference for effective development of layer Sandstone Reservoir. According to the system model, there is only one variable B_{bl}, benefit at the first stage of reserve yield, which could be predicted based on the follow-up oil production（N_{bl}）from planning time of the upper-layer beginning production to the time of the economic ultimate water cut (EUWC) or of block abandoned of the first layer section. Then the upper layer development method was determined by comparing the cumulative oil production with the chart calculated by system economic model.

Therefore, EUWC of the block should be calculated firstly. Then the accumulated oil production to EUWC (N_{bl}) ought to be calculated.

2.2 The accumulated oil production (N_{bl}) to EUWC

The water drive stage development characteristics after polymer flooded strictly conformed to the water drive characteristic (Lu *et al.*, 2002; Wang *et al.*, 2007; Tang *et al.*, 2011; Gao *et al.*, 2011; Yu *et al.*, 2000; Yu *et al.*, 1998). Due to the influence of the swept volume and water cut rising in the ultra-high water cut stage, the higher predicted recoverable reserves and oil recovery value were obtained using the characteristic curve method of water drive (Zhou *et al.*, 2014; Yu *et al.*, 2000). The inverse tangent curve method was used to predict the water cut, while the recovery degree could be predicted based on water-drive curve method, which could eliminate the influence of high-prediction values from water drive curve method.

2.2.1 N_{bl}

According to the contrast, the d-type water drive rule curve method was chosen as the mai n method for accumulated oil production prediction (Gao *et al.*, 2007; Zou *et al.*, 2011).

$$\frac{L_p}{N_p} = A + B \cdot W_p \tag{6}$$

where,
$$N_p = \lg\left(\frac{f_w}{1-f_w}\right) - \frac{A+\lg(2.303B)}{B} \tag{7}$$

The reserve production N_{bl} of the first layer in follow-up water drive results from the cumulative oil production to EUWC minus the initial oil production of the upper layer.

$$N_{bl}=N_{PL}-N_{Pf} \tag{8}$$

where, $N_{PL} = \lg\left(\frac{f_{wl}}{1-f_{wl}}\right) - \frac{A+\lg(2.303B)}{B}$ and $N_{Pf} = \lg\left(\frac{f_{wf}}{1-f_{wf}}\right) - \frac{A+\lg(2.303B)}{B}$.

2.2.2 Water cut

The water cut curve of follow-up water flood after polymer flooded is shown in Fig. 2. The water cut increases rapidly in next 2 ~ 3 years after the polymer flooding stage, and then rises slowly, which could be approximately predicted by the arc tangent method (Lu *et al.*, 2002).

$$f_w = \frac{2}{\pi} \cdot \mathrm{arctg}(at+b) \tag{9}$$

Then,

$$tg\left(\frac{\pi}{2} \cdot f_w\right) = at+b \tag{10}$$

.It is found that the graph was a straight line with $\frac{\pi}{2} \cdot f_w$. Here, “a” is the slope of the straight line and “b” is the intercept. Thus, the oil block water cut and recovery degree could be predicted according to Formula 10.

2.2.3 Economical ultimate water cut (EUWC)

When the sales revenue equals to the cost, the water cut was EUWC of the block (Jiang *et al.*, 2008). EUWC could be calculated directly from current inputs and outputs based on the production data of oil block.

The basic formula of breakeven analysis was

$$(P - T_{\mathrm{r}})Q_{\mathrm{o}}T_{\mathrm{d}}a = B_{\mathrm{f}} + B_{\mathrm{v}} \tag{11}$$

Where, $B_v = CQ_oT_da + C_sQ_lT_d + (Q_l - Q_o + 1.31Q_o)C_{iw}T_d$ (12)

Formula (6) could be rewritten as

$$(P-T_r)\ Q_oT_da = B_f + CQ_oT_da + C_sQ_lT_d + (Q_l - Q_o + 1.31Q_o)C_{iw}T_d \tag{13}$$

After reorganized, the EUWC of the block was obtained:

$$f_{\mathrm{wl}} = \frac{B_{\mathrm{f}} - T_{\mathrm{d}}aQ_l(P - T_{\mathrm{r}}) + C_{\mathrm{s}}Q_lT_{\mathrm{d}} + CQ_lT_{\mathrm{d}}a + 1.31Q_lC_{\mathrm{iw}}T_{\mathrm{d}}}{CQ_lT_{\mathrm{d}}a + 0.31Q_lC_{\mathrm{iw}}T_{\mathrm{d}} - Q_lT_{\mathrm{d}}(P - T_{\mathrm{r}})a} \tag{14}$$

3 Results and discussion

3.1 Basic overview of Block SME

The northernmost structure of Daqing Oilfield was a typical layered sandstone reservoir controlled by short-axis anticline structure. It was the same hydrodynamic system with a unified oil and water interface. The block SME was in its southernmost, whose average burial depth was 958 ~ 1192m and the tectonic high point was 758m. The type II reservoir in the block included 16 sandstone groups such as SII, SIII, PI4-7, PII, and

GI1-4+5. In 2012, the block was determined to carry out the EOR development for type II reservoir. After preparing the reservoir engineering development plans, five layers combinations of SII1-6, SII7-16, SIII1-7, SIII8-PI4-7, and PII1-GI4+5 were identified for development. The first oil layer combination of SIII1-7 was developed. Its production time was August 2012, while the polymer injection time was March 2013. Till now, the block water cut is 97.07% (Table 1).

3.2 The system economic evaluation model calculation

Based on the static/dynamic data and economical parameters of SME block (Table 1, 2 and 3), the upper layer return development mode of the block was determined.

The cost of supplementary perforation and plugging in old well patterns are shown in Table 2, while Table 3 shows the cost of new wells' drilling and construction. The development mode of the block could be determined by the economic loss, which is caused by the oil production blocked at the first reservoir stage. Considering that the conversion rate between barrels/tons is 7.425, the commodity rate of crude oil is obtained as 98.37%.

According to the relationship between the actual strata and the well pattern, new well will be drilled on the optimal well position, so well adjustment could make contribute to higher oil recovery than old well pattern. Formula (5) could be changed to B_{bl} + 15.43 > 305.64-B_{bl}-A_B. According to the following production B_{bl} of the first formation and EOR (A_B) of DNWM and UEWM methods, theory chart under different oil prices could be set up and the development method could be chosen from it.

According to the statistics of the parameters in block SME, the geological reserves of the target return strata is 1759.2×10^4 t. DNWM could increase the recovery rate by about 2% compared to UEWM. The increased oil production is 35.2×10^4t. Then $A_B=N_o\cdot\sigma\cdot dth\cdot a\cdot P=1759.2\cdot2\%\cdot dth\cdot a\cdot P=35.2\cdot d_{th}\cdot a\cdot P$ could be obtained. The crude oil commodity rate is 98.37%. The reference chart of the actual development was calculated under different oil price of 40, 50, 60, 70, 80, and 90 $/BBL (Fig.3), which could be used to judge the upper (downer) layer development way of a block visually. When the oil price is $40/BBL, the initial production contribution is less than 32×10^4t. As for $70/BBL, the initial production contribution is less than 10.8×10^4t and the UEWM method should be adopted. Otherwise, the DNWM method should be chosen.

3.3 Calculation of cumulative oil production in the First Section of block

3.3.1 Water cut prediction

The injection time of the SME block was March 2013. The production had been already sustained for 63 months by May 2018. According to the Formula (10), we put tangent of the actual water cut and production time into the CARTESIAN coordinate system. $tg(\frac{\pi}{2}\cdot f_w)$ is in a straight line with time t (Fig.4). Here, a=0.3816, b=7.0326, the formula (10) was then changed to $tg(\frac{\pi}{2}\cdot f_w)=0.3816+7.0326$. The water cut per time could be calculated using the formula. The results were shown in Table 5. The relative error of water cut is less than 0.2% (Table 5), which could be used to optimize the block development model.

3.3.2 Cumulative oil production

According to the block's production data from May 2018 to July 2019， $\frac{L_P}{N_P}$ versus W_P was drawn in Fig. 5, which is a straight line. Here A=0.0026，B=7.5341 and the correlation is 0.9999. Formula (7) could be rewritten as $N_p=1\text{g}\left(\frac{f_w}{1-f_w}\right)-\frac{7.5341+1\text{g}\left(2.303\times0.0026\right)}{0.0026}$ (Fig.5). Then the cumulative oil production per time was calculated. The prediction error of oil production was about 1.0% (Table.4).

3.3.3 EUWC calculation of block

According to the economic parameters of SME oil block in 2019 (Table 5), the EUWC (Fig. 6) was calculated. When the oil price increases, water cut also increases at the same liquid condition. As liquid increases, water cut increases slowly. Besides, the EUWC tends to be the same when liquid is higher. When the liquid volume is 140 t/d and oil price is \$40/BBL, the EUWC becomes 97.55% and the daily oil production reaches 3.43 t/d.

3.4 Determination of block development mode

Return time of block SME was expected to be January 2023 based on design planning. According to the calculation method in chapter 3.3.1, predicted water cut will be 98.34% in that time. When oil price is \$40/BBL, the EUWC of the block is 97.55%. The time was May 2020 when the block reached to abandon level, earlier than the planned return production time January 2023. Then its cumulative oil production would be 0.0×10^4t, which is less than the cumulative production limit of 32×10^4 t. In this case, UEWM should be chosen. When the oil price is \$70/BBL, EUWC is 98.93% and the corresponding time is August 2027. From the planned return time January 2023 to August 2027, the block has a cumulative oil production of 25.54×10^4t, greater than the cumulative oil limitation 10.8×10^4t. Hence, the DNWM method should be chosen.

4 Conclusions

The system economic model was established based on the EUWC model of block. Combining the solution prediction model of arctangent water cut curve and water drive curve method, the type II reservoir secondary upper (downer) layer development model of SME block was built. The planning return time of block is January 2023 when the oil price is 40 \$/BBL. Here the UEWM mode should be chosen. However, when the oil price is 70 \$/BBL, the accumulated oil production reached to 24.3×10^4 t from the planned return production time, which was higher than the limited cumulative production (10.8×10^4 t). In this case, DNWM method should be chosen for SME block.

The model provides definite suggestions on whether to drill in the development of a specific block. Significant guidance is given to the development of layered sandstone reservoir. However, only one block can be considered at the same time and the specific economic parameter should be provided, which need further investigations.

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Declarations

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

WFL and ZYF worked on data collection and wrote the manuscript. FYJ directed the project, providing ideas and goals as well as logistical support. All the authors proofread the manuscript and provided their comments and insights. All the authors read and approved the final manuscript.

Availability of data and materials

The economic parameters and well production parameters in this paper are all obtained in Daqing Field. They are being used now and are reliable.

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Nomenclature

B_{sf} = The benefit of the upper layer return section will produce oil, M$

B_{bl} = Retention benefits of cumulative oil that produced by first reservoir , M$

B_{fd} = Perforation block charge of the first reservoir layer section, M$

B_{bk} = The cost of the old well perforate upper layer, M$

B_z = Drilling new well costs, M$

B_j = New well construction cost, M$

B_s = Perforation cost, M$

B_{sf1} = Cumulative oil production benefit of return to upper reservoir interval, M$

B_{bl} = Benefit of retaining yield of the first stage, M$

A_B = the benefit of recovery improved that new well drilling method increased than old well used through well infill and adjustment, M$

N = Remaining recoverable reserves of the target returning layer when existing well pattern was used to develop, M$

dth = Ton and barrel unit conversion rate, 7.425

hl = Exchange rate of RMB to US dollar，6.19

a = Commodity rate of crude oil，98.37%

,N_{bL} = The first development formation has remaining recoverable reserves, 10^4t

n_{do} = The number of oil wells that need to be plugged for using to upper layer

P_{do} = Unit price of oil well plugging first layer, M$

n_{dw} = The number of water wells that need to be plugged for using to upper layer

P_{dW} = The unit price of water well plugging, M$

n_{bo} = Number of oil wells to be supplementary perforation used for upper layer development

P_{bo} = Unit price of oil well supplementary perforation, M$ per well

n_{bw} = Number of water wells to be supplementary perforation used for lower layer development

P_{bw} = Unit price of water injection well supplementary perforation, M$

n_{zo} = Number of oil wells drilled in new drilling method

n_{zw} = Number of water injection wells drilled in new drilling method

H_z = Drilling depth，m

P_z = Unit drilling footage price，$/m

n_{jo} = Oil well number for construction

n_{jw} = Water injection well number for construction

P_j = Construction investment per well，M$

n_{so} = Number of oil well perforated in DNWM

n_{sw} =Number of water well perforated DNWM

P_s = Perforation cost per well，M$

N_1 = Remaining recoverable reserves of upper layer after development use new drilled well，10^4t

N_0 = The upper layer geologic reserve，10^4t

σ = EOR of new drilling well pattern encryption and adjustment than old well used to develop, %

B_v = Variable costs，composed with fluid production、oil production and water injection costs, $

T_d = Average annual production time for a single well, days

Q_o = Daily oil production, t/d; a: commodity rate of crude oil, %

Q_l = Daily liquid production, t/d

T_r = Tax of a ton oil, it consists of value added tax, urban construction fee, resources tax and surtax for education expense, $ /t

C = The sum of material cost per ton oil、fuel charge and power cost, Yuan

C_s = Treatment cost of a ton of liquid, Yuan

P = Price of crude oil, $/ t;

C_{iw} = Water injection cost, $ / m^3

f_{wl} = Economic ultimate water cut, decimal

B_f = The average fixed total cost of a single well, which is composed of salary, up-hole operation cost, oilfield maintenance charge, mine field cost, enterprise management fee, overhaul fund, scientific research fee and depreciation fee, $

f_w = Water cut of block, decimal

t = Time, month

a，b = Parameters need to calculate

L_P = Fluid cumulative production of block, 10^4t

N_P = Cumulative oil production of block, 10^4t

W_P = Cumulative water produced of block, 10^4t

N_{PL} = Block oil production cumulative when block is economic abandoned, 10^4t

N_{Pf} = Cumulative oil production at the time of upper layer need to production, 10^4t

f_{wl} = Economic limited water cut，decimal

f_{wf} = Water cut when the time of upper layer need production, decimal

A, B = Parameters need to calculate

Figures

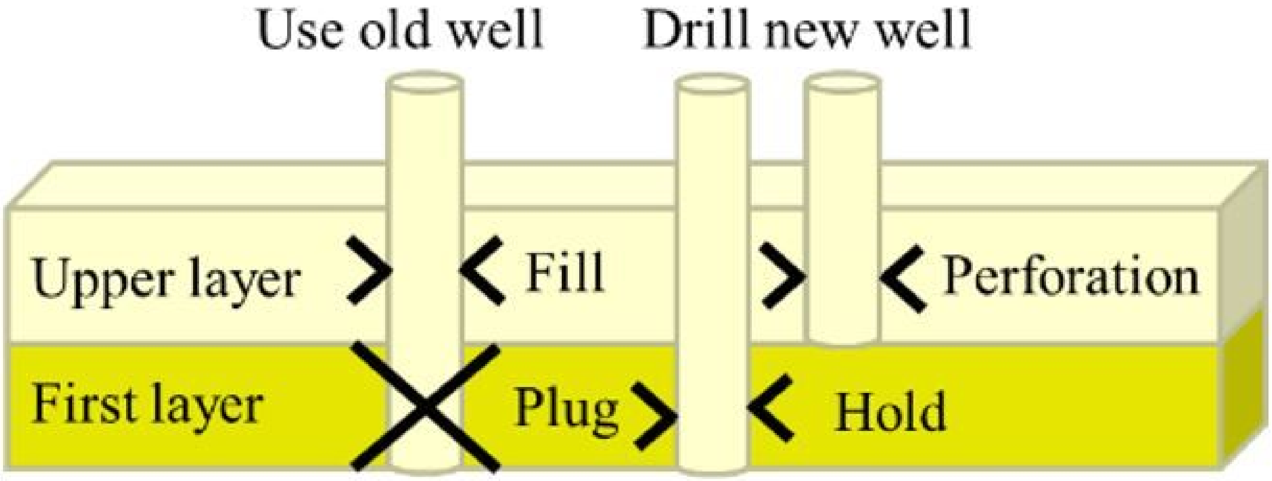

Figure 1

UEWM and NWM system model sketch map

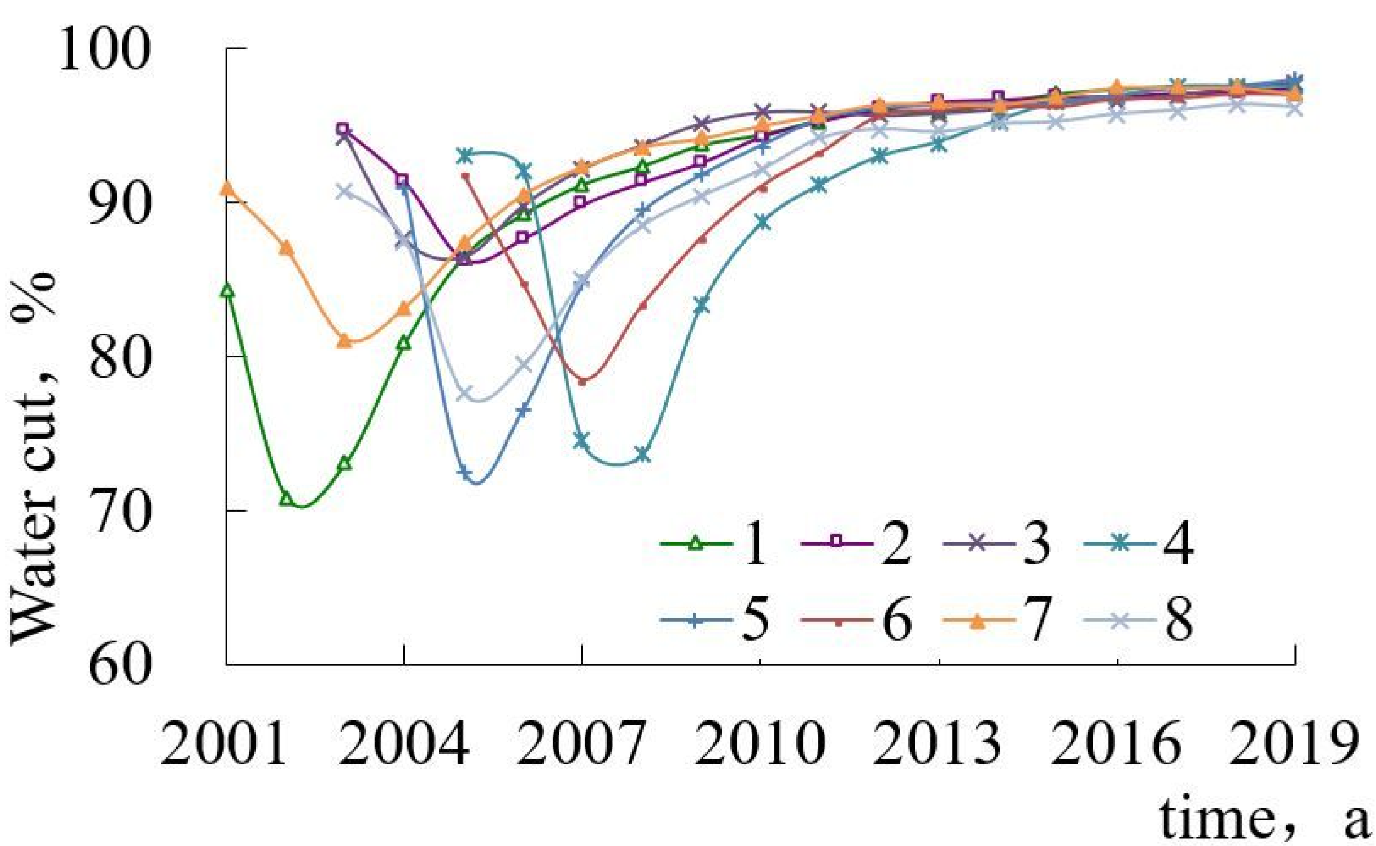

Figure 2

Water cut of polymer flooded oil block

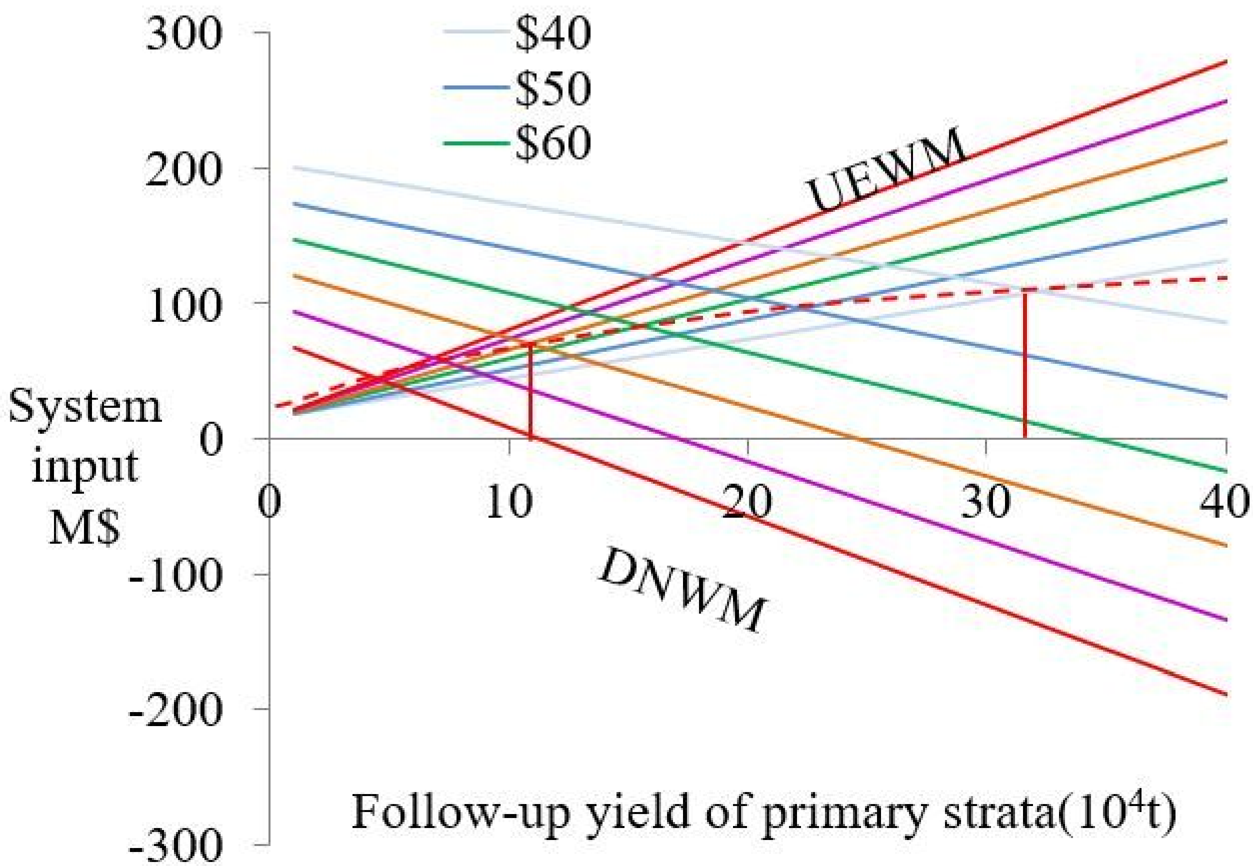

Figure 3

Chart of UEWM and DNWM in SME oil block

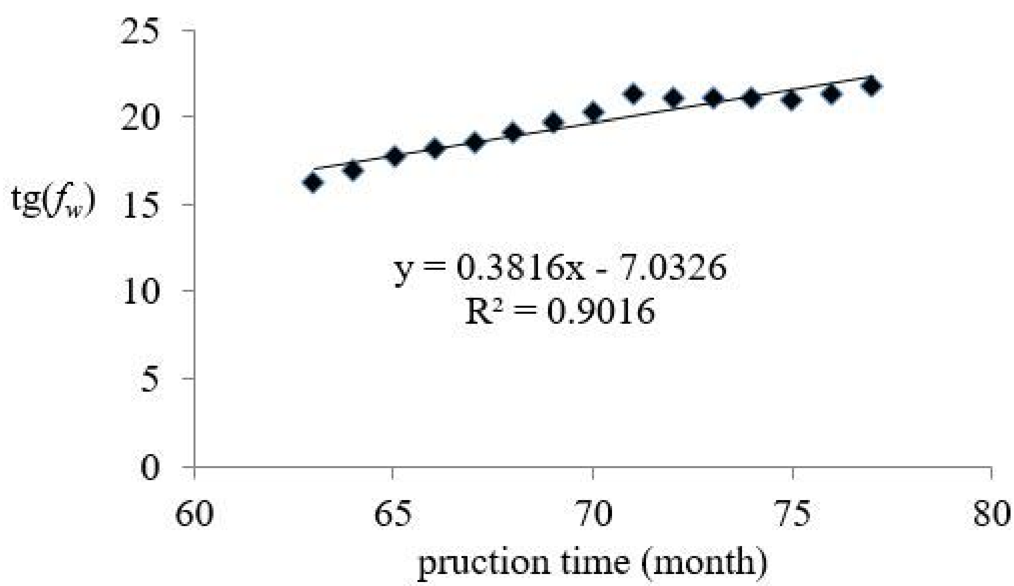

Figure 4

Water cut tangent and production time curve

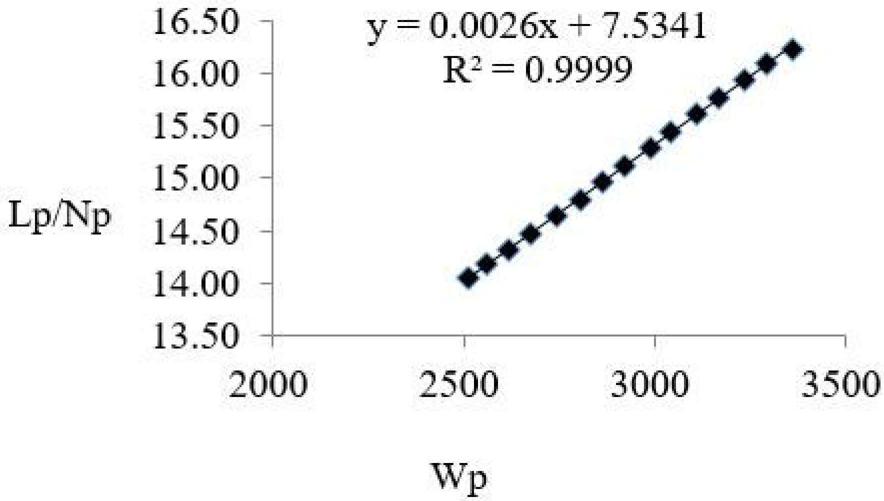

Figure 5

LP/NP and Wp curve

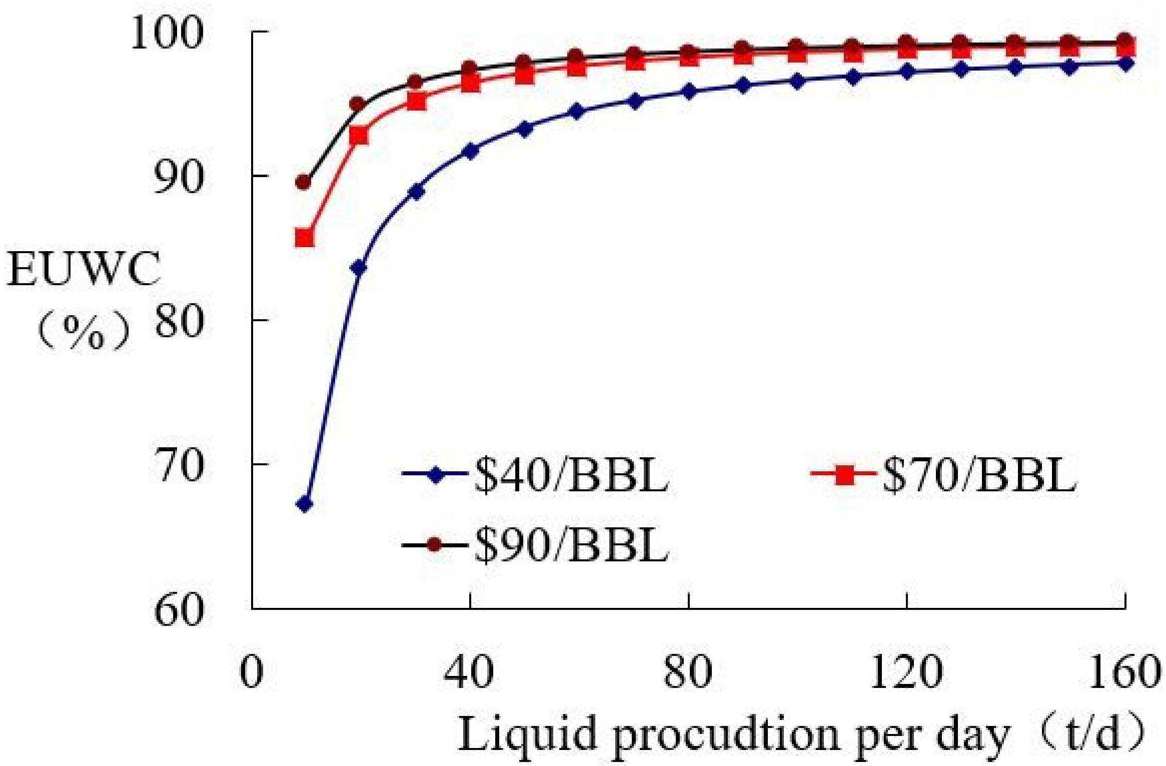

Figure 6

EUWC chart of oil block SME